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EARTH AND ENVIRONMENTAL SCIENCE IN FOCUS

YEAR 12

Christopher Huxley
Thomas Hubble
Steven McClean
Susan Filan

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Susan Filan
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INTRODUCTION

Earth and Environmental Science in Focus Year 12 has been written to meet the requirements of the NESA NSW Earth and Environmental Science Stage 6 Syllabus (2017). The text has been written to enable students to meet the requirements for achieving a Band 6 in the Higher School Certificate. It also allows all students to maximise their learning and results.

Earth and Environmental Science deals with renewable and non-renewable earth resources and how these can be extracted. It explores environmental issues as well as our ability to live sustainably on planet Earth.

Earth and environmental scientists are not just concerned with studying resources. They explain observations and make predictions using models, laws and theories. Models can be expressed in a range of ways – via words, images, mathematics (numerical, algebraic, geometric and graphical) or physical constructions. Looking at past environments and events, using models and computerised simulations helps Earth and environmental scientists make predictions about the future.

In this age of rapid scientific change and constant access to information, it is important that people are able to be discerning and apply a scientific approach to understanding and evaluating what is presented in the media. This book has therefore been written to develop scientific literacy, encouraging students to use evidence to evaluate claims and conclusions presented. Earth and environmental scientists need to be able to apply their own reasoning and knowledge to construct a valid scientific argument.

Earth and Environmental Science in Focus Year 12 has been written by academic and classroom teaching experts. The authors were chosen for their comprehensive knowledge of the Earth and Environmental Science discipline and best teaching practice in Earth and Environmental Science education at secondary and tertiary levels. They have written the text to make it accessible, readable and appealing to students. Numerous current contexts are included to ensure students gain a wide perspective on the breadth and depth of Earth and Environmental Science. The rigorous and methodological approach is designed to ensure that students can reach the highest possible standard. The intention has been to ensure all students achieve the depth and interest necessary to pursue tertiary studies in Earth and Environmental Science.

Each chapter of *Earth and Environmental Science in Focus 12* text follows a consistent pattern. Learning outcomes appear on the opening page. The text is then broken into manageable sections under headings and subheadings. Question sets are found at the end of each section. Diagrams that are easy to interpret illustrate important concepts to support the text. New terms are introduced in **bold type** and are defined in a glossary at the end of the book. Important concepts are summarised to help students to make notes.

A comprehensive set of review questions at the end of each chapter expands on the question sets for further revision and practice. Questions have been set to accommodate the abilities of all students. Complete worked answers appear on the student website.

Investigations demonstrate the high level of importance the authors attach to exploring and discovering the world through practical activities that use the investigative skills of a working scientist. The hands-on activities introduce, reinforce and enable students to practise the Working Scientifically strand of investigation skills of the NSW syllabus, especially experimental design, data collection, analysis and conclusions. Chapter 1 explores in detail the concepts of reliability, validity and the nature of scientific investigation using the scientific method; it provides valuable information for performing and analysing investigations and carrying out depth studies. Detailed information is provided to enhance students' experiences and to provide them with information that will maximise their marks in this fundamental area. Student learning is reinforced throughout the course.

Students are encouraged to evaluate experimental design and consider ideas for improvement, taking into account accuracy, precision, uncertainty and error, all of which are concepts that are introduced in the first chapter. This invaluable tool supports student learning through chapter questions and investigations.

Earth and Environmental Science in Focus Year 12 provides students with a comprehensive study of modern Earth and Environmental Science that will fully prepare them for exams and future studies in the area.

AUTHOR TEAM

Christopher Huxley

Christopher Huxley holds Science degrees in Applied Biology from the University of New South Wales, and in Geology and Geophysics from Macquarie University. He also holds Masters degrees in Education from the University of New South Wales and ICT and Education from Charles Sturt University. Chris has taught HSC Earth and Environmental Science since 2000 and has experience in teaching HSC Physics and Biology.

Chris seeks to show his students the wonder and utility of scientific understanding. His passion for teaching Science has led him to present workshops on a range of subjects to other teachers and to develop extensive experience in Science curriculum writing and assessment. He is a recipient of a Distinguished Service Award from the Science Teachers' Association of NSW.

Chris currently teaches at Kinross Wolaroi School in Orange and has worked previously in independent, state and Catholic high schools. Chris has previously co-authored a two-volume text on Earth and Environmental Science. He is looking forward to extending his knowledge of inland ecology after the completion of this text.

Thomas Hubble

Thomas Hubble is a marine geologist who teaches Engineering Geology and Introductory Geology classes to undergraduate students and Rock Engineering to postgraduate students at the University of Sydney. He has developed primary and secondary school curricula for the NSW Board of Studies and Australian Curriculum and Reporting Authority.

Tom has worked in the CAPSTAN program, which trains postgraduate Marine Science students aboard the CSIRO's deepwater research vessel RV *Investigator*, and has been recognised for good teaching with University of Sydney and Australian College of Educators awards. He has served as an Associate Dean and Prodean in the Faculty of Science between 2004 and 2017. Tom also convened the 4th International Conference on Soil-Eco-Engineering at the University of Sydney in July 2016.

Steven McClean

Steven McClean has a BAppSc (Geology) from University of Technology Sydney and a MAppSc (Environmental Geology, Engineering Geology and Hydrogeology) from the University of New South Wales. He worked as an exploration geologist from 1978 to 1985. He has taught Geology to first and second year university students (at University of Technology Sydney). He has taught Computing, Geology, Chemistry (in New South Wales and Great Britain), Biology and Earth and Environmental Science to HSC students since 1985 at Barker College, Marist High School Kogarah, Marist Sisters College, Knox Grammar School and The Perse School (England). His current position is at The Pittwater House Schools. He is a member of the Geological Society of Australia (GSA) and the Australian College of Education. He has presented papers at GSA conferences over the last 20 years and is a regular book reviewer for the GSA.

Susan Filan

Susan Filan is a NSW Education Officer for Australian Earth Science Education. She received her BA (*summa cum laude*) in Biological Sciences from Mount Holyoke College (USA) and MA in Organismic and Evolutionary Biology from Harvard University (USA). She first travelled to Australia on a Fulbright Fellowship to hunt for fossils at Riversleigh in Queensland. Susan worked in medical research before gaining her GradDip Ed (Secondary Science) from Macquarie University. In addition to teaching, Susan has been involved in curriculum writing and has authored textbook chapters for Years 7–10 Science. She is an experienced teacher of Earth and Environmental Science who regularly presents at Meet the Markers and other professional development events.

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Chris Huxley would like to thank his wife **Leanne** for her support throughout the writing process, without which he could not have succeeded.

Steve McClean would like to dedicate his contribution to his three wonderful children – **William**, **Penelope** and **Christopher**.

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USING *EARTH AND ENVIRONMENTAL SCIENCE IN FOCUS*

Earth and Environmental Science in Focus Year 12 has been purposely crafted to enable you, the student, to achieve maximum understanding and success in this subject. The text has been authored and reviewed by experienced educators, academics and researchers to ensure up-to-date scientific accuracy for users. Each page has been carefully considered to provide you with all the information you need without appearing cluttered or overwhelming. You will find it easy to navigate through each chapter and see connections between chapters through the use of margin notes. Practical investigations have been integrated in the text so you can see the importance of the interconnectedness between the conceptual and practical aspects of Earth and Environmental Science.

The content is organised under four modules as set out in the NESA Stage 6 Earth and Environmental Science syllabus. Each module begins with a **module opening page**.

Each chapter begins with a **chapter opening page**. This presents the learning outcomes written in student-friendly language from the NESA Stage 6 Earth and Environmental Science syllabus that will be covered in the chapter.

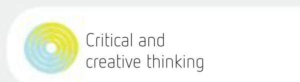
To improve comprehension, several strategies have been applied to the preparation of the text to improve literacy and understanding. One of these is the use of shorter sentences and paragraphs. This is coupled with clear and concise explanations and real-world examples. New terms are bolded as they are introduced and are consolidated in an end-of-book glossary.

Throughout the text, important ideas, concepts and theories are summarised in **concept boxes**. These provide repetition and summary for improved assimilation of new ideas.

KEY CONCEPTS

- Local initiatives are an effective way to address ecological problems in local areas.
- Sustainability initiatives build community among local residents.
- Bathurst Council improved biodiversity by mapping and rehabilitating roadside vegetation.
- Solar my School resulted in substantial greenhouse gas reductions by installing solar panels in schools.

Learning across the curriculum content has been identified by NESA as important learning for all students. This content provides you with the opportunity to develop general capabilities beyond the Earth and Environmental Science course, as well as links into areas that are important to Australia and beyond. This content has been identified by a margin icon.



Earth and Environmental Science is a science and you need to be given the opportunity to explore and discover the living world through practical investigations. The **investigations** introduce and reinforce the Working scientifically skills listed in the NESA Stage 6 Earth and Environmental Science syllabus. In some cases, the investigations are open-ended. These provide you the opportunity to design and carry out your own scientific investigation, either individually or in a group. At times, you are prompted to consider ideas for improvement or further investigation to illustrate that science is an ongoing and improving process. Other investigations are secondary sourced, meaning that you need to research the subject using data and information gained by other people. Further information on how to conduct a scientific investigation can be found in chapter 1.

INVESTIGATION 7.4

Open-ended investigation – build an earthquake resistant structure

Engineers must carefully test building designs to determine their resistance to seismic forces. In order to test these designs, they place components of a building or scale models on a shake table and test them during simulated earthquakes.

Information and communication technology capability

Critical and creative thinking

Literacy

AIM

To build a shake table that can be used to replicate earthquake ground movement and use it to test resistant structures

CHAPTER 7 » PREVENTING NATURAL DISASTERS 175

Risk assessment tables occur within the investigations. These tables highlight the risks of the investigation and provide suggestions on how to minimise these risks; the tables are not to be considered comprehensive. Teachers are expected to amend tables in the case of substitutions or in the case of any additional risks. This may mean obtaining and following Safety Data Sheets for certain chemicals. All teachers are required to follow the safety guidelines of their school and associated government legislation when students are in their care.

RISK ASSESSMENT

Full understanding of a concept is often constructed from many pieces of information. Due to the sequential nature of a book, this information cannot always be presented together as it is best placed in other chapters. Links between concepts that occur on other pages and chapters are indicated using the **margin notes**.

You will learn more about the minerals of the mantle and crust in Chapter 3.

Regular opportunities to recall new terms and review recent concepts are provided as short **Check your understanding** question sets throughout each chapter.

CHECK YOUR UNDERSTANDING 2.1

1 Identify the two factors that enable life to thrive on Earth.
2 Describe the oldest evidence for microbial activity on Earth.
3 a Name the materials that Miller placed in his experimental apparatus.
  b Name the materials that were synthesised in the Miller–Urey experiment.
  c How did the Miller and Urey experiment provide evidence that life could have started in abiotic processes?
4 Name two or more organic materials that are essential for Earth's organisms to function.
5 a List some of the organic materials discovered within the Murchision meteorite.
  b Explain the significance of this finding in relation to life on Earth.
6 Outline the main points of the panspermia hypothesis.
7 Name the three types of hydrothermal vent, describe their characteristics and indicate where they are found.
8 Name the inorganic materials that precipitate to form black smoker chimneys.
9 Name the inorganic materials that precipitate to form white smoker chimneys.
10 What type of hydrothermal vent occurs in the Atlantic Ocean's Lost City vent field? Why are vents the subject of great scientific interest?
11 a Name the nutrients released by hydrothermal vents that chemosynthetic bacteria use to produce carbohydrates.
  b Identify some of the organisms that consume the carbohydrates produced by chemosynthetic microbes at hydrothermal vents.

The **end-of-chapter review** provides:

- a full list of all the key concepts covered in the chapter. This **chapter summary** will be a valuable tool when you are revising for tests and exams.

2 CHAPTER SUMMARY

- Unmetamorphosed sedimentary rocks of early Archean age are very rare. This makes the search for the signs of ancient life very difficult. Nevertheless, there is good geological evidence for active microbial organisms being active on Earth 3.8 billion years ago.
- Stanley Miller and Harold Urey synthesised amino acids and other organic compounds by discharging electrical sparks through a gaseous mixture of CH_4, NH_3, H_2O and H_2, and demonstrated that amino acids, the precursor components of proteins, could have been generated from inorganic processes.
- Comets and carbonaceous meteorites commonly contain phosphorus and a variety of complex organic molecules that are precursor materials required for the development of microbial organisms.
- The panspermia hypothesis proposes that life occurs everywhere in the universe and that Earth's organisms could have evolved from organic material that was brought to Earth from space on meteorites or comets.
- Hydrothermal vents are features on the deep sea floor where jets of sea water are ejected. The jets of sea water contain dissolved sulfides and sulfates, which support ecosystems in which chemosynthetic microbes produce carbohydrates and organic material that are consumed by browsers and filter feeders. In turn, these organisms are consumed by scavengers and predators.
- There are three common types of hydrothermal vents. Black smokers eject very hot (350°C) sea water rich in dissolved iron and copper sulphides. White smokers eject hot (250°C) sea water rich in calcium and barium sulfates. Alkaline vents eject warm (60°C) sea water rich in hydrogen and sulfur, dissolved silica as well as calcium, magnesium, nickel, iron and carbonates.
- Stromatolites are a type of layered organic sedimentary deposit formed by photosynthetic microbial colonies. Extracellular slime produced by the microbes traps layers of sediment and as the microbial colony grows towards the light, their layers of sediment develop very distinctive cone-shaped, dome-shaped, flat or wavy layered structures.
- The oldest known stromatolites formed 3.4–3.5 billion years ago and are known from deposits such as Western Australia's Strelley Pools. There is a continuous record of stromatolites from these very ancient examples through to the present day.
- Modern-day stromatolites are colonies of prokaryotic microbes. The upper layers are dominated by photosynthetic cyanobacteria and purple bacteria producers. The lower layers consist of consumer prokaryotes, including anaerobic bacteria, sulfate-reducing bacteria and methanogenic archea. Stromatolitic cyanobacteria generate oxygen as a photosynthesis by-product.
- Cyanobacteria are single-celled, photosynthetic prokaryotic microbes that occur in most Earth environments that receive sunlight. Modern cyanobacteria produce oxygen by photosynthesis utilising chlorophyll. Chloroplasts are a type of symbiotic cyanobacteria that have been incorporated into the cells of eukaryotic plants.
- The oldest known fossils of cyanobacteria are 2600 million years old. The first cyanobacteria probably evolved by 2700 million years ago, but this group of prokaryotes may have appeared even earlier in the Archean.
- Stromatolites are largely responsible for increasing the concentration of oxygen in the Archaen atmosphere.
- Evolutionary events in the biosphere increased oxygen production by photosynthetic organisms and contributed to changing the composition of the atmosphere and surface conditions on Earth during the Great Oxidation Event and the Neoproterozoic Oxidation Event, and due to the proliferation of terrestrial plants during the Devonian and Carboniferous periods.
- The Great Oxidation Event occurred between 2500 million and 2000 million years ago. The proliferation of photosynthetic cyanobacteria at this time oxygenated the oceans and produced most of Earth's banded iron formations. Reduced atmospheric CO_2 also reduced the greenhouse effect, which cooled the planet and generated extensive continental icesheets and a major period of global glacial conditions.
- The Neoproterozoic Oxidation Event occurred between about 800 million and 600 million years ago. It is associated with global cooling, extensive continental glaciations and increased oxygenation of the oceans and the atmosphere to levels similar to those of the present day. This is one of the factors required for the evolution and survival of large marine animals.
- The colonisation of the land masses by plants in the Devonian and Carboniferous periods between 400 million and 350 million years ago also caused a significant increase in atmospheric oxygen and an associated reduction in atmospheric CO_2. This event contributed to global cooling and helped cause a globally significant extended period of continental glaciation.
- The characteristics and extent of chemical weathering of rocks changed due to the Great Oxidation Event and the Neoproterozoic Oxidation Event. Sulfide minerals ceased to be stable at Earth's surface after the Great Oxidation Event, and clay mineral production by chemical weathering increased during and after the Neoproterozoic Oxidation Event.
- The colonisation of terrestrial environments by plant species in the Devonian probably stabilised soils by anchoring to the layer of bedrock underneath the soil as tree root

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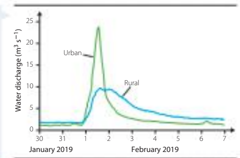
- **end-of-chapter review questions** that review understanding and provide opportunities for application and analysis of concepts and how they interrelate.

6 CHAPTER REVIEW QUESTIONS

Review quiz

1 Explain why different systems are used to classify explosive and effusive volcanos.
2 List the effects on the biosphere of a major explosive volcanic eruption and a major effusive volcanic eruption. What are the differences between the two lists?
3 Compare the effects on the atmosphere of a major explosive volcanic eruption and a major effusive volcanic eruption.
4 Evaluate the effects on the atmosphere if an eruption of VEI 6 produced large volumes of sulfate aerosols.
5 A major eruption of a volcano in Iceland has the potential to produce serious changes in temperature in the northern hemisphere but only limited changes in the southern hemisphere. Explain why this is the case.
6 The island of Java has a very high population density while the Okhotsk Peninsula in Russia has a very low population density. Both geographic locations have a similar density of active, explosive volcanos. Outline how a major eruption would have different impacts on the biosphere in both locations.
7 Explain why the location, chemistry of the eruption cloud and style of eruption all combined to produce global temperature change after the eruption at Mount Pinatubo in 1991.
8 Mount St Helens in 1980 and El Chicon in 1982 had similar VEIs and sulfur dioxide levels produced in the eruption. Explain why the 1980 eruption produced a much smaller global temperature change than the 1982 eruption.
9 The 1991 eruption of Mount Pinatubo was the second largest of the 20th century. Very few human deaths occurred as a direct result of the eruption. Explain why this was the case.
10 There are four subduction volcanos on the island of Luzon. Mount Pinatubo is the only volcano in the north-west of the island of Luzon that has erupted in the last 500 years but when geological mapping was done around the volcano, there was extensive evidence of lahars from older eruptions. Imagine that you are a senior geologist attached to the Philippine government. What programs would you put in place if a series of earthquakes was detected near each of the other three volcanos on Luzon?
11 Gases released from volcanos have the potential to produce both heating and cooling of the atmosphere. Explain how this can occur.
12 Flash floods are becoming more common as the intensity of thunderstorms increases with climate change. Much of the water involved in flash flooding comes from urban roof drainage. What practices could a local council put in place to reduce the amount of stormwater run-off from suburban houses?
13 In 2012, the New South Wales government implemented a new bushfire management plan for the state. The plan limits the building materials that can be used in the construction of new buildings within 1 km from bushland. Research the requirements for windows, doors and decks under the new bushfire management plan and evaluate whether there is an advantage in making the changes retrospective.
14 Discuss and evaluate whether water in large shallow dam impoundments should be kept or released as a series of timed environmental flows to duplicate the historical flood pulses that would have moved down inland river systems.
15 Level 1 water restrictions have been put in place in a number of locations as dam levels have dropped. Some country regions are on Level 4 restrictions. What can you do at your home to reduce the water usage in your house and around your property?
16 Many areas of National Parks in New South Wales have not had a substantial bushfire through them in many years. What effect would this be having on native plant life?
17 Figure 6.32 shows the discharge of water through two flood areas in 2019. The green line represents a flood in an urban area, the blue line represents a flood in a rural area. Explain the differences in the two graphs.

FIGURE 6.32 Discharge of water through two flood areas in 2019



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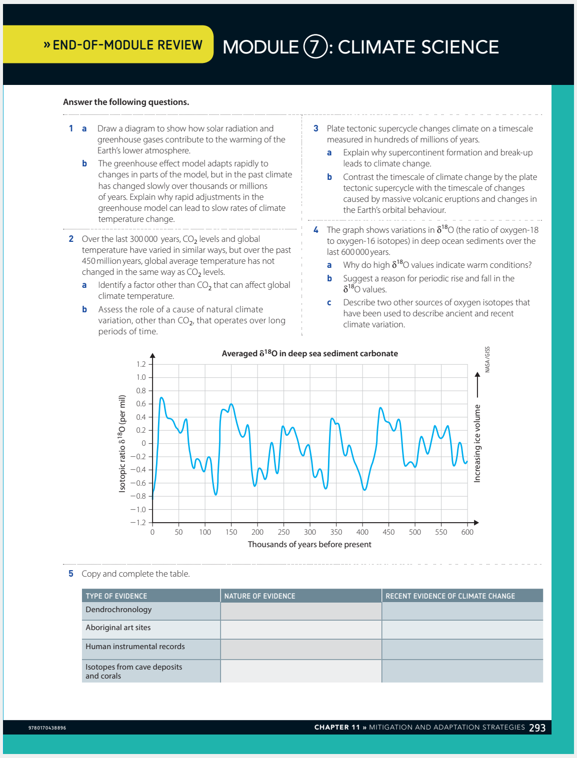
Each module concludes with a **module review**. This contains short-answer questions that provide you with the opportunity to assimilate content that may occur across the chapters that fall within that module.



» END-OF-MODULE REVIEW

MODULE 7: CLIMATE SCIENCE

Answer the following questions.

1 a Draw a diagram to show how solar radiation and greenhouse gases contribute to the warming of the Earth's lower atmosphere.

b The greenhouse effect model adapts rapidly to changes in parts of the model, but in the past climate has changed slowly over thousands or millions of years. Explain why rapid adjustments in the greenhouse model can lead to slow rates of climate temperature change.

2 Over the last 300 000 years, CO_2 levels and global temperature have varied in similar ways, but over the past 450 million years, global average temperature has not changed in the same way as CO_2 levels.

a Identify a factor other than CO_2 that can affect global climate temperature.

b Assess the role of a cause of natural climate variation, other than CO_2, that operates over long periods of time.

3 Plate tectonic supercycle changes climate on a timescale measured in hundreds of millions of years.

a Explain why supercontinent formation and break-up leads to climate change.

b Contrast the timescale of climate change by the plate tectonic supercycle with the timescale of changes caused by massive volcanic eruptions and changes in the Earth's orbital behaviour.

4 The graph shows variations in $\delta^{18}O$ (the ratio of oxygen-18 to oxygen-16 isotopes) in deep ocean sediments over the last 600 000 years.

a Why do high $\delta^{18}O$ values indicate warm conditions?

b Suggest a reason for periodic rise and fall in the $\delta^{18}O$ values.

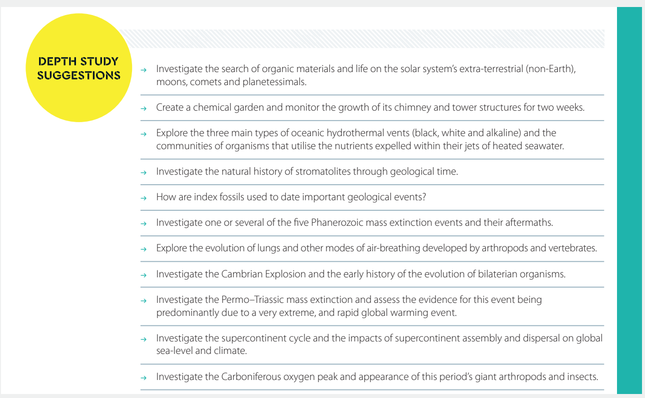
c Describe two other sources of oxygen isotopes that have been used to describe ancient and recent climate variation.

5 Copy and complete the table.

TYPE OF EVIDENCE	NATURE OF EVIDENCE	RECENT EVIDENCE OF CLIMATE CHANGE
Dendrochronology		
Aboriginal art sites		
Human instrumental records		
Isotopes from cave deposits and corals		

9780170438896 CHAPTER 11 » MITIGATION AND ADAPTATION STRATEGIES 293

The **depth study** provides you with the opportunity to pursue a topic of interest from the course. The depth study enables you to study a topic in more depth and present your findings in a format of your choice. Advice and support to assist you in undertaking your depth study can be found in Chapter 1, as well as suggestions for topics provided at the end of each module review. Refer to the NESA Stage 6 Earth and Environmental Science syllabus for the full details on scoping and completion of your depth study.



DEPTH STUDY SUGGESTIONS

- Investigate the search of organic materials and life on the solar system's extra-terrestrial (non-Earth), moons, comets and planetessimals.
- Create a chemical garden and monitor the growth of its chimney and tower structures for two weeks.
- Explore the three main types of oceanic hydrothermal vents (black, white and alkaline) and the communities of organisms that utilise the nutrients expelled within their jets of heated seawater.
- Investigate the natural history of stromatolites through geological time.
- How are index fossils used to date important geological events?
- Investigate one or several of the five Phanerozoic mass extinction events and their aftermaths.
- Explore the evolution of lungs and other modes of air-breathing developed by arthropods and vertebrates.
- Investigate the Cambrian Explosion and the early history of the evolution of bilaterian organisms.
- Investigate the Permo–Triassic mass extinction and assess the evidence for this event being predominantly due to a very extreme, and rapid global warming event.
- Investigate the supercontinent cycle and the impacts of supercontinent assembly and dispersal on global sea-level and climate.
- Investigate the Carboniferous oxygen peak and appearance of this period's giant arthropods and insects.

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Each chapter is supplemented with the following digital resources.

- Worksheets to review concepts and to practise applying understanding to new examples
- A review quiz containing 20 auto-correcting multiple-choice questions to review understanding
- Links to websites that contain extra information. These are hotspotted within the NelsonNetBook and they can also be accessed at **nelsonnet.com.au**.

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1 Working scientifically and depth studies

OUTCOMES

In this chapter you will learn about:

- developing skills that can be used in investigating scientifically
- how to develop and evaluate scientific questions that can be tested scientifically
- how to design and evaluate investigations to obtain primary or secondary data
- conducting investigations to obtain primary and secondary data
- conducting investigations so that data obtained are valid and reliable
- selecting and processing different types of data
- analysing and evaluating different types of data
- using evidence and critical thinking to solve scientific problems
- communicating to different audiences.

Getty Images/PamelaJoeMcFarlane

FIGURE 1.1 Collecting samples in the field. In how many scientific disciplines might scientists use such samples in their research?

Science is the systematic study, by observation and experiment, of the natural and physical world (Figure 1.1). Science is characterised by a way of thinking and working and, fundamentally, by questioning. The knowledge and understanding that arises from this questioning is not in itself science. It is the product of science, as is the technology that arises from this knowledge and understanding. Science is **empirical**, which means that when scientists ask questions, they seek to answer them using systematic methods to gather and test evidence. Scientists use both observational and experimental evidence in their work. Science also involves verifying and testing evidence. Scientists expose their research to the critical scrutiny of other scientists, a process called **peer review**.

Earth and Environmental Science is an interdisciplinary field of research that integrates a wide range of scientific disciplines in the study of Earth and the environment to contribute to solutions to environmental issues. The subject has its origins in the study of nature that predates modern science. Until the 19th century, the study of nature and Earth was referred to as natural philosophy. Today many scientific disciplines investigate aspects of Earth and the environment. To study it requires knowledge and investigation methods drawn from a range of other scientific disciplines, including ecology, geology, biology, chemistry, physics, mineralogy, applied mathematics, soil science, meteorology, information science, geography and many other specialist disciplines.

1.1 The nature of Earth and Environmental Science

In Earth and Environmental Science, observations lead to questions. Questions lead to investigations and these in turn are used to generate testable scientific theories. Rather than testing to prove a theory, true scientists test theories to try to disprove them. For a theory to be considered scientific, it must be testable and **falsifiable** – able to be disproved. This sets science apart from many other areas of inquiry in which there are theories that cannot be tested or disproved. Such theories are not scientific.

Scientists talk about providing evidence to support a theory rather than proving a theory. When a large amount of evidence has been gathered to support a theory, the theory is accepted by the scientific community. Plate tectonics and the role of biodiversity in ecological stability are good examples of theories in Earth and Environmental Science that have much evidence supporting them. However, no matter how much evidence is gathered to support a theory, it only takes one experiment or a verifiable observation that disagrees to disprove a theory. As Einstein said: 'No amount of experimentation can ever prove me right; a single experiment can prove me wrong.'

There are many examples of theories and hypotheses in Earth and Environmental Science that were proposed and later rejected or changed when new evidence came to light. For example, in the late 18th century, a group known as the Neptunists proposed that all crystalline rocks were formed by the crystallisation of minerals in an ancient ocean. Opposing the ideas of the Neptunists were the Plutonists, who argued that many crystalline rocks, such as granite, had their origin in molten rock from within Earth. Careful field observations and reasoning showed the Neptunist theory to be wrong and led to our modern understanding of how igneous rocks form. Some theories have been rejected because the scientific method used could not be repeated and was later shown to be invalid, but the accumulation of evidence and willingness of some scientists to view things in new ways mean that science is most often self-correcting over time.

KEY CONCEPTS

- Scientific theories are falsifiable: they can be disproved but they cannot be proved. For a theory to be accepted, it must be supported by a great deal of evidence.
- A good hypothesis is testable and falsifiable. It only takes one study that disagrees with the hypothesis to disprove it.
- No amount of success in testing a hypothesis can prove a theory right. Each confirming instance only increases our confidence in an idea.

The scientific method – an overview

The **scientific method** is the process of systematically gathering data by observation and measurement and using the data to formulate and test hypotheses. The body of scientific knowledge that we accept today has been accumulated from such investigations.

Critical and creative thinking

Hypotheses

The scientific method begins with asking questions (sometimes called research questions). Based on these questions you formulate a **hypothesis**, which is a tentative answer to your question. This usually involves reading the literature to see if anyone has already answered your question or investigated a similar question. For example, we might hypothesise that if a salt solution is cooled slowly, the crystals formed will grow larger than if the solution is cooled rapidly. This hypothesis could be tested by performing experiments in which we measure the size of crystals formed in salt solutions cooled at different rates.

In scientific investigations, progress is often not a straight line from one point to the next, but a series of progressions that sometimes veer off the original path. Often the results of initial experiments and new observations will lead to a reassessment of the direction taken and a change in hypothesis and a redefinition of the experimental design. The scientific method is summarised in Figure 1.2 (page 4).

Experiment design and validity of results

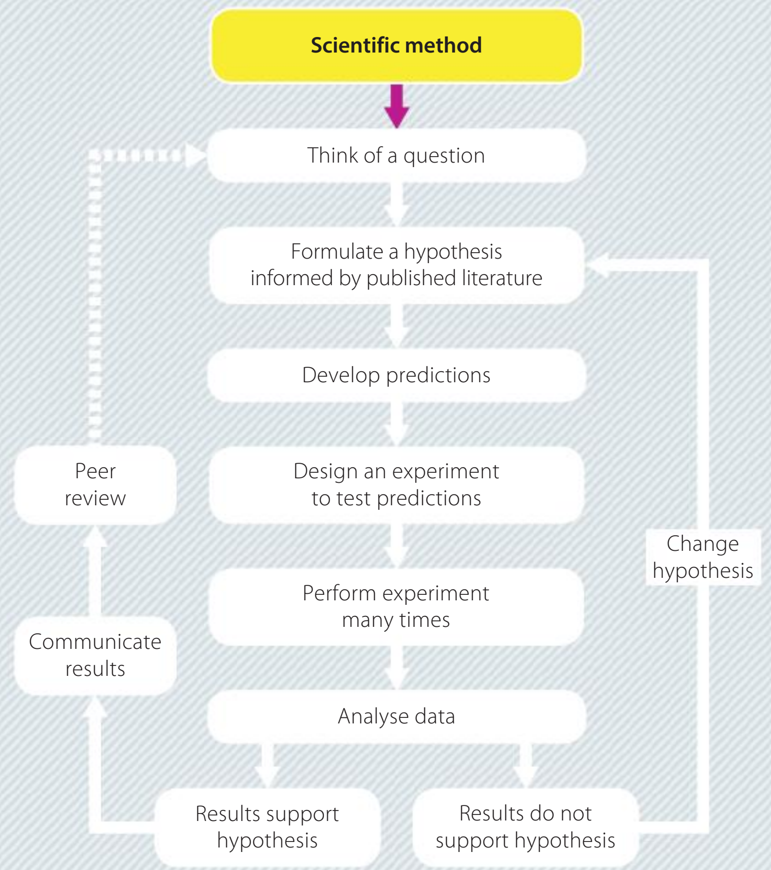
An experiment is designed and performed to test a hypothesis and the results are analysed. If the results of the experiment agree with the hypothesis, then the hypothesis is supported. However, the hypothesis is not proved but only supported. There may be other hypotheses that would also be supported by the results. Be aware that in some areas of Earth and Environmental Science it is normal practice to try to generate multiple hypotheses to explain data and then reduce their number by testing. If the results of a well-designed experiment do not agree with the prediction, then the hypothesis is not supported and the scientist needs to investigate another explanation.

An experiment is considered **valid** when the intended hypothesis is tested and repeating the experiment gives consistent results. A valid experiment involves setting up controls and making sure that the only thing that changes in the experiment is the variable being tested. All other conditions must be **controlled** to remain the same.

An experiment is considered **reliable** when it can be repeated to give the same results and random error is eliminated or minimised.

An experiment is considered accurate when its measurements are close to the true value. For **accuracy** to be achieved, the risk of error in measurement must be kept to a minimum. For an experiment to be valid, it must be reliable and accurate. This will be dealt with in more detail in section 1.3 (page 17).

FIGURE 1.2
The scientific method



Communication and peer review

Reproducibility and peer review are important aspects of science. If an experiment cannot be repeated to give the same results, then there is a good chance that a mistake was made. Experiments are considered valid when they can be repeated to give the same results. If the uncertainties in the measurements are so large that you cannot draw any conclusions from the data, then the experiment is not valid.

Scientists communicate their work to each other to share new ideas and information and as a way of contributing to the ongoing development of science. Scientists usually communicate new findings to each other by writing articles for scientific journals. When you conduct an experiment and write a report on it, the report is very much like a scientific paper.

Before a scientific paper is published, it is reviewed and evaluated by other scientists who are experts in their field of science. They try to determine whether the experiments conducted were appropriate, whether the conclusions drawn were valid, and whether the hypothesis was clearly supported or not. If the paper is considered to make a useful contribution to science, and the experiments and analysis are valid, it will be published. Other scientists can then access the paper and use it to inform their own work. Scientists also communicate their work to the public and to students in other ways.

Descriptions of the scientific method are somewhat idealised. In practice, the scientific method may be a bit messy and not follow the steps in order. Sometimes scientists only have questions but no hypothesis to answer them. In these cases, scientists do experiments or make observations to try to form a hypothesis that can then be tested. Sometimes, while trying to answer one question, new and more interesting questions arise, so a scientist will change their experiments to work on the new questions instead. However, once scientific discoveries are made, even when a new and exciting discovery is made by accident, the scientific method will still be used to formulate and test hypotheses that arise to explain it.

Science and pseudoscience

Read this article about the scientific method and come up with your own explanation of the difference between science and pseudoscience.

KEY CONCEPTS

- A hypothesis is a tentative answer to a research question.
- The scientific method consists of questioning and formulating hypotheses, making measurements to test the hypotheses, analysing the results and communicating them for peer review. It is the process by which science progresses.

Earth and Environmental Science as a scientific discipline

Disciplines within science can be characterised by the types of questions that they ask. The disciplines that are part of Earth and Environmental Science pose questions about the structure and evolution of Earth systems and components, how such systems evolve over time, how society affects and is affected by Earth systems, and how the parts of Earth that humans have affected may be remediated.

Earth and environmental scientists try to answer these questions in a variety of ways. Describing, mapping, classification and experimentation occur at a range of levels. Scientists ask questions and seek answers to those questions at the macroscopic, microscopic, molecular and atomic levels. Earth and environmental scientists also use a broad range of technologies in their work. Tools range from tape measures for mapping distributions and hand lenses for observing to instruments that measure the abundance of atomic isotopes for dating and planet-wide remote sensing by satellites. Technology and scientific knowledge evolve together. New understanding drives the need for better technology, and new technologies allow scientists to study things more successfully.

The more we find out about our world, the more questions are generated. There are many unanswered questions. As current and future scientists investigate and answer these questions, yet more questions arise. It is likely that the constantly evolving Earth and its systems will never be fully understood.

Through observation, questioning and testing their answers, scientists have constructed **models** of how Earth processes function and change over time. These models also change as more evidence, better answers to existing questions and new questions are generated. Models are representations of structures and processes – they are not the reality itself any more than a model aeroplane is a real aeroplane. Models can be physical models, some are mathematical models described by equations and data, and others are conceptual models consisting of principles, laws and theories. Scientists use all sorts of models as they ask and seek to answer questions. In Earth and Environmental Science, models often contain sub-models created in several different disciplines.

Models in Earth and Environmental Science have two important purposes: to explain how things work and to predict what will happen. A model that does not accurately predict the results of an experiment will generally be revised or replaced. Two models may give similar results in some situations but different results in others.

Model selection is important to obtain valid and reliable results. For example, in ecological research it is often necessary to estimate the abundance and distribution of one or more species. There are several models that may be used, including a quadrat model, a mark–recapture model, a transect model and a direct-count model. Each model relies on its own set of assumptions. If animals are relatively fast moving, a closed population mark–recapture model may be used. This model makes assumptions that there are no deaths, births or emigration within the population; all animals have the same probability of being caught; and the marks or tags are not lost. For plants, fungi and lichens that occur in relatively large numbers, a distance sampling model (line transect with point counts) or a quadrat model are preferable. No one model is always correct or true; it depends very much on the nature of what is being measured. Choosing the right model for a situation is an important skill in solving research problems.

KEY CONCEPT

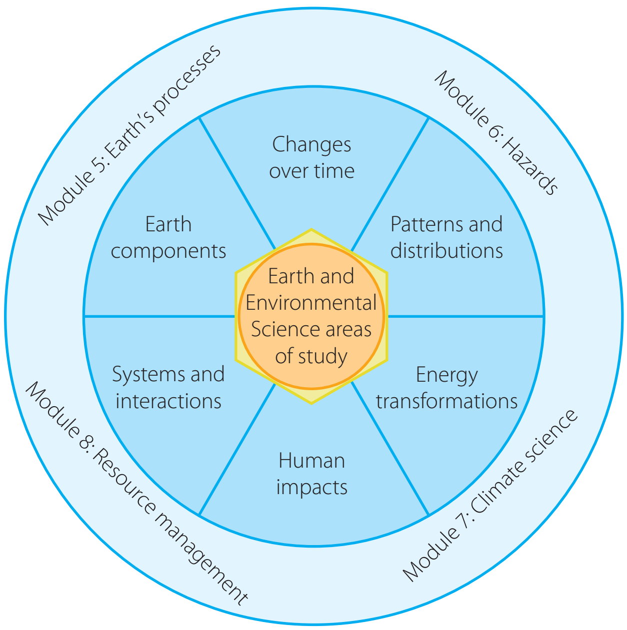
- Earth and Environmental Science uses physical, mathematical and conceptual models to describe Earth systems and to make and test hypotheses. Models are constantly being refined as we learn more.

Earth and Environmental Science – knowledge and understanding

As you progress through the Earth and Environmental Science course, you will learn a lot of useful skills and practise working scientifically by performing investigations and depth studies. You will also gain some knowledge and develop a deeper understanding of Earth and its systems.

The knowledge that arises from answering questions asked by Earth and Environmental scientists can be classified in several ways. One approach is to broadly categorise what is studied into six areas: the nature and uses of Earth's components, patterns and distributions, energy transformations, systems and interactions, changes over time, and human impacts. Figure 1.3 shows the six areas but note that the four modules address many of the areas.

FIGURE 1.3 Unifying concepts in Earth and Environmental Science



As you learn more of the content knowledge of Earth and Environmental Science, you can create your own mental models to help you understand it. Concept maps and labelled drawings are useful ways to represent your mental models. They help to remind you that what you are studying is not simply a collection of facts and that every idea is connected to other ideas. For each module, you should create a concept map to record the content you learn and to make connections between different content areas and modules. Refer to Figure 1.3 from time to time to see how many of the areas you have studied in the module.

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1.2 Solving scientific problems: depth studies

Depth studies are your opportunity to work scientifically and solve scientific problems. When performing a depth study, you will pose questions, develop hypotheses to answer your questions and then seek evidence to support or disprove your hypotheses. The evidence may come from the published scientific literature, or from your own experiments. You will need to analyse data to determine whether your hypotheses are supported. To be analysed, data usually need to be represented in some other way, often mathematically or graphically. Finally, as scientists do, you need to communicate your findings to others. There are many ways to do this, and you need to choose the method most appropriate for your audience.

Types of depth studies

There are two broad types of depth studies:

1. first-hand or practical investigations, in which you design and perform experiments to gather primary data or test a claim or device
2. investigations based on secondary sources, in which you research and review information and data collected by other people.

First-hand investigations to gather primary data may be:

- work undertaken in a laboratory
- field work, where observations are undertaken at home, school or elsewhere; for example, on excursions or by engaging with community experts
- the creation and testing of a model or device.

Secondary-sourced depth studies may include:

- undertaking a literature review
- investigating emerging technologies and their applications in Earth and Environmental Science
- analysing a science-fiction movie or novel
- developing an evidence-based argument or a historical or theoretical account.

Depth studies may be presented in different forms, including:

- written texts (experiment reports, field-work reports, media reports, journal articles, essays and management plans)
- visual presentations (diagrams, flow charts, keys or decision trees, posters and portfolios)
- multimedia presentations
- physical models
- a blend of the above.

All depth studies will involve analysing data, either **primary data** that you collect first-hand or **secondary data** that you collect from analysing research, such as longitudinal data or resource-management data. To look for patterns and trends in data, you will construct and analyse graphs, tables, flow charts, diagrams, keys, spreadsheets, tables and databases. This will be dealt with in more detail in section 1.3. You may also wish to refer to the NESA Earth and Environmental Science Stage 6 Syllabus document for more information.

Why undertake a depth study?

Depth studies encourage you to identify areas of interest and enable you to deepen your understanding in a chosen area by taking responsibility for your own learning. Although your teacher may select a field of study, you may pursue your own area of interest within this field, be it technology, current research, Earth and environmental scientists working in the field or another topic.

Depth studies provide you with the time and an opportunity to:

- use the research methods that scientists use
- analyse works for scientific relevance and validity
- broaden your range of reading in a field of interest
- extend your depth of thinking and understanding
- ask questions and investigate areas that do not have definite answers
- investigate contentious issues and use critical-thinking skills to consider the validity of views expressed in a variety of sources
- use inquiry-based learning and develop your creative thinking in an area of your own choosing, at your own level.

Stages in a depth study

The summary below outlines the four main stages of conducting a depth study, as well as the scientific skills that you will need to develop and apply at each stage. Refer to the NESA Earth and Environmental Science Stage 6 Syllabus to see how the skills described here map to the Working Scientifically skills listed in the syllabus.

1 Initiating and planning

In this stage you will generate and evaluate questions and hypotheses that will be suitable for scientific investigation. Reading, observation and writing all help in this phase of a depth study. You will also design the method through which you will generate your own data. The data may be primary or secondary information. This part of the study may involve trialling a method to ensure that you collect reliable information.

2 Implementing and recording

The conduct of the investigation may occur over a short or a long time, depending on your subject. A key feature of this stage will be attention to the data by ensuring that what you collect is valid and reliable. Having gathered the data, your next task is to process them. This will involve selecting and arranging data, perhaps into new tables, and preparing your data for analysis.

3 Analysing and problem solving

In this phase of the investigation you will analyse your data by seeking trends, patterns and unexpected outcomes. While seeking relationships in your data, you should constantly evaluate its quality and assess how well it relates to your hypothesis or question. You will also have to apply your problem-solving skills in this phase of the investigation. Judge what you see in a critical way and try to propose and assess different interpretations.

4 Communicating

Like a practising scientist, you will have to communicate your scientific understanding to an audience. It is important to craft your report using suitable language and terminology for the audience you present your work to. Part of science is about persuasion. You need to present your results and conclusions in a manner that convinces your audience of your understanding and good scientific practice.

Critical and creative thinking

Posing questions and formulating hypotheses

The first step in any investigation or depth study is to decide on a question. A good research question is one that can be answered by conducting an experiment, making observations or conducting a secondary-sourced investigation.

It is a good idea to investigate something that you find interesting. If you are working in a group, try to find something that is interesting to everyone in the group.

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FIGURE 1.4 Brainstorm as many ideas as you can in your group.

A good way to start is to *brainstorm* ideas. This works whether you are working on your own or in a group. Write down as many ideas that can think of. Don't be critical at this stage. Ensure everyone in the group contributes and ensure you accept all contributions (Figure 1.4). Write down every idea.

When you have run out of ideas, it is time to start being critical. Decide which questions or ideas are the most interesting. Think about which of these questions it is possible to investigate, given the time and resources available. Don't forget that the most important resources you have are the skills of the people in the group. Make a short list of questions but keep a long list too for the moment. Once you have your short list it is time to start refining your ideas.

A good **research question** should define the investigation, set boundaries and provide some direction. The difference between developing a research question and formulating a hypothesis can be summed up as 'known versus unknown'. You need to do some research of the known results in your area of interest (research questions) before deciding on the expected outcome of an experiment (hypothesis).

Six methods of data collections and analysis

Writing a literature review – refining your question

Your depth study will be from one of the areas described in Figure 1.3, based on the NESA Earth and Environmental Science Stage 6 Syllabus document. These areas are described in the remaining chapters. However, you will need to go beyond the basic syllabus content because the purpose of a depth study is to extend your knowledge while building your skills at working scientifically.

The next step is to find out what is already known about the ideas on your list. You need to do a literature review. If your depth study is a secondary-sourced investigation, then the literature review itself may be the investigation. A formal written literature review includes the information you have found and complete references to the sources of information. It also includes interpretation and critique of what you have read. This is particularly important for a secondary-sourced investigation.

Literacy

Information and communication technology capability

Critical and creative thinking

Why are literature reviews important?

Literature reviews are important because they help you to:

- increase your breadth of knowledge and identify what is and is not known about an area of research
- identify gaps in current knowledge that you may wish to research or recommend to be researched by scientists in the future
- identify methods that could be relevant to your project (avoid reinventing the wheel or making the same mistakes as others)
- learn from others and stimulate new ideas that may be relevant to a research project
- identify the variety of views (sometimes opposing views) in an area of research and consider how these fit in with your own views.

Your literature review

A **literature review** is a search and evaluation of the available literature in a particular subject area. It has a specific focus and is always defined by a research question or hypothesis.

The process of conducting a literature review involves researching, analysing and evaluating the literature. It is not merely a descriptive list of the information gathered on a topic or a summary of one piece of literature after another. A literature review outlines any opposing points of view in the research and expresses the writer's perspective of the strengths and weaknesses of the research being reviewed. A literature review brings together the results of different studies, highlighting areas where researchers or studies agree, where they disagree and where major questions remain. By identifying gaps in research, literature reviews often indicate the direction of future research.

When planning an investigation, a literature review will give you an idea of past findings and the procedures, techniques and research designs used. It will help you to decide which methods are worth replicating, which need modifying and which to avoid (those that have been inconclusive or invalid). You may plan your investigation to target a gap in the research or try to replicate an investigation to test and validate claims and ideas.

The length of your literature review will depend on its purpose. If it is a depth study, it will need to be more detailed and draw conclusions about the research. If it is used as an introduction to inform your research, it will be shorter and more focused. Discuss this with your teacher.

Reasons for writing a literature review include to:

- extract information from sources
- consider the validity of views expressed in each source
- consider how existing views fit in with a research project, to place it in context and demonstrate how the research is linked to a body of scientific knowledge
- be a conclusion; for example, to use the findings of a secondary-sourced research assignment to support a concluding judgement
- be a starting point to plan a primary investigation, identifying the known and current gaps in research.

A good literature review:

- helps the reader know what knowledge and ideas have been established on a topic and the areas of strength and weakness in the research
- organises the information gathered into sections that present themes
- does not attempt to list all published material, but rather brings together and evaluates the literature according to a question, hypothesis or guiding concept.

How to write a literature review

1 Getting started: define the topic or research questions (key concepts) and formulate a literature review question. (You may have to do some wide reading before finalising this step.) Write a list of key words.

2 Finding articles: use library catalogues, databases and the Internet. Refine your search technique using specific words that narrow your search to the focus question. Interpret and evaluate your search results. Record search words that are successful and, if necessary, modify your search strategy.

3 Structuring and writing your literature review:

   i Introduction – define the topic and establish your reasons for reviewing the literature; state the focus of the review; and explain the organisation or sequence of your review.

   ii Body – group the literature according to common themes; provide an explanation of the relationship between the research question and the literature reviewed; proceed from the general wider view of the research to the specific area you are targeting. Include information about the usefulness, recency and major sources of the literature.

   iii Conclusion – summarise major contributions of the literature; point out major flaws or gaps in research if appropriate; explain the link between your focus question and the literature reviewed (if the literature review is your depth study) or why you have chosen your area of investigation (if the literature review was conducted to refine your investigation).

Literature review

More detail on how to write a good literature review

Evaluating sources

Always be critical of what you read. Be wary of pseudoscience and any material that has not been peer reviewed. Apply the CRAAP (Currency, Relevance, Authority, Accuracy and Purpose) test to websites that you find. The most reliable sites are from educational institutions (particularly universities), government and scientific organisations (such as CSIRO and WHO), and professional journals such as *Australian Ecology* or the *Australian Journal of Earth Sciences* and international equivalents. You can narrow your search to specific types of sites by including 'site:edu' or 'site:gov' in your search terms so that you find sites from education or government sources.

The CRAAP test

Apply the CRAAP test to any websites that you find.

Make sure you keep a record of the information that you find as well as the sources so that you can reference them correctly later. It would be a good idea to start a logbook at this stage. You can write in references or attach printouts to your logbook. This can save you a lot of time later. Your logbook may be hard copy or electronic but, either way, begin keeping it now (Figure 1.5).

Finally, talk to your teacher about your ideas. They will be able to tell you whether your ideas are likely to be possible given the equipment available. They may have had students with similar ideas in the past and can make suggestions.

After you have researched your questions and ideas, you should be able to narrow the shortlist down to the one question that you want to tackle. If none of the questions or ideas looks possible (or still interesting), you need to go back to the long list.

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FIGURE 1.5 Start researching your topic and keep a record of all your references. Good record keeping is important in scientific research and it begins at this stage of the investigation.

Proposing a research question and hypothesis

If you are doing a primary-sourced investigation, you need to define a research question and hypothesis. For example, you may begin by thinking about how the evaporation of water affects the warming of water. However, to turn this into a specific research question, you need to add more detail. The research question may be: 'I wonder how much evaporation of water affects the temperature change of a water body in sunlight?' The question needs to be specific enough to guide the design of your experiment. It needs to include what you will be varying (e.g. allowing or preventing evaporation) and what result you will expect (e.g. measured temperature changes).

Once you have decided on your research question, further reading will help you to design a suitable experiment. In this example, you would read about the specific heat of water, ways of measuring temperature change over time and how evaporation is known to affect ocean waters. You would then decide what you will be changing (such as varying the rate of evaporation from a surface) and what you will measure (amount of water evaporated, temperature change over time). The research question can then be turned into a hypothesis: 'If a shallow body of water loses water due to sunlight exposure, its temperature change will be positively correlated with the amount of water evaporated'.

KEY CONCEPTS

- Frame your research question carefully by making it specific enough to guide the design of the investigation.
- Poor research question: 'What is the best type of mineral extraction?' 'Best' is a vague term. What you mean by 'best' may not be what someone else means.
- Good research question: 'Does open-pit or underground mining provide both large volumes of ore extraction and reduced effects on natural water systems?' This question is not vague. It tells you what you will be comparing and what you will be measuring. It also gives a criterion for judging whether you have answered the question.

Formulating a hypothesis

A hypothesis is a predictive statement about the relationship between the variables and is an expected answer to your question. A hypothesis is often written as an '*If* … *then* …' statement, to explain an expected relationship, such as: If x is introduced/increased/decreased, then y will increase/decrease/stay the same.

An example of a hypothesis is: '*If* the rate of bore water extraction is greater than the rate of aquifer recharge, *then* the number of working bores in the area will decrease over time.' Your hypothesis should give a prediction that you can test, ideally **quantitatively**, by taking measurements.

A hypothesis is usually based on an existing model or theory. It is a prediction of what will happen in a specific situation based on that model. For example, investigators may use a model that describes how surface water accumulates and moves slowly in the porous sandstone of an aquifer. A hypothesis based on the aquifer model may predict how the size of the stored water body will change over time, affecting the ability of bores near the aquifer to extract water from it.

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FIGURE 1.6 Frame your research question carefully.

A good research question or hypothesis identifies the variables that will be investigated (Figure 1.6). Usually you will have one dependent variable and one independent variable. For a depth study you may have two or more independent variables that you control; for example, you may test two fertilisers rather than one, if time and resources allow.

If your experiments agree with predictions based on your hypothesis, then you can claim that they support your hypothesis. This increases your confidence in your model, but it does not prove that it is true. Hence, an aim for an experiment should *never* begin '*To prove* …' because it is not possible to prove a hypothesis, only to disprove it.

If your experimental results disagree with your hypothesis, then you may have disproved it. This is not a bad thing. Often the most interesting discoveries in science start when a hypothesis based on an existing model is disproved because this raises more questions.

Even if your question or hypothesis meets these criteria, do not be surprised if you change or modify it in the course of your investigation or depth study. In scientific research, the question you set out to answer is often only a starting point for more questions.

KEY CONCEPTS

- Investigations begin with a question that is used to formulate a hypothesis.
- A literature review helps to refine your question or hypothesis. It helps you know what knowledge and ideas have been established on a topic and the areas of strength and weakness in the research.
- A good hypothesis is a statement that predicts the results of an experiment, states the expected relationship between the variables and can be tested using quantitative measurements.

1.3 Planning your depth study

Critical and creative thinking

There are many things to consider when planning and designing an investigation. You need to think about how much time you have, what space and equipment you will need, and where you will go if you want to make measurements or observations outside. If you are doing a secondary-sourced investigation or another type of depth study such as a creative work (like building a physical model), you still need to plan ahead to make sure you have the resources you need.

You may be working in a group or on your own. Most scientists work in groups. If you can choose who to work with, think about it carefully. It is not always best to work with friends. Think about working with people who have skills that are different from your own.

Having a plan helps to ensure that you collect the data, whether primary or secondary sourced, that is needed to test your hypothesis. The longer the investigation, the more important it is that you have a clear plan. There are several things to consider, as set out in Table 1.1.

TABLE 1.1 Planning your depth study

PRIMARY-SOURCED INVESTIGATION	SECONDARY-SOURCED INVESTIGATION
What data will you need to collect?	What information will you need to gather?
What materials and equipment will you need?	What sources will you use?
When and where will you collect the data?	When and where will you gather the information?
If you are working in a group, which tasks are assigned to which people?	If you are working in a group, which tasks are assigned to which people?
Who will collect the data?	Who will collect what information?
Who will be responsible for record keeping?	How will record keeping be done to avoid plagiarism?
How will the data be analysed?	How will the information be analysed?
How will sources be referenced?	How will sources be referenced?

Devising a plan for your investigation

The most common problem that students have is time management. It is important to plan to have enough time to perform the experiments, including repeat measurements, and to analyse and report on them.

A good plan will help you keep on track. Your teacher may ask you to hand in a plan of your depth study before you begin the implementation stage. Table 1.2 (page 14) presents some things you should think about.

TABLE 1.2 Depth study plan

INTRODUCTION TO DEPTH STUDY PLAN		
Title What?	Choose a title for your depth study.	
Rationale Why?	Explain why you have chosen this area of research. Describe what you are hoping to achieve through this investigation. Include any ways you think your investigation may benefit your class and possibly your family, friends, the school and the wider community (if applicable).	
Type of depth study and research model (where applicable) Which?	State the type of depth study you intend to conduct (e.g. literature review or practical investigation). Where applicable, describe any theoretical models that you will use for your depth study. Include references to your reading and explain why you chose this model.	
TIMELINE		
Action and time frame When?	Working scientifically skills How?	
1 Initiating and planning When? (e.g. weeks 1–2)	*Questioning and predicting*: formulate questions and a hypothesis; make predictions about ideas, issues or problems. *Planning*: wide reading – research background information; assess risks and ethical issues; plan valid, reliable and accurate methods; select appropriate materials and technologies; identify variables; plan experimental controls and how to measure them.	
2 Implementing and recording When? (e.g. weeks 2–4)	*Conducting investigations*: safely carry out valid investigations; make observations or accurate measurements; use appropriate technology and measuring instruments. *Processing and recording data and information*: collect, organise, record and process information and data as you go.	
3 Analysing and interpreting When? (e.g. week 4–mid week 5)	*Analysing data and information*: reduce large amounts of data by summarising or coding them; begin looking for trends, patterns or mathematical relationships. *Problem-solving*: evaluate the adequacy of data (relevance, accuracy, validity and reliability) from primary and secondary sources.	
4 Communicating When? (week 5–mid week 6)	*Presenting your depth study*: Use appropriate language, scientific terminology, calculations, diagrams, graphing and other models of representation; acknowledge your sources.	
Final presentation	Due date: end of week 6	
DATA COLLECTION		
Note that what you submit in your final depth study may be different from your initial planning list.		
Action – independent variable Describe what you will change in your investigation.	**Outcome – dependent variable** What will you measure and how will you measure it? Is it quantitative or qualitative data?	**Validity – controlled variables** What will you need to keep constant to make this a fair test? What control(s) will you use (if applicable)?
DATA ANALYSIS AND PROBLEM SOLVING		
Data analysis What method(s) will you use to analyse the data? How will you represent the trends and patterns?	**Conclusion** How will you judge whether the experiment was valid? How will the data allow you to test your hypothesis or answer your question?	

Selecting equipment

A well-framed question or hypothesis will help you choose the equipment that you need. For example, if your hypothesis predicts a temperature change of 0.5°C, then you will need a thermometer that can measure to at least this precision. (Precision and accuracy are discussed on page 19.) You also need to know how to use the equipment correctly. Always ask if you are unsure. Read the user manual; it will usually specify the precision of the device and let you know of any potential safety risks.

You need to think about how to minimise uncertainties and errors. Minimising uncertainty is not just about using the most precise equipment available; it is also about clever experimental technique.

Working safely – risk assessment

Ethical understanding

Work and enterprise

Personal and social capability

You may be required to complete a risk assessment before you begin your investigation. If so, you need to think about three things.

1 What are the possible risks to you, to other people and to the environment or property?
2 How likely is it that there will be an injury or damage?
3 If there is an injury or damage to a person, property or environment, how serious are the consequences likely to be?

A risk matrix, as shown in Table 1.3, can be used to assess the severity of a risk associated with an investigation. 'Negligible' may be soiling your clothes. 'Marginal' might be a bruise from falling off a bike, or a broken branch in a tree. 'Severe' could be a more substantial injury or a broken window. 'Catastrophic' would be a death or the release of a toxin into the environment. You need to ensure that your investigation is low risk.

TABLE 1.3 Risk matrix for assessing severity of risk

CONSEQUENCES → LIKELIHOOD ↓	NEGLIGIBLE	MARGINAL	SEVERE	CATASTROPHIC
RARE	Low risk	Low risk	Moderate risk	High risk
UNLIKELY	Low risk	Low risk	High risk	Extreme risk
POSSIBLE	Low risk	Moderate risk	Extreme risk	Extreme risk
LIKELY	Moderate risk	High risk	Extreme risk	Extreme risk
CERTAIN	Moderate risk	High risk	Extreme risk	Extreme risk

Once you have considered what the possible risks are, you need to think about what you will do about them. What will you do to minimise them and what will you do to deal with the consequences if something does happen? You can use a risk-assessment table like Table 1.4 below.

TABLE 1.4 Example risk-assessment table

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Potassium permanganate is an eye irritant.	Wear safety glasses. If the solution comes in contact with your eyes, use an eyewash.
Glassware can be broken and may cut the skin.	Handle all glassware with care. If glass breaks, sweep it up with a brush and dustpan.

Consider where you will perform your experiments or observations. Will you need to consider the convenience or safety of others? Talk to your teacher about what space is available.

Ethical considerations

There are ethical frameworks for scientific investigations that are concerned with protecting the environment and the lives of animals and humans. You need to consider ethical principles before you begin your research. You need to think about basic human values, animal welfare, the rights of children and whether the use of some technologies has ethical repercussions. Include information about ethical codes of conduct related to your investigation in your research for your literature review. In a secondary-sourced investigation, take precautions with cyber safety and remember to keep your personal information private.

KEY CONCEPTS

- In primary-sourced investigations, you collect and analyse your own data. In secondary-sourced investigations, you analyse data collected by someone else.
- Investigations need to be carefully planned so that they answer your research question. You also need to consider the safety, ethical issues and possible environmental impacts of your investigation.

Designing your investigation

Data: reliability, accuracy, validity and relevance

Literacy

Numeracy

Information and communication technology capability

When designing your investigation, think about how you can minimise uncertainties and overcome failure. For example, collecting enough information about earthquakes in an area to identify a pattern will depend on the length of time during which the earthquakes occurred. Twenty years of data will generally provide more information than one year's of data. Try to think of all the things that could go wrong in your experiment and put preventative measures in place. You may also need to come up with a back-up plan so start early in case things go wrong and you need to re-do your experiment.

If you are conducting a secondary-sourced investigation, then your literature review will be the basis of your investigation. Remember that a literature review is not simply a summary of what you have read; you need to add meaning. This may come from comparing and contrasting competing models to construct an argument, or by analysing and presenting secondary-sourced data. When using secondary sources, remember to make comparisons between data and claims in several reputable sources, including science texts, scientific journals and reputable websites, and to reference these appropriately.

If you are doing a primary-sourced investigation, a brief literature review will form the background information and then you will perform measurements to gather data yourself. You can collect data by performing experiments or making observations in the field. You will gain practice at making measurements if you do some of the investigations in the following chapters. These investigations might form a basis for your depth study.

Variables

When doing experiments, you need to decide the variable you will change, what you will measure and the variables you will control. Consider which variables you can control and which you cannot. Typically, an experiment will have three types of variables. They are:

- an **independent variable**, which you are testing and you deliberately change or vary
- a **dependent variable**, which is the result that you measure. This varies as a result of changing the independent variable. We assume that the dependent variable is in some way dependent on the independent variable.
- **controlled variables**, which are kept constant so that they do not interfere with your results.

Reliability

Whenever possible you should make repeated measurements. This allows you to check that your measurements are reliable. Your results are reliable if repeated measurements give the same results within experimental uncertainty. If a result is not reproducible, it is not a reliable result. The cause may be that a variable other than the one you are controlling may be affecting it. If this is the case, you need to determine what this other variable is and control it if possible. Results may also be unreliable if random errors occur in the method. A reliable experiment is one that. if repeated many times, gives the same result (within an acceptable margin of error). Reliable sources such as scientific journals and texts are sources whose information is trustworthy because they are written by qualified professionals and the information is consistent across multiple sources.

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Accuracy

Accuracy may refer to a result or to an experimental procedure. Accuracy of a result (data) is a measure of how close it is to an expected value given in scientific literature (such as scientific journals). Secondary-sourced information is accurate when it is found to be similar to information presented in peer-reviewed scientific journals.

To improve accuracy in experiments, we use the most precise measuring instruments available, avoid human error (e.g. measuring errors), and carry out repeat trials. Finding an average can smooth out random errors so that the value we obtain approaches the expected value more closely.

Accuracy is also linked to uncertainty in measurement. For example, we can determine the size of red blood cells by estimating their number in a field of view and dividing by the size of that field of view. Alternatively, we can measure their size with less uncertainty using a mini grid slide or a calibrated digital microscope.

Plausible accuracy is accuracy that is estimated, taking into consideration the evident sources of error and the limitations of the instruments used in making the measurements.

Validity

To ensure that results are valid in a primary investigation, you must carry out a fair test. You must:

- identify variables that need to be kept constant
- develop and use strategies to ensure these variables are kept constant
- demonstrate the use of a control
- use appropriate data-collection techniques
- trial procedures and repeat them, checking that the results are the same each time.

In a control, you remove the factor being tested in the experiment to show that a negative result is obtained without that factor. These steps ensure that the data that you measure are what you intended by the process you used. Results need to be valid if you are going to be able to draw conclusions from them.

An investigation is valid if factors that may vary within an experiment are deliberately held constant to ensure a fair test. These controlled variables are kept the same so that the only factor allowed to change in the experiment is the independent variable.

Evaluating your investigation

Some good questions to ask to assess reliability, validity, accuracy and precision are listed in Table 1.5.

TABLE 1.5 Assessing reliability, accuracy and validity in investigations

	PRIMARY INFORMATION AND DATA	SECONDARY INFORMATION AND DATA
Reliability	Have I tested with repetition? Have I done multiple trials and found an average to eliminate random errors?	How consistent is the information with information from other reputable sources? Is the data presented based on repeatable processes?
Accuracy	Do the results of the investigation agree with the scientifically accepted value? Have I used the best measuring equipment available?	Is this information similar to information presented in peer-reviewed scientific journals?
Validity	Does my experiment measure the variable of interest? Does it test the hypothesis that I want it to? Have all variables, apart from those being tested, been kept constant? Have errors been kept to a minimum? Are my results accurate and reliable?	Do the findings relate to the hypothesis or problem? Are the findings accurate and the sources reliable?

KEY CONCEPTS

- An experiment will have three types of variable: dependent, independent and controlled.
- Reliability of first-hand data is the degree to which repeated observations or measurements taken under identical circumstances yield the same results.
  - To assess reliability, compare results from repeat experiments to see if they are same.
  - To improve reliability, control all variables other than those being tested, repeat and average results to reduce random errors, and use precise measuring equipment so that the same result can be obtained each time the experiment is repeated.
- To assess accuracy, examine how close a measurement is to its true value or how similar information is to that in peer-reviewed scientific literature.
  - To improve accuracy, minimise uncertainty, reduce systematic errors and use the most precise measuring equipment available. Use peer-reviewed secondary sources.
- To assess validity in a primary-sourced investigation, evaluate how closely the processes and resultant data measure what was intended.
  - In a secondary-sourced investigation, assess whether the information is relevant to the topic and if it is from reliable sources.
  - To improve validity, refine the experiment design to reduce complex variables that cannot be kept constant and to reduce errors.

Gathering data

You also need to consider how many data points to collect. In general, it is better to have more data than less. However, you will have limited time to collect your data, and you need to allow time for analysis and communicating your results. A minimum of 6–10 data points is usually required to establish a relationship between variables if the relationship is linear. A linear relationship is one in which if you plot one variable against the other you get a straight line. If you think the relationship might not be linear then collect more data points and think carefully about how they will be spaced. You should try to collect more data in the range where you expect the dependent variable to be changing quickly. For example, if you are measuring temperature of a hot object as it cools as a function of time, then you should collect more data early, when you expect cooling to be rapid.

You will need to keep a record of what you do during your investigation. You do this in a hard copy or an electronic logbook.

Keeping a logbook

Scientists keep a **logbook** for each project that they work on. A logbook is a legal document for a working scientist. If the work is called into question, the logbook acts as important evidence. Logbooks are sometimes even provided as evidence in court cases (e.g. in patent disputes). Every entry in a scientist's logbook is dated, records are kept in indelible form (pen, not pencil), and entries may be signed. Never record data on scraps of paper instead of your logbook.

Your logbook includes:

- notes taken during the planning of your investigation
- a record of when, where and how you carried out each experiment
- diagrams showing the experimental set-ups, biological drawings etc.
- all your raw results
- all your derived results, analysis and graphs
- all the ideas you had while planning, carrying out experiments and analysing data
- printouts, file names and locations of any data not recorded directly in the logbook.

A logbook is not a neat record, but it is a complete record. Your teacher may check your logbook at various intervals to assess your progress.

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Your logbook

Always write down what you do as you do it (Figure 1.7). It is easy to forget what you did if you do not write it down immediately. Your logbook may be hard copy or electronic. Either way, your logbook is a detailed record of what you did and what you found out during your investigation. Make an entry in the logbook every time you work on your depth study.

Logbooks are important working documents for scientists. All your data should be recorded in a logbook, along with all records of your investigations.

Shutterstock.com/ESB Professional

FIGURE 1.7 Keep an accurate record of what you do as you do it.

Recording data

If you are planning to collect multiple data points, then it is a good idea to create a table to record them in. Ensure tables are ruled straight and are fully enclosed with appropriate headings. Label the columns in the table with the name and units of the variables. If you know that the uncertainty in all your measurements is the same, then you can record this at the top of the column as well (page 21). Otherwise, each data entry should have its uncertainty recorded in the cell with it. When constructing a results table, put the units in the headings and not in the body of the table. If you are drawing a vertical table, it is best practice to put the independent variable in the first column and the dependent variable in the second. For a horizontal table, the independent variable is placed in the top horizontal row and the dependent variable in the second row.

It is a good idea to start your analysis while you are collecting your data. If you spot an outlier and you are still making measurements, then you have the opportunity to repeat the measurement. If you made a mistake, put a line through the mistake and write in the new measurement.

Plotting and analysing data as you go is sometimes beneficial because it allows you to spot something that may be of interest early in your investigation. You then have a choice between revising your hypothesis or question to follow this new discovery or continuing with your plan. Many investigations start with one question and end up answering a completely different one. These are often the most fun, because they involve something new and exciting. Some of the most significant finds (e.g. the discovery of the hole in the ozone layer) have come from unexpected results of experiments or serendipity.

Accuracy, precision and errors in measurement

When making measurements, your aim is to be as precise and accurate as possible. An accurately measured result is one that represents the true value of the measured quantity as closely as possible. When we take repeated measurements, we assume that the mean (average) of the measurements will be close to the true value of the variable. However, this may not always be the case. For example, if you have ever been a passenger in a car with an analogue speedometer and tried to read it, your reading will be consistently different from that of the driver. This is because of parallax error. The needle sits above the scale, and when viewed from the side it does not line up correctly with the true speed. Beware of parallax error with any equipment using a needle above a scale. This is an example of a **systematic error**, in which measurements differ from the true value by a consistent amount. Note that often we do not know what the true value is.

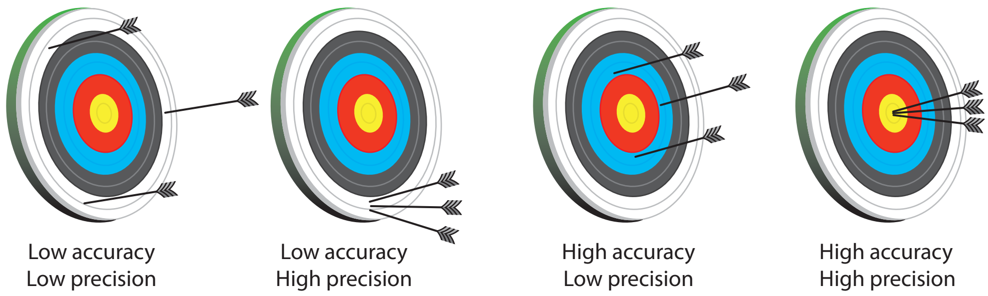
Scientists should be aware of the possibility of error all at stages of an investigation. Notes on possible sources of error should be kept in the logbook.

- Planning stage: errors may arise because of limitations of time or materials. Assess the possibility and adjust the method so that errors are minimised.
- Data collection and processing stages: remember to assess the degree of uncertainty and to keep note of the accuracy of measuring devices.

- Concluding stage: evaluate the validity of the investigation and discuss any sources of error and possible ways of reducing them in future investigations.

Sometimes it is difficult to remember the difference between accuracy and precision. On a dart board, think of accuracy as how close to the centre your dart hits, and precision as how closely you can group your shots (Figure 1.8).

FIGURE 1.8 On a dart board, accuracy is determined by how close to the centre (bullseye) your dart lands. Precision is how closely you can group your darts.



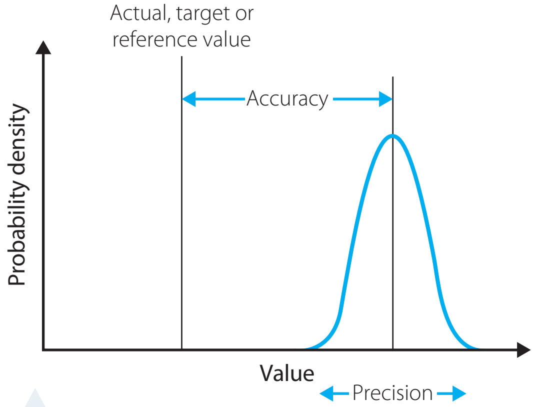
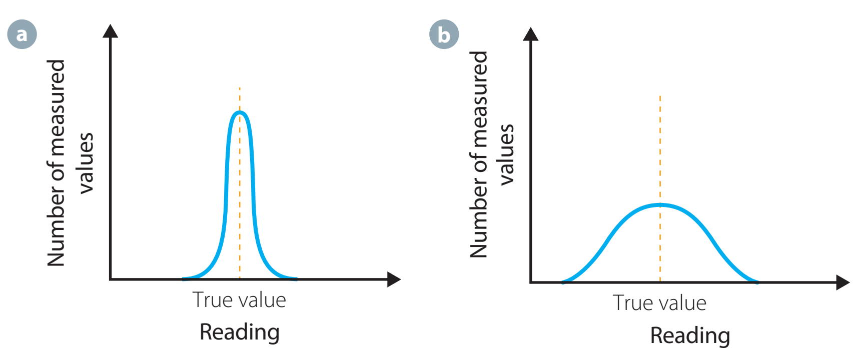


FIGURE 1.9 A graph distinguishing between accuracy and precision

In scientfic experiments, measurements that are close to the known value are said to be accurate, whereas measurements that are close to each other are said to be **precise**. Therefore, for measurements to be accurate and precise, they must be close to the known value and the spread of measurements has to be small. A graph may be used to show the relationship between accuracy and precision, as in Figure 1.9.

In the scientific definition, precision is a measure of the variability of the measurements, which is the spread of the repeated measurements about the mean value. The smaller the spread, the greater the precision. This is shown in Figure 1.10. Figure 1.10a shows precise measurements; Figure 1.10b shows less precise measurements. Note that both datasets are centred on the same mean, so they have the same accuracy.

FIGURE 1.10 Plots of number of measured values versus reading. **a** Results have a small spread about the mean and therefore are more precise. **b** Results have a larger spread about the mean and are less precise.



There is always the risk that errors in measurement may arise when actually doing the measuring, but some errors arise when we are calculating derived data. We need to keep both types of error to a minimum if our results are to be reliable, accurate and valid.

Accuracy and precision

Look at the weblink *Accuracy and precision* to increase your understanding of minimising error and to clarify some concepts about processing raw data. This weblink deals with precision and accuracy and gives an easy but realistic example of how and why it is necessary to process raw data and to calculate the percentage, mean and standard deviation.

Estimating uncertainties

When you perform experiments there are typically several sources of uncertainty in your data. Sources of **uncertainty** that you need to consider are the:

- limit of reading of measuring devices
- precision of measuring devices
- variation of the **measurand** (the variable being measured).

For all devices there is an uncertainty arising from the limit of reading of the device. The limit of reading is different for analogue and digital devices.

People often confuse precision with the resolution of a measuring device. The resolution tells us about the *degree to which an instrument can be read*. Precision is the *degree to which an instrument can be read repeatably and reliably*.

Analogue devices have continuous scales and include swinging-needle multimeters and liquid-in-glass thermometers. For an analogue device, the **limit of reading**, sometimes called the resolution, is half the smallest division on the scale. We take it as half the smallest division because you will generally be able to see which division mark the indicator (the needle or fluid level) is closest to. So, for a liquid-in-glass thermometer with a scale marked in degrees Celsius (Figure 1.11a), the limit of reading is 0.5°C.

FIGURE 1.11 Digital and analogue thermometers with different resolutions (reading limits)

Digital devices such as digital multimeters and digital thermometers have numerical scales. A digital device has a limit of reading uncertainty of a whole division. So a digital thermometer that reads to whole degrees (Figure 1.11b) has an uncertainty of 1°C. For a digital device, the limit of reading is always a whole division, not a half, because you do not know whether it rounds up or down, or at what point it rounds. The digital device in Figure 1.11c has a greater resolution than the devices shown in Figures 1.11a and b because it measures to one decimal place.

The resolution or limit of reading is the minimum uncertainty in any measurement. Usually the uncertainty is greater than this minimum.

Measuring devices such as data loggers have a precision that is usually given in the user manual.

Many students think that digital devices are more precise than analogue devices. This is often not the case. A digital device may be easier for you to read, but this does not mean it is more precise. The uncertainty due to the limited precision of the device is generally greater than the limit of reading.

Resolution and precision

KEY CONCEPTS

- Systematic error is due to the measuring device (e.g. if it is not calibrated correctly).
- Random error is due to uncontrollable variations in the environment that affect measurements.
- Accuracy refers to the closeness of a measured value to a standard or known value.
- Precision refers to the closeness of two or more measurements to each other.
- The uncertainty in any measurement depends upon the limit of reading of the measuring device and the precision of the device.

Critical and creative thinking

Numeracy

Information and communication technology capability

Analysing data

When you have collected all your data you will need to analyse them. Record all your analyses in your logbook. If you have more than a few data points, it is a good idea to display them in a table. Tables of data need to have headings with units for each column, and a caption stating what the data mean or how they were collected. (See how to construct a table on page 19.) Tables are used for recording raw data and for organising derived data.

Calculating derived data from raw data

Raw data are what you measured (with units and uncertainties). **Derived data** are data that you have calculated using your raw data. For example, your raw data may be individual masses and volumes of a series of rock samples. From these data you may choose to derive average masses and volumes for each type of rock and then calculate the average densities.

Drawing and using graphs

If you look at any science journal, you will see that almost every article contains graphs. Graphs are not only a useful way of representing data, they are also commonly used to analyse relationships between variables. You should have a lot of graphs in your logbook as part of your exploration of the data. It is often useful to plot your data in different ways, especially if you are unsure what relationship to expect between your dependent and independent variables.

Graphs should be large and clear. The axes should be labelled with the names of the variables and their units. The independent variable is placed on the x-axis and the dependent variable on the y-axis. Choose a scale so that your data takes up most of the plot area. The scale is plotted in equal increments.

To determine a relationship, you need to have enough data points and the range of your data points should be as large as possible. A minimum of six data points is generally considered adequate if the relationship is expected to be linear (a straight line), but always collect as many as you reasonably can in the available time.

For non-linear relationships, you need more data points than this.

Data points
Some helpful advice on deciding the number of data points

Types of graphs

There are different types of graphs and you need to know which type to use, depending on what you have measured.

TABLE 1.6 Height of shoots in seedlings with varying lengths of light exposure

TIME EXPOSED TO LIGHT PER DAY FOR 2 WEEKS (h)	HEIGHT OF SHOOTS (mm)
0	24
2	18
4	17
6	15
8	13
10	11
12	9
14	7

Scatter graphs are plotted when you are looking for a relationship between variables. This is a graph showing your data as points. Do not join the points up as in a dot-to-dot picture. Use a line of best fit (page 24). An example is shown in Figure 1.12a.

Line graphs are used to find a relationship between the variables. When both the independent and dependent variables are continuous, a line graph is drawn to show how one variable will affect the other. For example, the independent variable may be the number of hours seedlings were exposed to light and the dependent variable may be the average height of the shoots, as in Table 1.6.

Column or bar graphs are used to group things that have been counted into unrelated categories; for example, the relative amount of silica in different types of rock (Figure 1.12b). A bar graph has categories on

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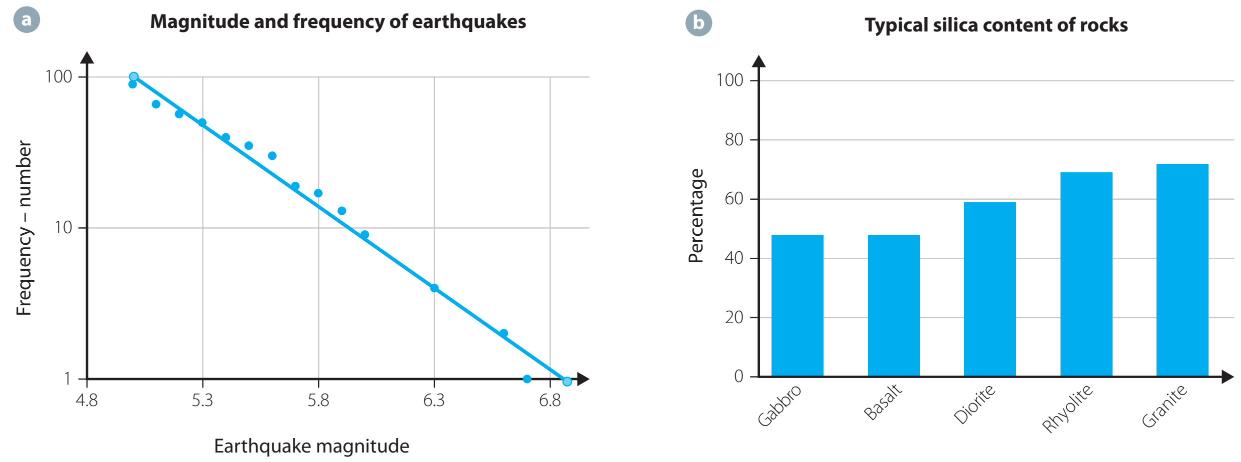


FIGURE 1.12 **a** A scatter plot demonstrating a mathematical relationship. **b** A column graph comparing different categories.

the *y*-axis and numbers on the *x*-axis. A column graph has numbers on the *y*-axis and categories on the *x*-axis. The columns or bars have a gap between them and do not touch.

A **histogram** looks similar to a column graph, but the columns touch each other. Histograms are used for data where the categories have a natural order, such as seasons or grouped numerical data. The average monthly rainfall in Sydney during autumn and winter is an example of data that could be shown in a histogram. See Table 1.7.

TABLE 1.7 **Average rainfall in Sydney during autumn and winter**

MONTH	AVERAGE RAINFALL (mm)
March	130
April	129
May	120
June	133
July	97
August	81

A **sector or pie graph** is used to compare parts of a whole; for example, the chemical composition of a rock, as listed in Table 1.8, is graphed in Figure 1.13. A protractor must be used when drawing a pie chart.

TABLE 1.8 **Chemical composition of granite**

COMPONENT	CONTRIBUTION (%)
SiO_2	72.0
Al_2O_3	14.4
K_2O	4.1
Na_2O	3.7
Iron oxides (FeO, Fe_2O_3)	2.9
P_2O_5 and other oxides	2.9

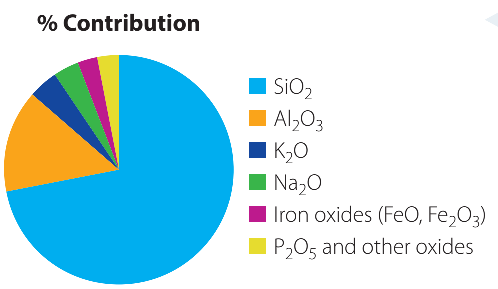


FIGURE 1.13 The data from Table 1.8 shown as a pie graph

Linear lines of best fit

A good graph to start with is simply a graph of the raw data. You will usually be able to tell by looking whether the graph is linear. If it is, then fit a straight line (**line of best fit**).

Removing outliers

When you plot your raw data, you may find that one or two points are **outliers**. These are points that do not fit the pattern of the rest of the data. These points may be mistakes. For example, they may have been incorrectly recorded or a mistake may have been made during measurement. They may also be telling you something important. For example, if they occur at extreme values of the independent variable then it might be that the behaviour of the system is linear in a certain range only. You may choose to remove or ignore outliers when fitting a line to your data, but you should be able to justify why.

Non-linear lines of best fit

Relationships between variables are often not linear. If you plot your raw data and the points form a curve, then do not draw a straight line through it. In this case you need to think a little harder. If your hypothesis predicts the shape of the curve, then try fitting a theoretical curve to your data. If it fits well, then your hypothesis is supported.

Note that a line of best fit is not the same as joining the dots. It is rarely useful or appropriate to join the dots, even though this is often the default setting in spreadsheet software.

KEY CONCEPTS

- Data are usually recorded in tables.
- Graphs are used to represent and analyse data.
- Linear graphs are useful for analysing data.

Interpreting your results

Once you have analysed your results, you need to interpret them. This means being able to either answer your research question or state whether your results support your hypothesis.

You need to consider the uncertainties in your results when you decide whether or not they support your hypothesis. For example, you may have hypothesised that the temperature range in which a native species of fish will reproduce most is between 18.0°C and 20.0°C. If your results show that the maximum reproductive activity occurs between 19.0°C and 21.0°C, you may think that this result does not support your hypothesis. To say whether the result agrees with the prediction, you need to consider the uncertainty. If the uncertainty is 0.5°C, then the results are not consistent with the hypothesis. If the uncertainty is 2°C or more, then the results do agree and the hypothesis is supported.

If your hypothesis is not supported, it is not enough to simply say 'our hypothesis is wrong'. If the hypothesis is wrong, why is it wrong?

It may be that you have used a model that is too simple. For example, when designing an experiment to estimate the effect of fire on weed colonisation of an area, you may base your hypothesis on a model that says weeds will colonise disturbed areas rapidly if there is no competition. In your experiment, you then find that the distribution of weeds three months after a fire varies up the slope of a valley. This may be because you were not aware of the effect of soil moisture or sun exposure on the weed species under study. Therefore, your hypothesis may be better described by a model that considers the idea that the rate of colonisation depends on a range of environmental factors in addition to ground disturbance by fire. However, before you decide that the model is at fault, it is a good idea to check carefully that you have not made any mistakes.

It is never good enough to conclude that the experiment didn't work. Either a mistake was made or the model used was not appropriate for the situation. It is your job to work out which. In doing so, you will come up with more questions.

Fire and weeds

Learn more about fire and weeds with this booklet from the Nature Conservation Council.

Experiments that do not support predictions based on existing models are crucial in the progress of science. These experiments tell us that there is more to find out and inspire our curiosity as scientists.

KEY CONCEPT

- You must know the uncertainty in your results to be able to test your hypothesis.
- If a hypothesis is not supported, or wrong, you need to be able to explain why.

1.4 Communicating your understanding

Literacy

Numeracy

Information and communication technology capability

If research is not reported on, then no one else can learn from it. An investigation is not complete until the results have been communicated. Most commonly, a report is written. Scientists also use other means, such as posters and talks, to communicate their research to each other. To communicate their work to the public, scientists may use science shows, demonstrations, public lectures, websites, videos and blogs. All of these are useful ways of communicating your understanding, and you need to select the mode that best suits the content you wish to communicate and the audience you wish to communicate it to.

Writing reports

A report is a formal and carefully structured account of your investigation or depth study. It is based on the data and analysis in your logbook. However, the report is a summary and it contains only a small fraction of the information that you collected.

A report consists of several distinct sections, each with a particular purpose. When writing a report for a science journal, you will need to provide an abstract and an introduction, but for secondary school purposes the following headings are suggested.

- Aim
- Background information
- Method and risk assessment
- Results and analysis
- Discussion and analysis of results
- Conclusion
- Acknowledgements
- References
- Appendixes

Reports in scientific journals are always written in the past tense, because they describe what you have done. They start with an abstract – a very short summary of the entire report that is typically between 50 and 200 words long. It appears at the start of the report but is always the last thing that you write. Try writing just one sentence to summarise each part of your report.

At school level, your report may be written in the present or past tense. Start with a clearly stated aim, making sure it includes the variables and the change you will be measuring.

Background information

The background information tells the reader why you did this investigation or depth study and how you developed your research question or hypothesis. This is the place to explain why this research is interesting. The introduction also includes the literature review, which gives the background information needed to be able to understand the rest of the report. The introduction for a secondary-sourced report is similar to that for a primary-sourced investigation. In both cases it is important to reference all your sources correctly.

Hypothesis

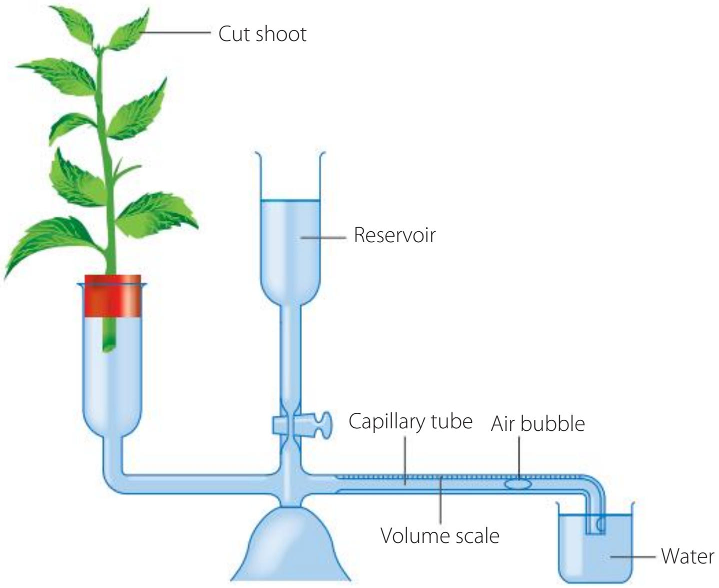
The hypothesis is written as a predictive '*If* … *then* …' statement stating your expected result, and it must be falsifiable; that is, it must be able to be disproved. It does not give a reason why you expect that result.

Method

The method summarises what you did. It says what you measured and how you measured it. It is not a recipe for someone else to follow. It also explains, briefly, why you chose a particular method or technique. The method is written in point form. If in the present tense, each sentence usually starts with a verb. The method also describes how you will measure your results and record your information.

For a primary-sourced investigation, the method describes how you carried out your experiments or observations in enough detail that someone with a similar knowledge level could repeat your experiments. It should include large, clear diagrams of equipment setup. You should have diagrams in your logbook, but these are generally rough sketches. Diagrams should be redrawn neatly for a report, as in Figure 1.14. For example, this might be from a depth study analysing evapotranspiration.

FIGURE 1.14
A potometer is used to measure the rate of water uptake due to evaporation or transpiration.



The method section for a secondary-sourced investigation is generally shorter. If you are reviewing the current literature on a topic, then your method will state what literature searches you carried out and how you decided which sources to use.

Results

The results section is a summary of your results. It is usually combined with the analysis section, although they may be kept separate.

Tables comparing the results of different experiments or secondary sources are useful. Avoid including long tables of raw data in your report. Wherever possible, use a graph instead of a table. If you need to include a lot of raw data, then put it in an appendix attached to the end of the report.

Think about what sort of graph is appropriate. If you want to show a relationship between two variables, then use a scatter plot. Display your data as points with uncertainty bars and clearly label any lines you have fitted to the data. Column and bar charts are used for comparing different datasets. Do not use a column or bar chart to try to show a mathematical relationship between variables.

Any data and derived results should be given in correct **SI units** with their uncertainties. If you performed calculations, then show the equations you used. You might want to show one example calculation, but do not show more than one if the procedure used is repeated.

Discussion

The discussion should summarise what your results mean. If you began with a research question, give the answer to the question here. If you began with a hypothesis, state whether or not your results supported your hypothesis. If not, explain why. If your investigation led you to more questions, as is often the case, say what further work could be done to answer those questions.

Conclusion

The conclusion is a very brief summary of the results and their implications. State what you found. A conclusion should only be a few sentences long and should not contain any inferences. Make sure your conclusion relates back to your aim and hypothesis. This is where you state whether or not your hypothesis is supported.

Acknowledgements and references

Scientific reports often include acknowledgements thanking people and organisations that helped with the investigation. This includes people who supplied equipment or funding, as well as people who gave you good ideas or helped with the analysis. In science, as in other aspects of your life, it is always polite to say thank you.

The final section of a report is the reference list. It details the sources of all information that were actually used to write the report. This will generally be longer for a secondary-sourced investigation. Wherever a piece of information or quotation is used in your report it must be referenced at that point. This is typically done either by placing a note number in brackets at the point (e.g. [2]) or the author and year of publication (e.g. (Smith, 2016)). The reference list is then provided either in a footnote at the end of each page or as a single complete list at the end of the report. There are different formats possible for referencing, so check with your teacher which format they prefer. There are several good online guides to referencing.

Referencing guide
This guide is designed to help you with referencing your sources.

References versus bibliographies

Note that a reference list is not the same as a bibliography. A bibliography is a list of sources that are useful to understanding the research. They may or may not have actually been used in the report. You should have a bibliography in your logbook from the planning stage of your investigation. The references will be a subset of these sources. A primary-sourced investigation does not include a bibliography. A secondary-sourced investigation may include a bibliography as well as references, to demonstrate the scope of your literature search. For some secondary-sourced investigations, such as an annotated bibliography, the bibliography itself may be a major section of the report.

Referencing i-tutorial
This tutorial will help you understand referencing and show you how to avoid plagiarism.

KEY CONCEPT

- A formal report has the same structure as an article written by a scientist. It begins with an abstract (scientific journal) or an aim and, at school level, background information. It includes information from a literature review on the scientific principles behind the research and the research method selected. It includes a risk assessment, method, results and analysis, discussion and conclusion. All sources need to be referenced correctly.

Other ways of communicating your work

You may want to present the results of your investigation in another way. Scientists communicate their work in many ways. Sometimes a poster is presented or a seminar is given. An article or blog may be written or a webpage created. Scientists usually use more than one means, and sometimes several, to communicate about a very interesting investigation.

Look at examples of science investigations reported on websites, in newspapers, on TV and other mediums. This will give you an idea of the different styles used in the different mediums. Think about the purpose. Is it to inform, to persuade or both? What sort of language is used?

Think about your audience and purpose and use appropriate language and style. A poster is not usually as formal as a report. A video or webpage may be more or less formal, depending on your audience.

Website accessibility

The Royal Society for the Blind has information on making websites accessible.

Posters and websites use a lot of images. Images are usually more appealing than words and numbers, but they need to be relevant. Make sure they communicate the information you want them to.

Consider accessibility if you are creating a website. Fonts need to be large enough and clear on websites, and digital images should have tags. You can follow the weblink for more information on accessibility and webpage design.

If you make a video, consider who your audience is and what will appeal to them. Think about how you will balance content with entertainment.

A formal report uses referencing to show where you found information. Other means of communicating about your depth study or investigation also need to acknowledge the sources of information that you used. You also need to be very careful about using copyright content; for example, you cannot copy images from other people's websites without permission. Talk to your teacher about how they would like you to acknowledge your sources.

However you communicate your work, make sure you know what the message is and who the audience is. Once they are established, you will be able to let other people know about the interesting things you have discovered in your investigation.

Ideas for depth studies

As you progress through this book, you will see investigations in each chapter. Some of these investigations are described in detail. These investigations are designed to be useful as training exercises in learning how to perform primary investigations – how to set up equipment, take measurements and analyse data. Even if your depth study is secondary sourced, it is important to gain some experience of doing experiments because science is based on experiment.

At the end of each module there is a short section titled 'Depth study suggestions'. Here you will find ideas for primary- and secondary-sourced investigations that build on the content of the preceding chapters. These suggestions are sourced from experienced teachers, university academics and science education literature. Your teacher will also have ideas and suggestions. You can also generate your own ideas by reading about topics you are interested in. Consider what skills from other areas you might bring to a depth study, particularly if you are artistically creative or musical. Many Earth and environmental scientists combine their love of science with creative pursuits.

By carrying out depth studies you will extend your knowledge and understanding of science and Earth, but, more importantly, you will also learn how to work scientifically – you will learn how to do Earth and Environmental Science.

KEY CONCEPT

- There are many ways of communicating your findings. Choose a method that is appropriate to your investigation and your intended audience.

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» MODULE FIVE

EARTH'S PROCESSES

2 The development of the biosphere

3 The plate tectonic supercycle

4 Fossils and stratigraphy

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2 The development of the biosphere

OUTCOMES

In this chapter you will learn about:

- the evidence for the origin of organic molecules on Earth, including Urey and Miller's experiments, panspermia and meteorite origins and hydrothermal vent communities (seafloor sulfide chimneys) CCT ICT
- the development of photosynthetic life, including stromatolites and cyanobacteria ICT
- changes in the geosphere, atmosphere and hydroshere resulting from evolutionary events and development of the biosphere, including the effects of photosynthesising cyanobacteria and the Great Oxidation Event and the formation of banded iron formations CCT L
- evidence for the origin of multicellular life and resulting changes to ecosystems, including the Edicaran and Cambrian fauna and the invasion of land by plants and animals. CCT ICT L


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Earth provides the right physical conditions and mix of materials for life as we know it to thrive. The size, position and distance of Earth from the Sun create conditions that have maintained a permanent atmosphere since soon after Earth's formation. This also enables water to exist as a liquid, a solid and a gas at the surface of Earth, and is why Earth has oceans.

Earth's size and composition are important too. The elements carbon, oxygen, hydrogen, nitrogen, sulfur and phosphorus as well as salt and a variety of metals are required to make the water, lipids, sugars, amino acids, proteins and adenosine triphosphate (ATP) that are essential to life.

These elements were all common components of the young Earth's atmosphere, hydrosphere or geosphere when the planet cooled and conditions on the surface stabilised at the end of the Hadean eon. Scientists think that this marks the point in time when the numbers of meteors and comets left over from the accretion of the solar system decreased to the point where they stopped constantly bombarding Earth's surface and vapourising the bodies of water that collected on the surface of the geosphere. Earth has had oceans for about 4 billion years.

Scientists are still determining how the vast variety of modern-day organisms developed from a few simple chemical compounds. But scientists understand many of the steps involved in the evolution of life and have identified when these steps occurred in the geological record. This includes evidence for the first organic life, the first microbial ecosystems, the advent of widespread oxygenic photosynthesis, the origins of plants and animals in the oceans and then their subsequent invasion of the land.

Much of this evidence was hard to find in the geological record but biologists, geologists, and palaeontologists discovered that the story of life reaches all the way back to the young Earth's first oceans. These oceans have supported organic life for most of the time since their formation 4 billion years ago.

FIGURE 2.1 An artist's impression of the Archean eon (4600–2500 million years ago) showing mound-like stromatolites formed from single-celled cyanobacteria

2.1 Evidence for the emergence of life

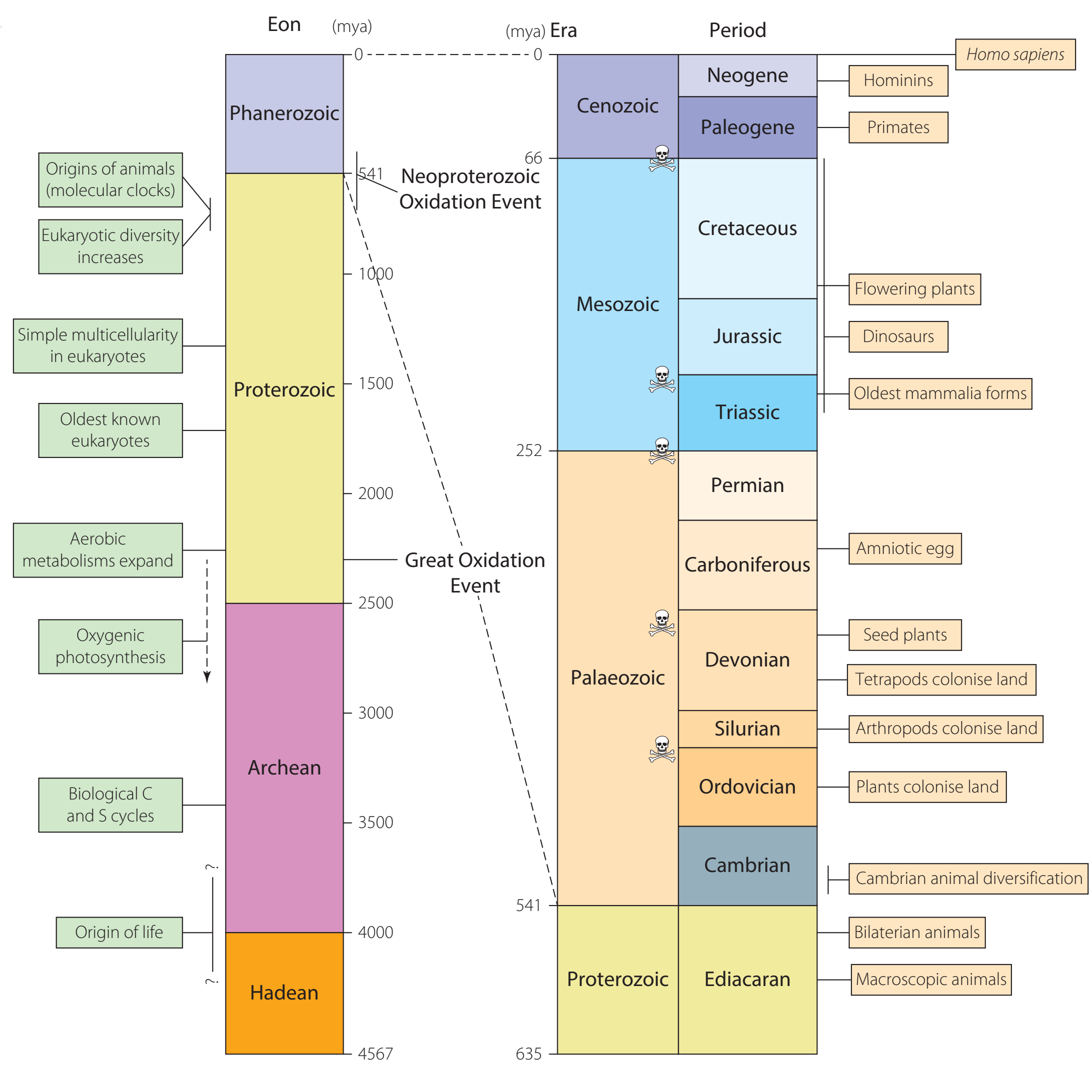
Throughout the 19th and much of the 20th centuries, there was not a lot of evidence that natural scientists could use to explore how life on Earth had arisen from a **primordial soup** of inorganic materials. Consequently, the philosophers and scientists who considered the problem tended to focus on identifying the major questions that needed to be considered such as:

- When did life first arise on Earth?
- Can organic compounds be created spontaneously from inorganic materials?
- What are the essential characteristics of a cell?
- What enabled early cells to replicate?
- Is life unique to Earth or will living things be found elsewhere in the universe?

Geologists and palaeontologists found very old sedimentary rocks, often in remote places with extreme climates, which enabled them to assemble a timeline for some of the major steps in the history of life (Figure 2.2). This timeline goes back before the more easily identified events recorded in the more abundant rocks of the Phanerozoic eon.

The Archean and Proterozoic rock record contains much surprising information. During the 1970s and 1980s, 3.4-billion-year-old microbial ecosystems were discovered at several sites in the Pilbara

FIGURE 2.2 A timeline showing the major steps in the history of life on Earth. A skull and crossbones indicates a mass extinction event.



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region of Western Australia. These **stromatolites** (Figure 2.1) indicated a much longer history for life on Earth than Charles Darwin and his contempories ever imagined. Similarly, the 3.8-billion-year-old black-siliceous mudstsones discovered at Isua in Greenland contain such high concentrations of the light carbon isotope ^{12}C that it is thought that microbial life must have evolved by this time. Other rocks found at Isua have sulfur isotope compositions that also indicate that biological activity was established on Earth within 200 million years of the end of the Hadean eon.

Other biologically important events recorded in sedimentary rock include:

- major increases in atmospheric and oceanic oxygen concentrations at the end of the Archean and the Proterozoic
- the appearance of eukaryotes at the beginning of the Proterozoic
- the appearance of the first marine plants about 1200 million years ago
- the appearance of the first marine animals about 700 million years ago.

Miller–Urey experiment

Proteins are essential for functioning cells. So one of the most important questions about the origins of life is where proteins came from. Proteins perform and regulate most of the activities within a cell. Proteins can be structural, where they are involved in the transport of material within and between cells, or they can transmit messages within and between cells. Proteins include enzymes, antibodies and hormones. Your muscles are made up of several different types of proteins. Without proteins, cells as we know them would not exist.

Proteins are natural polymers made up of amino acids. So other important, more fundamental, questions that scientists wanted to answer were 'Where did amino acids come from?' and 'Could they have formed spontaneously on the young Earth?' These questions were investigated by US chemists Stanley Miller and Harold Urey at the University of Chicago in the early 1950s. They were investigating the general idea that the atmospheric and physical conditions of early Earth enabled or even promoted the formation of amino acids.

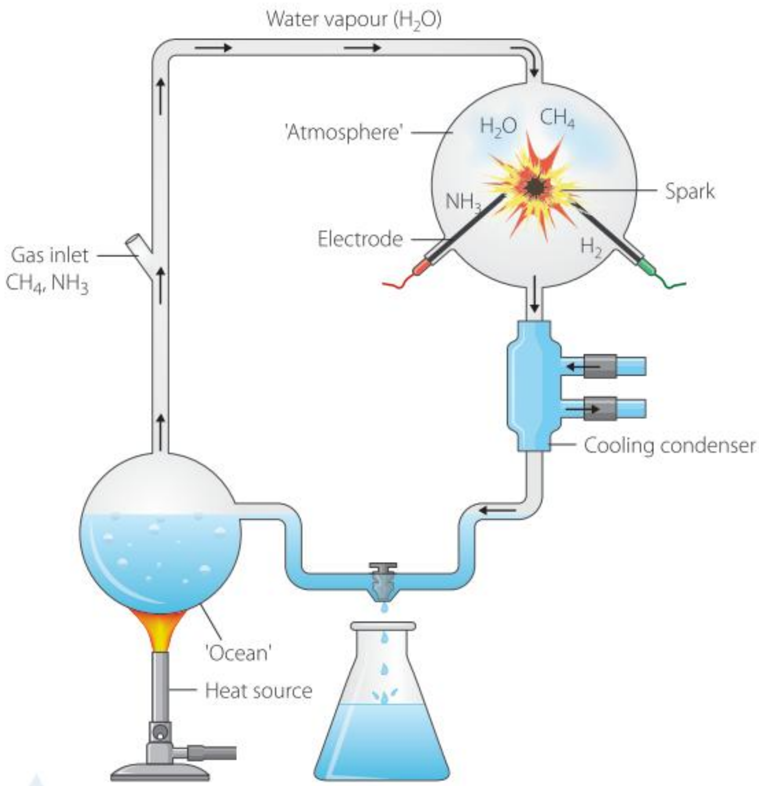


FIGURE 2.3 The set-up for Miller and Urey's experiment simulating the formation of amino acids

To do this, Miller placed a mixture of methane (CH_4), ammonia (NH_3), water (H_2O) and hydrogen (H_2) into an apparatus that enabled these materials to circulate around a sealed loop of glass tubing. Joined to this tubing was a lower spherical flask of water, representing the ocean, and another spherical container, representing the atmosphere, in which an electrical spark was periodically discharged to simulate lightning (Figure 2.3). The lower spherical flask of water was heated to boiling point and the tube beneath the upper spherical flask was cooled so that the water circulated through the system continuously. Miller ran this experiment for a week.

More on the Miller–Urey experiment

The results, which were published in the prestigious journal *Science* in May 1953, were surprising to him and, as it turned out, to everyone else as well. Miller reported that the water turned pink after one day, and red by the end of the week. The experiment had synthesised a number of amino acids, including glycine, α-alanine and β-alanine. Miller, his colleagues and his students repeated the experiment by varying the starting composition of the atmosphere and including various iron and carbonate minerals into the ocean. This work demonstrated that nearly all of the 20 naturally occurring amino acids form spontaneously if the right mixture of starting materials is present.

At the beginning of the 20th century, **abiotic** (non-biological) synthesis of the essential organic components of life seemed to be highly improbable, but the work of Miller, Urey and other scientists suggests that, given time, it is possible. This makes it easier to understand and accept that subsequent steps led to the appearance of microbes and self-replicating cells and then the evolution of more complex organisms by natural processes.

Miller and Urey's work was the first to demonstrate that abiotic processes could generate the primary, essential components that are required for living organisms to evolve. The study of prebiotic chemistry and the abiotic synthesis of other essential molecules is a growing field of science. As well as studying amino acid and protein synthesis, this work looks at how nucleic acids and lipid molecules arose by abiotic processes. The nucleic acids DNA and RNA are necessary for cell replication and the transfer of genetic information. Lipids are essential for the construction of cell membranes.

Life from space?

Scientists have also looked at whether organic molecules on early Earth could have formed on carbonaceous chondrite meteorites and comets and survived long-distance journeys through space. This work has demonstrated that there is a more diverse range of abiotic organic compounds in carbonaceous chondrite meteors than was originally thought by mid-20th-century scientists.

For example, the Murchison meteorite (Figure 2.4a) contains a large number of organic materials, including complex organic polymers, water-soluble organic acids, aliphatic and aromatic hydrocarbons, amino acids, urea, ketones, alcohols, aldehydes and purines. Similarly, the Kuiper Belt comet Churyumov–Gerasimenko, which orbits Jupiter, contains the amino acid glycine and the amino acid precursors methylamine and ethylamine (Figure 2.4b). The Churyumov–Gerasimenko comet was visited by the European Space Agency's Rosetta Probe between 2014 and 2015. Several other complex organic molecules and phosphorus – a vital component of ATP – were also detected.

These discoveries have provided support for the **panspermia hypothesis**. This hypothesis suggests that organic life occurs everywhere in the universe and that the original precursor materials or micro-organisms that led to life developing on Earth arrived from space on comets and meteorites rather than developing on Earth from abiotic precursors.

One reason why some scientists support the panspermia hypothesis is that the fossil record indicates that organisms were definitely present on Earth within 200 million years of the beginning of the Archean eon, and possibly much earlier. This suggests that life started on Earth almost as early as it could have.

Alamy Stock Photo/Science History Images

Alamy Stock Photo/The Natural History Museum

FIGURE 2.4 **a** The Murchison meteorite and **b** the comet 67P/Churyumov–Gerasimenko contain a large number of organic materials.

The relatively short span of time between the stabilisation of conditions that could support life and the appearance of life increases the appeal of an extraterrestrial, panspermic origin for Earth's organisms.

Hydrothermal vent communities

In the 1960s, scientists proposed that mid-ocean ridges composed of young, recently erupted basalts and near surface magma chambers would generate submarine hydrothermal flow systems. In 1977, a major expedition to the Galapagos Rift off South America discovered hydrothermal vents and their characteristic sulfide chimneys and towers. They also found that these hydrothermal systems provide a home for an important and unusual type of deep marine ecosystem dominated by tube worms and mussels. These animals feed on bacteria that use **chemosynthetic** processes rather than photosynthetic pathways to convert hydrogen sulfide (H_2S), CH_4 and carbon dioxide (CO_2) into carbohydrates (Figure 2.5).

Hydrothermal vents are the underwater equivalent of terrestrial geothermal systems like New Zealand's hot springs at Rotorua and Pohutu Geyser. They are often located on the deep sea floor near active mid-ocean ridges and submarine volcanoes where jets of very hot sea water are ejected. In a manner similar to the heating of groundwater by cooling volcanic rocks and bodies of subsurface magma, the sea water ejected by submarine hydrothermal vents is heated by a convective system that circulates cold sea water through basalts that were erupted at the axis of the mid-ocean ridge.

The hot water expelled from a submarine hydrothermal vent is at 350–400°C and contains large amounts of dissolved materials. Some precipitate instantly as the streaming jet of hot water cools down suddenly as it mixes with cold, deep oceanic sea water (2–4°C). This process usually builds vertical, chimney-like tubes (Figure 2.6) composed of layers of sulfide or sulfate minerals and silica above the vent.

Sulfide chimneys are commonly 5–10 metres tall. Larger chimneys are called sulfide towers and can be up to 40 metres high. As the fluid ejected from active sulfide chimneys mixes with the cold sea water, metal sulfides precipitate and produce a material that resembles black smoke. This is why these chimneys are also called black smokers. The precipitated sulfides are mostly small grains of the minerals pyrite (FeS_2), sphalerite (ZnS) and chalcopyrite ($CuFeS_2$). These minerals also form the layers of the chimneys. Figures 2.6 and 2.7 show some

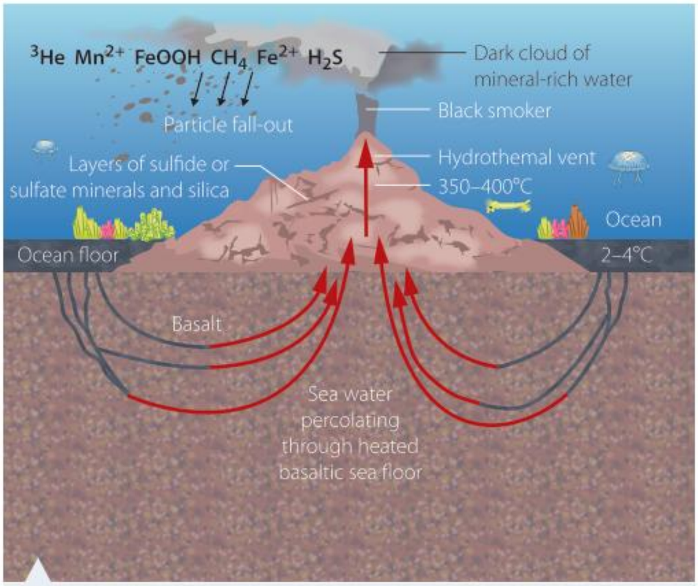
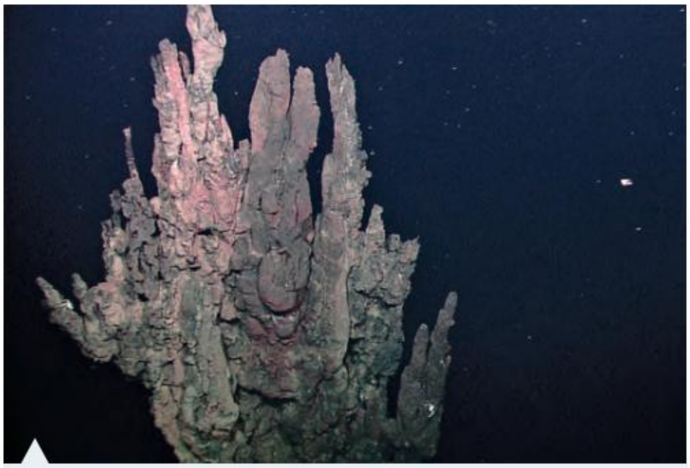
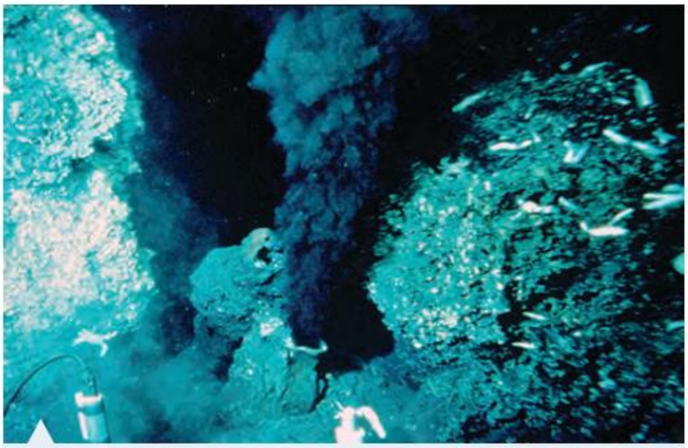


FIGURE 2.5 High-temperature hydrothermal vents form as a result of circulation of sea water through oceanic crust near mid-ocean ridges.



NOAA Office of Ocean Exploration and Research

FIGURE 2.6 The top of a 40-metre-high inactive sulfide tower at the Galapagos Rift



U.S. Geological Survey/W. R. Normack (photographer)

FIGURE 2.7 A black smoker at a mid-ocean ridge hydrothermal vent in the East Pacific Ocean


Image courtesy Submarine Ring of Fire 2004 Exploration, NOAA Vents Program

FIGURE 2.8 Two halves of a black smoker hydrothermal vent chimney


Image courtesy Submarine Ring of Fire 2004 Exploration, NOAA Vents Program

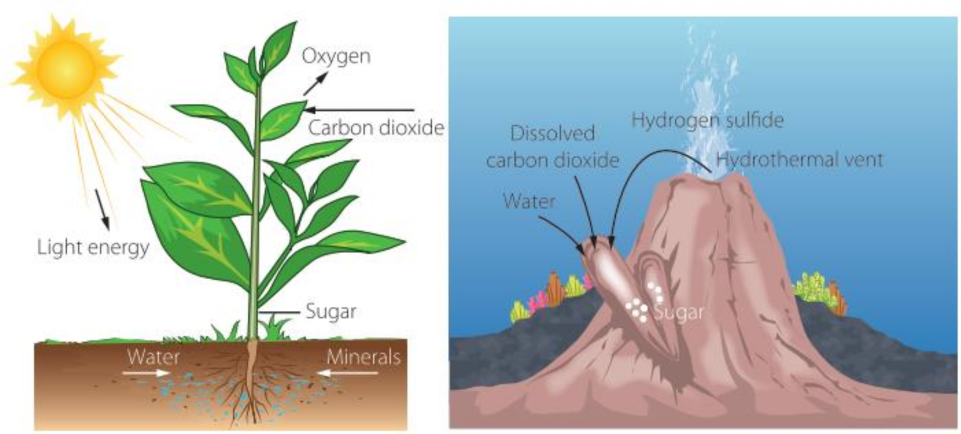
FIGURE 2.9 These white smoker hydrothermal vent chimneys are the Champagne Vents at Mariana Ridge in the Pacific Ocean.

examples of hydrothermal vents. Figure 2.8 shows two sections of a black smoker chimney that has been cut in half. You can see the inner greenish-black chalcopyrite and pyrite layers and the outer grey and white layers, which are composed of barite ($BaSO_4$), anhydrite ($CaSO_4$), sphalerite and pyrite.

If the jet of water ejected from the hydrothermal vent is cooler, about 250°C, then the dissolved materials are mostly calcium, barium and sulfate ions and the minerals barite and anhydrite precipitate. Barite and anhydrite are white and so these chimneys are known as white smokers. White smoker chimneys tend to occur further away from mid-ocean ridges than black smokers because the fractured rocks the sea water circulates through are cooler than the younger rocks near the ridge axis (Figure 2.9).

The convective circulation of sea water that builds sulfide chimneys starts with cold sea water seeping into natural fractures in lower levels of the ridge. The water gradually flows through fractured hot rock above the ridge's magma chamber where it heats up to 350–400°C, and is returned into the ocean. As the sea water is heated in the layers of fractured seafloor basalt, it cools the young ocean-ridge basaltic rocks that form the ridge and reacts with the basalts. These reactions leach a variety of materials out of the basalt's pyroxenes, feldspars, oxides and sulfide minerals. These materials include metallic ions such as calcium, barium, iron, magnesium, manganese, copper and zinc, which are concentrated in the circulating sea water. These precipitate as sulfides and sulfates and build the chimneys and form layers of metal-rich sediments on the sea floor around the hydrothermal vents. Other reactions concentrate CO_2, H_2S, chlorine, H_2 and CH_4 in the hot, saline water of the hydrothermal vent. This second group of materials, especially CO_2, H_2S and CH_4, are released into the sea water surrounding the vent and provide a supply of nutrients for chemosynthetic bacteria, archea and **eukaryotes**, which form the base of the foodweb of organisms that live in and around hydrothermal vents (Figure 2.10).

FIGURE 2.10 Photosynthesis compared to chemosynthesis. In photosynthesis, plants convert carbon dioxide and water into sugars and oxygen in the presence of light. In chemosynthesis, bacteria convert carbon-containing molecules into simple sugars, using energy from chemical reactions rather than light. Different species use different chemical pathways. Some bacteria make organic matter by reducing sulfide or oxidising methane. Chemosynthesis provides nutrients for organisms that live around the hydrothermal vents.



Photosynthesis

$$6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2$$

Chemosynthesis

$$6CO_2 + 6H_2O + 3H_2S \rightarrow C_6H_{12}O_6 + 3H_2SO_4$$

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INVESTIGATION 2.1

Modelling hydrothermal vents

Critical and creative thinking

AIM

To use everyday items to model a hydrothermal vent

MATERIALS

- 1 L beaker
- Small glass bottle with a narrow neck
- Food colouring
- String
- Funnel
- Hot and cold water

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Hot water can scald skin.	Use heatproof gloves when carrying hot water and place containers in the middle of the bench.
Broken glassware can cut skin.	If any glassware breaks, do not attempt to clean it up yourself; notify your teacher.

What other risks can you identify in this investigation? How will you manage them?

METHOD

1. Fill the 1 L beaker with cold water.
2. Tie the string around the neck of the small bottle, leaving about 30 cm to use as a handle.
3. Carefully use the funnel to fill the small bottle with hot water.
4. Add a couple of drops of food dye to the hot water in the small bottle.
5. Keeping the small bottle upright, use the string to lower it into the beaker and sit it upright on the bottom of the beaker.

RESULTS

Record what happens.

ANALYSIS OF RESULTS

1. What did the cold water represent?
2. What did the hot water represent?
3. Why did you dye the hot water?
4. Explain your observations when the smaller bottle was placed into the beaker.
5. Use your knowledge of energy transfer to explain these observations.
6. How well did this investigation model what occurs at a hydrothermal vent?
7. Did you experience any problems in conducting this investigation? If yes, how could you overcome these problems if you repeated this investigation?

CONCLUSION

How did this model assist you in understanding what happens at hydrothermal vents?

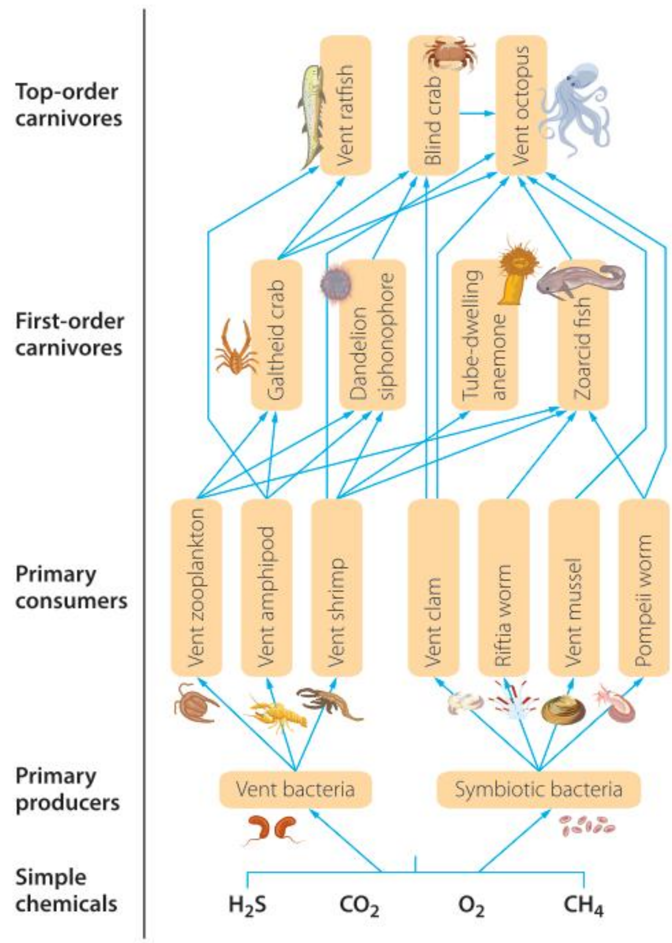
Watch hydrothermal vents in action.

Chemosynthetic microbes generate carbohydrates that support a range of species that are adapted to survive the high H_2S concentrations in sea water. These specialised species include barnacles, bivalve molluscs, crustacea, crabs and gastropods (Figure 2.11). Some mussels, clams, tubeworms and shrimp live in **symbiotic** relationships with chemosynthetic bacteria where they host colonies of the bacteria inside or on the surface of their bodies.

Hydrothermal vent ecosystems are special because their food supply is not generated by photosynthesis. The energy that sustains these deep-water communities is entirely sourced from Earth's internal heat and their food webs support carnivores that feed on consumers supported by chemosynthetic primary producers (Figure 2.12). It is thought that there is very little interaction

FIGURE 2.11 Common members of hydrothermal vent ecosystems: **a** tube worms encrusting an active hydrothermal vent; **b** mussels and scavenging galatheid crabs; **c** tube worms and shrimp

FIGURE 2.12 Simplified food web for the Galapagos hydrothermal vent chemosynthetic ecosystem



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of hydrothermal vent communities with surface water ecosystems. The hydrothermal vent communities can thrive completely independently of solar-energy-driven surface processes.

Alkaline hydrothermal vent systems

In the early 2000s, a third group of submarine hydrothermal vents was discovered away from the mid-ocean ridges. The water that circulates through these vents is much cooler and often interacts with lower levels of the ocean crust where olivine-rich rocks called peridotites are present. Sea water reacts with the ferro-magnesium silicate minerals olivine and pyroxene in the peridotites and converts them into serpentine, which is a hydrated magnesium silicate mineral. This sea water–rock hydration reaction is called serpentinisation and it converts the peridotites into a material called **serpentinite**.

Serpentinisation also generates highly alkaline sea water that contains large amounts of hydrogen and sulfur as well as dissolved silica, calcium, magnesium, nickel, iron and carbonate ions. This fluid is ejected from hydrothermal vents in a similar process to the one that forms black and white smoker chimneys. However, the sea water is much cooler (50–100°C), the fluid is generally clear and the chimneys and towers the vents are constructed from the calcium carbonate mineral calcite (Figure 2.13). The vents can be up to 60 metres tall. Alkaline hydrothermal vent systems based on serpentinisation of olivine-rich materials are thought to have been very common in the early Archean oceans when olivine-rich-basaltic rocks were erupted.

Scientists interested in these hydrothermal vent systems include chemists who study self-organising chemical systems and biochemists and microbiologists who investigate how organisms arose from abiotic processes. Their investigations have shown that the interaction of alkaline hydrothermal fluids with the Archean's acidic, CO_2-rich sea water could have provided just the right conditions for iron-nickel-sulfide catalysed reactions to produce organic molecules. These organic molecules could have included sugars, self-replicating molecules and possibly membrane-enclosed cells in the vent chimneys and towers, which are often porous and sponge-like rather than completely solid. In other words, these scientists think that alkaline hydrothermal vents could be where organic life arose on Earth during the early Archean.

a

NOAA

b

Alamy Stock Photo/916 collection

FIGURE 2.13 **a** Calcite chimneys and **b** towers of the Lost City alkaline hydrothermal vent field in the Atlantic Ocean

KEY CONCEPTS

- Unmetamorphosed sedimentary rocks of early Archean age are very rare. This makes the search for the signs of ancient life very difficult. Nevertheless, there is good geological evidence for active microbial organisms being active on Earth 3.8 billion years ago.
- Stanley Miller and Harold Urey synthesised amino acids and other organic compounds by discharging electrical sparks through a gaseous mixture of CH_4, NH_3, H_2O and H_2, and demonstrated that amino acids, the precursor components of proteins, could have been generated from inorganic processes.
- Comets and carbonaceous meteorites commonly contain phosphorus and a variety of complex organic molecules that are precursor materials required for the development of microbial organisms.
- The panspermia hypothesis proposes that life occurs everywhere in the universe and that Earth's organisms could have evolved from organic material that was brought to Earth from space on meteorites or comets.
- Hydrothermal vents are features on the deep sea floor where jets of sea water are ejected. The jets of sea water contain dissolved sulfides and sulfates, which support ecosystems in which chemosynthetic microbes produce carbohydrates and organic material that are consumed by browsers and filter feeders. In turn, these organisms are consumed by scavengers and predators.
- There are three common types of hydrothermal vents. Black smokers eject very hot (350°C) sea water rich in dissolved iron and copper sulphides. White smokers eject hot (250°C) sea water rich in calcium and barium sulfates. Alkaline vents eject warm (60°C) sea water rich in hydrogen and sulfur, dissolved silica as well as calcium, magnesium, nickel, iron and carbonate ions.

CHECK YOUR UNDERSTANDING 2.1

1 Identify the two factors that enable life to thrive on Earth.
2 Describe the oldest evidence for microbial activity on Earth.
3 a Name the materials that Miller placed in his experimental apparatus.
  b Name the materials that were synthesised in the Miller–Urey experiment.
  c How did the Miller–Urey experiment provide evidence that life could have started in abiotic processes?
4 Name two or more organic materials that are essential for Earth's organisms to function.
5 a List some of the organic materials discovered in the Murchision meteorite.
  b Explain the significance of this finding in relation to life on Earth.
6 Outline the main points of the panspermia hypothesis.
7 Name the three types of hydrothermal vent, describe their characteristics and indicate where they are found.
8 Name the inorganic materials that precipitate to form black smoker chimneys.
9 Name the inorganic materials that precipitate to form white smoker chimneys.
10 What type of hydrothermal vent occurs in the Atlantic Ocean's Lost City vent field? Why are vents the subject of great scientific interest?
11 a Name the nutrients released by hydrothermal vents that chemosynthetic bacteria use to produce carbohydrates.
  b Identify some of the organisms that consume the carbohydrates produced by chemosynthetic microbes at hydrothermal vents.

2.2 Development of photosynthetic organisms

Organisms living on early Earth obtained nutrients by chemosynthetic processes such as those found around hydrothermal vents. It was not until organisms could use the energy of sunlight to photosynthesise and release free oxygen molecules into the atmosphere that life on Earth started to evolve into how we know it today.

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Stromatolites and ancient photosynthetic ecosystems

Stromatolites that exist now are bacterial colonies. They are relatively rare and are found in harsh, unusually salty, shallow marine environments such as those at Western Australia's Shark Bay. Here, the rates of evaporation are high while rainfall and freshwater inflows are very low. These conditions are hostile to most modern-day organisms but the stromatolite colonies survive and thrive.

In the 1960s, the Shark Bay stromatolites were first recognised as the living equivalents of a major fossil group. Since then, they have been studied intensively. Stromatolites survive in their challenging environmental conditions because, rather than being single organisms, they are self-contained microbial ecosystems consisting of prokaryotic, photosynthetic producers and consumers.

The producer microbes are cyanobacteria and purple bacteria that occupy the surface and near-surface levels of the stromatolite. Cyanobacteria use sunlight to power the photosynthetic conversion of CO_2 and water into carbohydrates and oxygen. The purple bacteria chemosynthetically convert CO_2 and H_2S into carbohydrates and sulfur. Beneath the stromatolite's photosynthesising upper layers is a layer of consumer microbes that reprocess and metabolise the waste products and biomass generated by the producers. The consumer microbes include various species of anaerobic bacteria, sulfate-reducing bacteria and **methanogenic** archea.

The metabolic processes of these communal ecosystems generate a slime that sustains the stromatolite. The slime is produced by the photosynthesising microbes and the outer surface layers look like a mat of slime and green fur. The slimy material accumulates sediment very efficiently and the stromatolite grows upwards towards the light as layer after layer of sediment is trapped. This process generates the distinctive internal structure and layer geometry of domes, cones and wavy layers that enable geologists and palaeontologists to identify ancient Proterozoic and Archean stromatolites (Figure 2.14).

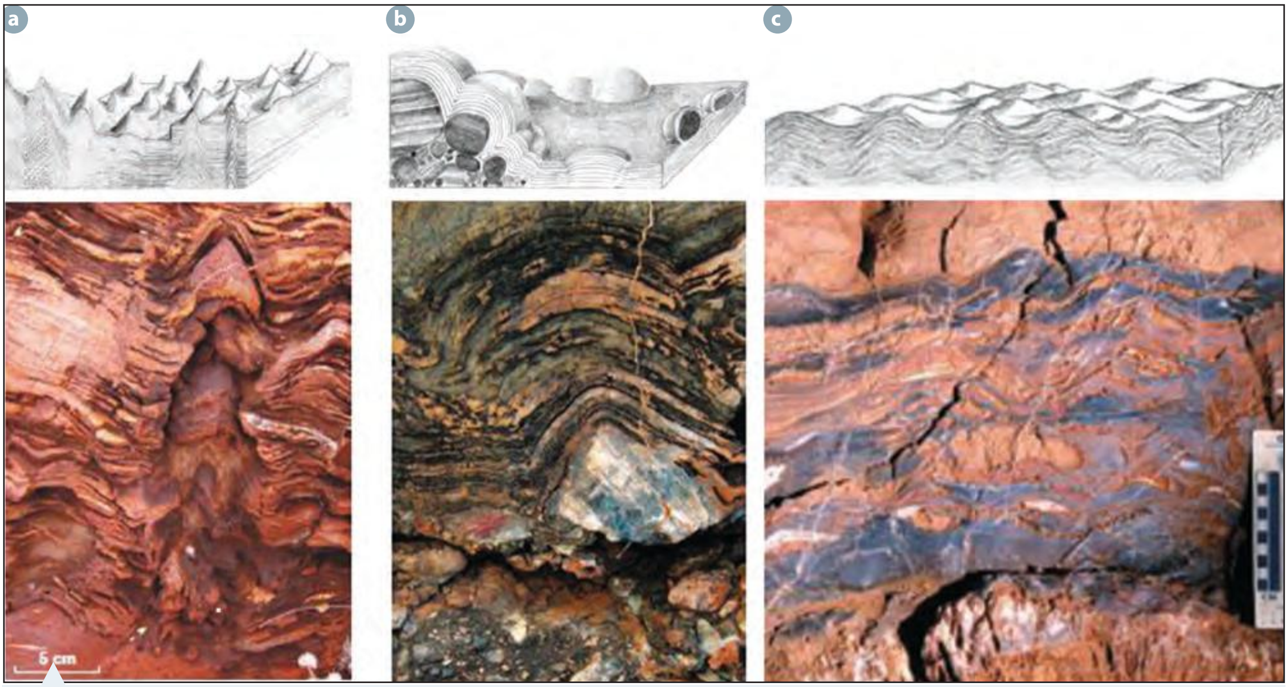


FIGURE 2.14 **a** Conical, **b** domical and **c** wavy stromatolites of the Pilbara's 3.43-billion-year-old Strelley Pool chert

Most of the stromatolites that have been found are extinct forms preserved as fossils in sedimentary rocks. Stromatolites are relatively commonly identified in Proterozoic rocks and late Archean rocks that are 600–2500 million years old, but some colonial organic structures are 3500 million years old. Stromatolites are also fairly common in Phanerozoic rocks.

Science Photo Library/Georgette Douwma

FIGURE 2.15 Stromatolites in Strelley Pool cherts, Pilbara, Western Australia

The oldest stromatolites of known organic origin are the abundant domical, conical and wavy stromatolites found in Strelley Pool cherts in the Pilbara, Western Australia (Figure 2.15). Chert is a very fine-grained quartz-rich mudstone that accumulates tiny grains of opaline silica precipitate and later crystallises into quartz. These impressive and intriguing stromatolites are about 3.4 billion years old. Their internal layering, particularly the conical forms (Figure 2.14a), are generally accepted to be a result of the stromatolite accreting successive layers by growing towards the light. That is, their distinctive organic layering is a direct consequence of photosynthesis.

WS Stromatolites

It is not possible to determine what type of photosynthetic processes and reactions were used by the microbes that formed the Strelley Pool stromatolites. It is not likely that they were oxygen producing because there is no evidence for this. Nevertheless, the palaeontologists that study them are convinced that these stromatolites are organic structures and that the microbes that built them were photosynthesisers.

The Strelley Pool stromatolites are important for establishing a timeline for life on Earth. It is generally accepted that these stromatolites indicate that bacterial ecosystems powered by organic photosynthesis were present on Earth in the early Archean. From this piece of evidence, it can also be inferred that microbial organisms must have been present on Earth long before this date 3.4 billion years ago, and possibly as early as the beginning of the Archean.

Cyanobacteria

Cyanobacteria are a group of single-celled, photosynthetic prokaryotic microbes that occur in most Earth environments that receive sunlight (Figure 2.16). All modern cyanobacteria use chlorophyll to produce oxygen by photosynthesis. Starting materials are generally CO_2 and water, and the energy source is sunlight. The common products of photosynthesis are carbohydrates. Chloroplasts are a group of symbiotic cyanobacteria that have taken up residence in the eukaryotic cells of marine and terrestrial plants and are the organelles that enable these organisms to photosynthesise. Many cyanobacteria can also fix atmospheric nitrogen. Being able to access this vital nutrient makes them self-sufficient.

Cyanobacteria are probably one of the most important groups of organisms that has ever inhabitated Earth. They are considered to be largely responsible for changing the composition of the atmosphere. During most of Precambrian time, the atmosphere was dominated by CO_2, nitrogen and water. During the Phanerozoic eon, the atmosphere was dominated by nitrogen, oxygen, water and CO_2. Some marine biologists consider cyanobacteria to be very important components of modern-day ocean plankton, which makes them a significant group of organisms both environmentally and ecologically. It is estimated that the total mass of cyanobacteria present in Earth's oceans is 1 billion tonnes – about two and half times the total mass of human beings currently occupying Earth.

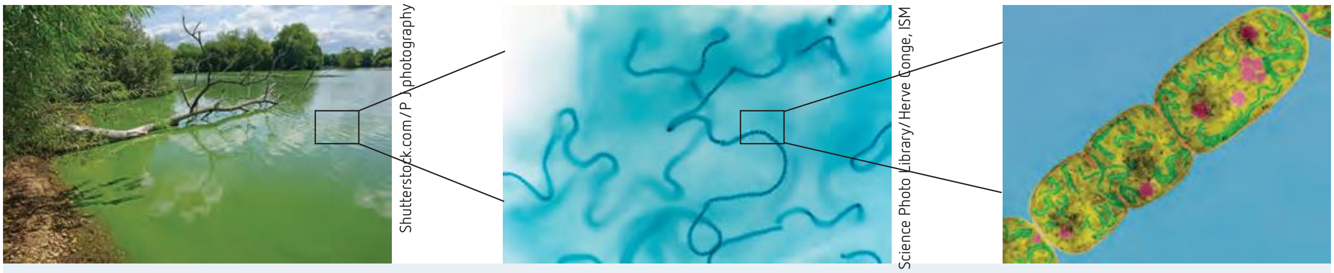


FIGURE 2.16 Cyanobacteria at a macro and micro level

Some cyanobacteria form microbial mats like those that build the Shark Bay stromatolites. It is possible that they are responsible for building many, perhaps nearly all, of the stromatolites that have been identified in the geological record.

Cyanobacteria are very robust organisms. The species that built the Shark Bay stromatolites can survive in a wide variety of environmental conditions and in conditions that change rapidly between strongly constrasting states – most other organisms struggle to cope with changes of this type. For example, cyanobacteria can live in **anoxic** (without oxygen) conditions and super-oxygenated conditions, very high and very low concentrations of sulfide and low-light conditions. Some terrestrial cyanobacteria tolerate high levels of ultraviolet radiation. Many marine species thrive in highly saline environments and at high temperatures that would challenge eukaryotic algae. Cyanobacteria can also cope with **desiccation** (drying) and cycles of wetting and drying.

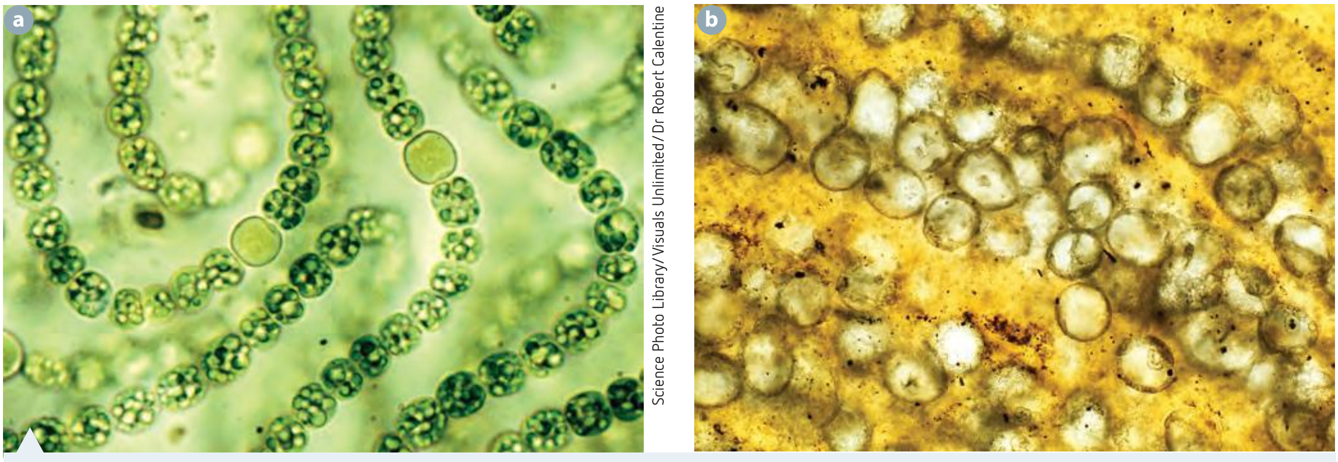
Oldest known fossil cyanobacteria

Photosynthesising microbes have been present on Earth for most of geological time. Evidence for this is the long and continuous presence of stromatolites in the geological record and the isotopic composition of preserved organic matter in stromatolitic deposits. Cyanobacteria and other forms of bacteria produce carbohydrates by photosynthetic pathways that use H_2S and by other anoxigenic pathways. Therefore, it is likely that most Archean stromatolites were constructed by anoxygenic photosynthesisers, possibly including anoxygenic cyanobacteria.

The fossil record provides good evidence for the presence of filamentous and colonial cyanobacteria in the latest Archean age stromatolitic rocks of the Transval's Campbell Group in South Africa (2600 million years old), and the early Proterozoic Kasegalik Formation of Canada's Belcher Islands (2100 million years old). These are the oldest accepted fossils of cyanobacteria and are generally accepted to have been oxygenic photosynthesisers.

The appearance, size and shape of the ancient forms is so similar to the modern forms that it has been suggested that they have hardly evolved in more than 2 billion years (Figure 2.17). These cyanobacteria are a very successful group of organisms – they are hardy ecological survivors, well adapted to their habitats and have persisted unchanged through vast periods of geological time.

Palaeontologists want to know how long cyanobacteria have been on Earth. However, there aren't enough unmetamorphosed sediments of Archean age to determine this. Low-temperature metamorphism destroys organic structures very effectively. The evidence currently available demonstrates that cyanobacteria have been part of Earth's biota for at least 2600 million years and that their ancestors must have arisen by 2700 million years ago. They may have appeared much earlier and it is possible that cyanobacteria helped construct the oldest stromatolites 3.5 billion years ago. But currently there is not enough evidence to make a definitive statement about when cyanobacteria first appeared on Earth.



Science Photo Library/Visuals Unlimited/Dr Robert Calentine

Science Source/Michael Abbey

FIGURE 2.17 **a** Modern Entophysalidacean cyanobacteria and **b** *Eoentophysalis belcherenisis* extracted from the 2100-million-year-old stromatolitic cherts of the Kasegalik Formation in the Belcher Islands, Canada

KEY CONCEPTS

- Stromatolites are a type of layered organic sedimentary deposit formed by photosynthetic microbial colonies. Extracellular slime produced by the microbes traps layers of sediment, and as the microbial colony grows towards the light, the layers of sediment develop very distinctive cone-shaped, dome-shaped, flat or wavy structures.
- The oldest known stromatolites formed 3.4–3.5 billion years ago and are known from deposits such as Western Australia's Strelley Pools. There is a continuous record of stromatolites from these very ancient examples through to the present day.
- Modern-day stromatolites are colonies of prokaryotic microbes. The upper layers are dominated by photosynthetic cyanobacteria and purple bacteria producers. The lower layers consist of consumer prokaryotes, including anaerobic bacteria, sulfate-reducing bacteria and methanogenic archea. Stromatolitic cyanobacteria generate oxygen as a photosynthesis by-product.
- Cyanobacteria are single-celled photosynthetic prokaryotic microbes that occur in most Earth environments that receive sunlight. Modern cyanobacteria produce oxygen by photosynthesis using chlorophyll. Chloroplasts are a type of symbiotic cyanobacteria that have been incorporated into the cells of eukaryotic plants.
- The oldest known fossils of cyanobacteria are 2600 million years old. The first cyanobacteria probably evolved by 2700 million years ago, but this group of prokaryotes may have appeared even earlier in the Archean.
- Stromatolites are largely responsible for increasing the concentration of oxygen in the Archean atmosphere.

CHECK YOUR UNDERSTANDING 2.2

1. What is a stromatolite?
2. What living organisms are thought to have produced stromatolites?
3. What is the significance of the photosynthetic cyanobacteria in the history of life on Earth?
4. Where were Earth's first stromatolites found and how old are they?
5. When do the first cyanobacteria appear in the fossil record?
6. **a** When did Earth's population of stromatolites begin to expand?
   b When did the relative abundance of this type of organic structure reach its peak?

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2.3 Interactions between the spheres

The Earth's biosphere, geosphere, atmosphere and hydrosphere interact in many ways. The impacts of the biosphere's photosynthetic organisms on the other three systems are possibly the most significant and long-lasting interactions.

Oxygen-producing photosynthesisers have dramatically changed the composition of the atmosphere and the conditions on the surface of Earth at least three times during the planet's 4.56-billion-year-long geological history. They have done this by consuming CO_2, and reducing the amount of CO_2 in the atmosphere, as they released oxygen into the oceans and the atmosphere as a by-product of generating carbohydrate and organic carbon by photosynthesis.

The first time this happened was when cyanobacteria proliferated at the end of the Archean and beginning of the Proterozoic. The dramatic increase in the abundance of these photosynthetic organisms led to the oxygenation of the oceans and the atmosphere. This is known as the Great Oxidation Event. Atmospheric oxygen rose to 10–20% of present-day levels. Before the Great Oxidation Event, Earth's atmosphere was probably anoxic and did not contain significant amounts of oxygen.

The second oxidation event was at the end of Proterozoic between 800 million and 600 million years ago after eukaryotic algae and marine plants had evolved. During this time, stromatolites became very abundant and the population of cyanobacteria on Earth may have expanded significantly. This event is called the Neoproterozoic Oxidation Event. Atmospheric oxygen rose to be similar to its present-day concentration, with oxygen forming about 20% of the volume of the atmosphere.

The third oxidation event was after the appearance of land plants during the Silurian and the Devonian and the formation of the extensive coal deposits in the northern hemisphere continents of Pangaea during the Carboniferous. This event has not been formally named because the increase in atmospheric oxygen wasn't permanent. Atmospheric oxygen content increased during the Carboniferous to a peak of about 30% of the total volume of the atmosphere (one and half times the current level), before dropping back to present-day levels during the Permian. This enabled giant flying insects such as griffenflies to evolve and dominate the Carboniferous skies. Some of these animals were ferocious predators that hunted similarly large walking insects (Figure 2.18).

Museum de Toulouse/Didier Descouens

FIGURE 2.18 This fossil is of the giant flying insect *Meganeura monyi*, a late Carboniferous griffenfly. It had a wing span of 68 cm, about 25 cm more than the combined width of the two pages you are currently reading.

During all three oxygenation events, the removal of CO_2 from the atmosphere is thought to have reduced the greenhouse effect to greater or lesser extents. However, it is difficult to determine how much global cooling was directly related to oxygen-producing photosynthetic organisms. This is because CO_2 was also being removed from the atmosphere by normal rock-weathering processes. It has even been suggested that the cooling of Earth due to an increase in rock weathering at the end of the Archean created conditions favourable to the expansion of Earth's population of cyanobacteria during the early Proterozoic.

Nevertheless it can be demonstrated that the removal of CO_2 from and release of oxygen into the atmosphere due to these evolutionary events in the biosphere contributed to major changes in the behaviour and nature of the geosphere and the hydrosphere. As the oceans and the planet cooled, ice sheets grew on the land masses and sea levels lowered. The growth of continental ice sheets resulted in long-lived globally significant continental glaciations that abraded and eroded the continental land masses. For example, climatologists are very confident that the Carboniferous oxygenation event also lowered the CO_2 content of the atmosphere and helped to trigger the Permo-Carboniferous ice age.

A second major consequence of the Neoproterozoic Oxidation Event was that enough dissolved oxygen was generated in the oceans to enable marine animals to evolve and grow to large sizes. The well-oxygenated atmosphere probably allowed the synthesis of sufficiently large and permanent volume of atmospheric ozone (O_3). Ozone blocks most of the Sun's ultraviolet light, so increasing numbers of microbial organisms were able to occupy terrestrial environments, and eventually plants and animals were able to colonise the land (Figure 2.19).

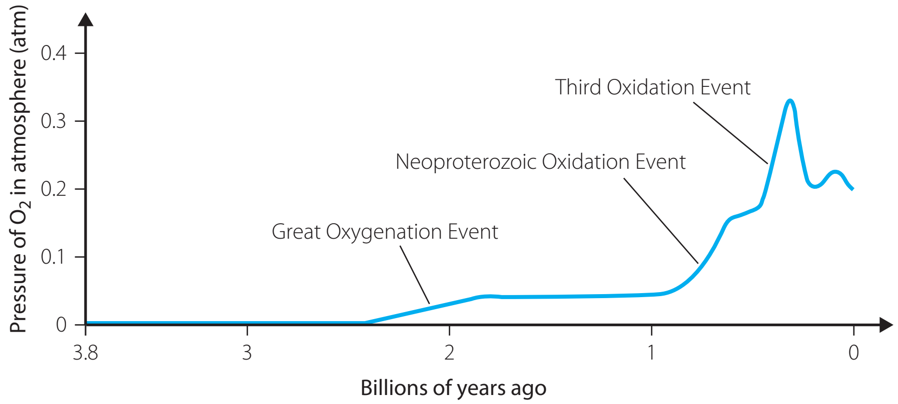

FIGURE 2.19 Estimate of the proportion of oxygen in the atmosphere as a proportion of total atmospheric pressure from the early Archean to the present day

Photosynthesing cyanobacteria, banded iron formations and the Great Oxidation Event

The fossil record suggests that oxygen-producing cyanobacteria in the global ocean started to proliferate at the beginning of the Proterozoic about 2500 million years ago. This increased the availability of oxygen in oceanic water and gradually changed the composition of Earth's atmosphere. The evidence for this change is the appearance in the rock record of banded iron formations – extensive shallow marine deposits of banded iron-oxide-rich cherts – as well as the deposition of iron-oxide rich red river sandstones.

Characteristically, the early Proterozoic's banded ironstones are fine-grained shallow marine sedimentary rocks consisting of alternating layers of iron-oxide-rich chert and iron-oxide-poor chert.

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The iron oxides that accumulated in the iron-rich layers are thought to have precipitated when sea water that was low in oxygen but high in dissolved reduced iron (Fe^{2+}), upwelled from the deep ocean. This mixed with shallow sea water that was rich in cyanobacteria and oxygen was produced (Figure 2.20). The dissolved iron was oxidised to hematite (Fe_2O_3), which precipitated and, being relatively dense, sank and accumulated in layers on the sea floor. Banded iron formations, such as the enormous deposits in Australia's Pilbara and Hammersley regions, are commonly mined for their iron. Individual bands are often continuous and can be traced for kilometres.

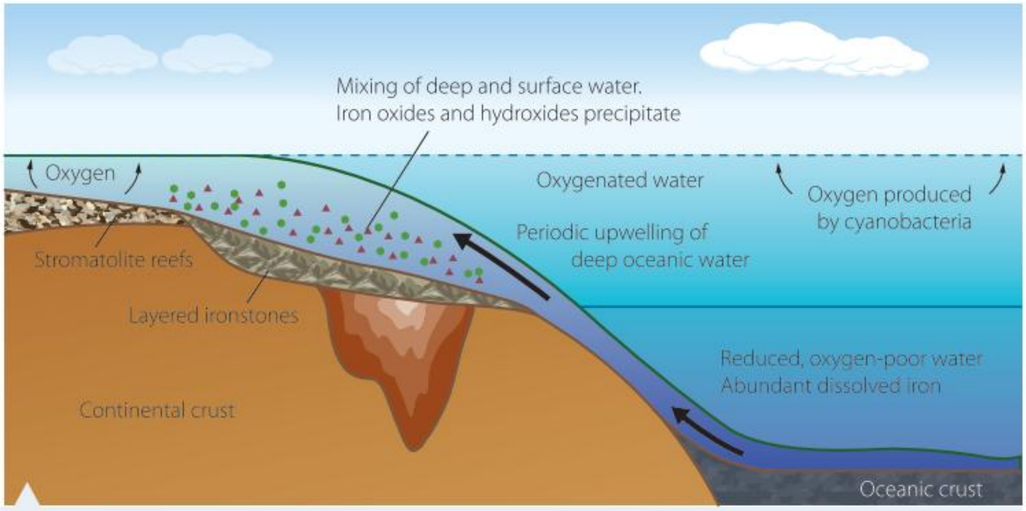

FIGURE 2.20 Creation of banded iron formations required the presence of oxygen.

Oxygen was starting to accumulate in the atmosphere by 2400 million years ago. Evidence for this is that pyrite (an iron sulfide mineral), siderite (an iron carbonate mineral) and uraninite (a uranium oxide mineral) stopped being deposited in terrestrial sandstones and conglomerates. This is because these minerals are not stable in the presence of free atmospheric oxygen. Pyrite and siderite both weather by oxidation and are converted into the iron oxide mineral hematite. Uraninite simply dissolves in water if small amounts of oxygen are present. Later, at about 2200 million years ago, significant amounts of red iron oxide rich river sandstones and lake mudstones began to be deposited in terrestrial environments.

It took about 500 million years for the photosynthetic cyanobacteria to generate enough oxygen to permanently oxygenate the oceans and then change the composition of the atmosphere. This is because there was an enormous amount of dissolved reduced iron in the global ocean at the beginning of the Proterozoic. It was only after all the dissolved oceanic iron was oxidised and had precipitated from the sea water and accumulated in banded iron formations (Figure 2.21) that photosynthetic oxygen could be released into the atmosphere.

We know this process took about 500 million years because most of Earth's marine banded iron formations were deposited between 2500 million and 2000 million years ago. This is the Great Oxidation Event process but it is also sometimes called the 'rusting of Earth' and the 'great rusting event'. It took another 200 million years for the oxygen content of the atmosphere to stabilise, but when the process was completed, the partial pressure of oxygen in the atmosphere was about 0.04 atm, which means that 1 in 25 of the molecules in the air was an oxygen molecule.

Auscape/Ian Beattie

FIGURE 2.21 Banded iron formations in Dales Gorge, Western Australia

INVESTIGATION 2.2

Critical and creative thinking

Reaction of dissolved iron and oxygen

Rust is a mixture of hydrated iron(III) oxides. Oxygen and dissolved iron react to form an insoluble iron oxide precipitate. Iron oxide forms the minerals haematite (Fe_3O_3) and magnetite (Fe_3O_4).

AIM

To model the conditions required for the formation of rust, and hence banded iron formations, in the early Proterozoic

MATERIALS

- Degassed water (boiled and cooled to remove gases)
- 4 test tubes
- Iron(II) sulfate
- Iron(III) chloride (anhydrous)
- Marking pen
- Paddle pop stick (to scoop out iron powder)
- Fish tank aerator and tubing
- Filter paper
- Filter funnel
- 4 × 250 mL beakers

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Iron(II) sulfate and iron(III) chloride are skin and eye irritants.	Wear safety glasses and wash hands after the experiment.
Iron oxide may stain clothing	Wear a laboratory coat.

What other risks can you identify in this investigation? How will you manage them?

METHOD

1 Copy the table in the Results section.
1 Place a small amount of iron(II) sulfate powder in two test tubes and a small amount of iron(III) chloride in another two test tubes. Label the test tubes.
2 Observe and record the colour of the powders.
3 Carefully add degassed water to fill approximately half of each test tube. Gently swirl the test tubes to dissolve all the powder.
4 Observe and record the colour of each solution.
5 Use the fish tank aerator to bubble air (rich in oxygen) through one of each of the test tubes containing the solution of iron(II) sulfate and one test tube containing iron(III) chloride. Label these test tubes 'Aerated'.
6 Observe and record any changes to the solutions.
7 Leave all four test tubes overnight and filter the resulting solutions.
8 Record your observations of the filtrate and residue for each iron compound.
9 Compare the aerated and non-aerated test tubes and record your observations.

»

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» RESULTS

Copy and complete this table.

CHEMICAL	COLOUR	OBSERVATIONS AFTER BUBBLING AIR THROUGH SOLUTIONS	OBSERVATIONS OF FILTRATE AND RESIDUE
Iron(II) sulfate powder			
Iron(III) chloride powder			
Iron(II) sulfate solution (not aerated)			
Iron(II) chloride solution (not aerated)			
Iron(II) sulfate solution (aerated)			
Iron(II) chloride solution (aerated)			

Analysis of results

1 Why was degassed water used for this experiment?
2 What conditions are required for the formation of rust?
3 How do your results support the theory that oxygen was present in the atmosphere during the early Proterozoic?
4 Why did you not aerate all four test tubes?
5 What are the two test tubes that were not aerated called?

Other impacts on the spheres

Two other major changes to Earth's surface processes occurred as a direct consequence of the Neoproterozoic Oxidation Event and then colonisation of Earth's surface by plants. The first of these changes was the effect of the abundant atmospheric oxygen on the weathering of rocks during the late Proterozoic. Increased oxidation of sulfide minerals in rocks generated sulfuric acid, which in turn enhanced the breakdown of feldspars and ferro-magnesium silicates to produce clay minerals such as kaolinite. As the near-surface weathered zone became occupied by microbes, the second important change, the influence of chemical weathering relative to physical weathering in rock increased and started the production of clay-rich soil on the land masses.

We know this change occurred because the composition of the fine-grained silt and clay-sized material eroded from the land masses and deposited in marine and terrestrial mudstone gradually changed. Before the Neoproterozoic Oxidation Event, mudstones mostly contained quartzand feldspar (Figure 2.22) Afterwards, mudstones mostly contained clays, quartz and muscovite (Figure 2.23). Today, clay minerals are mostly generated in biologically active soils. The global increase in clay production at the end of the Proterozoic has been described to be the start of the 'global clay mineral factory'.

FIGURE 2.22 A 2700-million-year-old gold- and pyrite-bearing conglomerate

FIGURE 2.23 Large quartz pebbles and small pyrite sand grains typical of sediments deposited on the beds of Archean river channels before the Great Oxidation Event

KEY CONCEPTS

- Evolutionary events in the biosphere increased oxygen production by photosynthetic organisms and contributed to changing the composition of the atmosphere and surface conditions on Earth during the Great Oxidation Event and the Neoproterozoic Oxidation Event, and due to the proliferation of terrestrial plants during the Devonian and Carboniferous.
- The Great Oxidation Event occurred between 2500 million and 2000 million years ago. The proliferation of photosynthetic cyanobacteria oxygenated the oceans and produced most of Earth's banded iron formations. Reduced atmospheric CO_2 also reduced the greenhouse effect, which cooled the planet and generated extensive continental icesheets and caused a major period of global glacial conditions.
- The Neoproterozoic Oxidation Event occurred between about 800 million and 600 million years ago. It is associated with global cooling, extensive continental glaciations and increased oxygenation of the oceans and the atmosphere to levels similar to those of the present day. This is one of the factors required for the evolution and survival of large marine animals.
- The colonisation of the land masses by plants in the Devonian and Carboniferous between 400 million and 350 million years ago also caused a significant increase in atmospheric oxygen and an associated reduction in atmospheric CO_2. This event contributed to global cooling and helped cause a globally significant extended period of continental glaciation.
- The characteristics and extent of chemical weathering of rocks changed due to the Great Oxidation Event and the Neoproterozoic Oxidation Event. Sulfide minerals ceased to be stable at Earth's surface after the Great Oxidation Event, and clay mineral production by chemical weathering increased during and after the Neoproterozoic Oxidation Event.

CHECK YOUR UNDERSTANDING 2.3

1. Identify the three major periods in Earth's history when the amount of atmospheric oxygen has significantly increased. Identify the group of organisms probably responsible for this change.
2. Describe three geologically significant consequences of the Great Oxidation Event.
3. Outline the environmental and biological consequences of the Neoproterozoic Oxidation Event.
4. What does the term 'global clay mineral factory' refer to?
5. Why did the largest flying insects ever known populate the sky in the Carboniferous?

2.4 Origin of multicellular life and changes to ecosystems

Earth's multicellular organisms include all of the animals and plants that live in the sea and on the land as well as most fungi and algae. Determining the steps on the evolutionary pathway between single-celled and multicellular organisms has proven to be difficult. This is because most of these ancient transitions occurred in microscopic or soft-tissue organisms that tend to not fossilise well. Many of these transitions occurred during the early and middle Proterozoic while the oceans were sulfide-rich. This limited the amount of oxygen available to help drive biochemistry within the cells of these organisms.

The first known marine plants were tiny red algae called *Bangiomorpha* (Figure 2.24a). These are minature forms of modern-day rhodophyte algae (Figure 2.24b). These first multiorgan plants appeared about 1000 million years ago with tiny but separate **holdfasts**, stems and reproductive organs. They were photosynthetic oxygen producers. There is very little evidence for the intermediary forms between *Bangiomorpha* and its single-celled eukaryotic algal predecessors.

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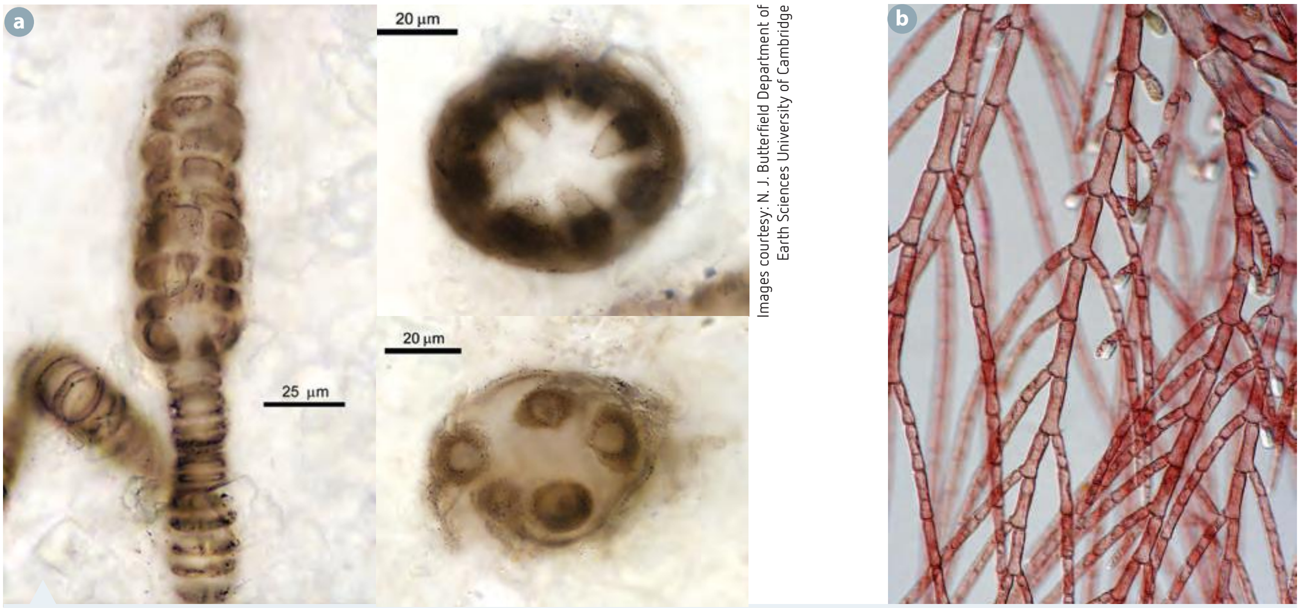

FIGURE 2.24 **a** *Bangiomorpha* and **b** a modern-day Rhodophyte red-algae

Images courtesy: N. J. Butterfield Department of Earth Sciences University of Cambridge

Shutterstock.com/F.Neidl

As oxygen levels in the oceans increased during the late Proterozoic, a new multicellular community of life appeared. These organisms varied from about 1 to 50 cm in size and were mostly immobile. They are collectively known as the **Ediacaran** fauna.

Ediacaran fauna

Fossil evidence of Ediacara fauna has been found in volcanic ash deposits and sandstones at more than 30 sites around the world. They are named after the first site where they were found to be abundant and well preserved. Geologist Reginald Sprigg, who was prospecting for uranium at the time, discovered them in the Ediacara Hills of South Australia in 1947, but it was another decade before the importance of his find was accepted. Ediacaran animals are soft-bodied organisms ranging from a few millimetres to about a metre across (Figure 2.25, page 52). They present several levels of complexity ranging from jelly-like globules (*Kimberella*) to quilted feathered fronds (*Charniodiscus*), radial-ribbed discs (*Tribrichadium*) to the worm or arthropod-like and suspected predator (*Spriggina*). These species lived in shallow marine environments and had complex structures that probably required sufficient oxygen to grow several different types of cell, which makes them metazoans. Their evolutionary relationships to **bilaterally symmetrical** organisms (or bilaterians) that dominate the Phanerozoic has not been determined but we do know that Ediacarans were not true bilaterians even though some of them do appear to be very nearly symmetrical. Most Ediacarans are thought to have been immobile because trace fossils generated by their body shapes are not known.

The Ediacaran lasted from 635 million years ago to the beginning of the Cambrian 541 million years ago, but most of the large Ediacaran animals appeared about 565 million years ago. These animals dominated the latest Proterozoic ecosystems before the explosion of bilaterian (bilaterally symmetrical) (2.26, page 53) organisms in the early Cambrian. Explaining the fossilisation of their bodies has presented a puzzle to palaeontologists. Their jelly-like bodies were probably covered in mucus, which enabled sand to stick to them when they died and decayed, holding the outer shape intact. It is possible that bacterial mats grew over the animals after they died, preserving their body shape during the decaying process. It is also possible that there were few scavengers or predators to consume the remains of their bodies, which could also mean that the evolution of scavengers and predators led to the demise and extinction of the Ediacarans.

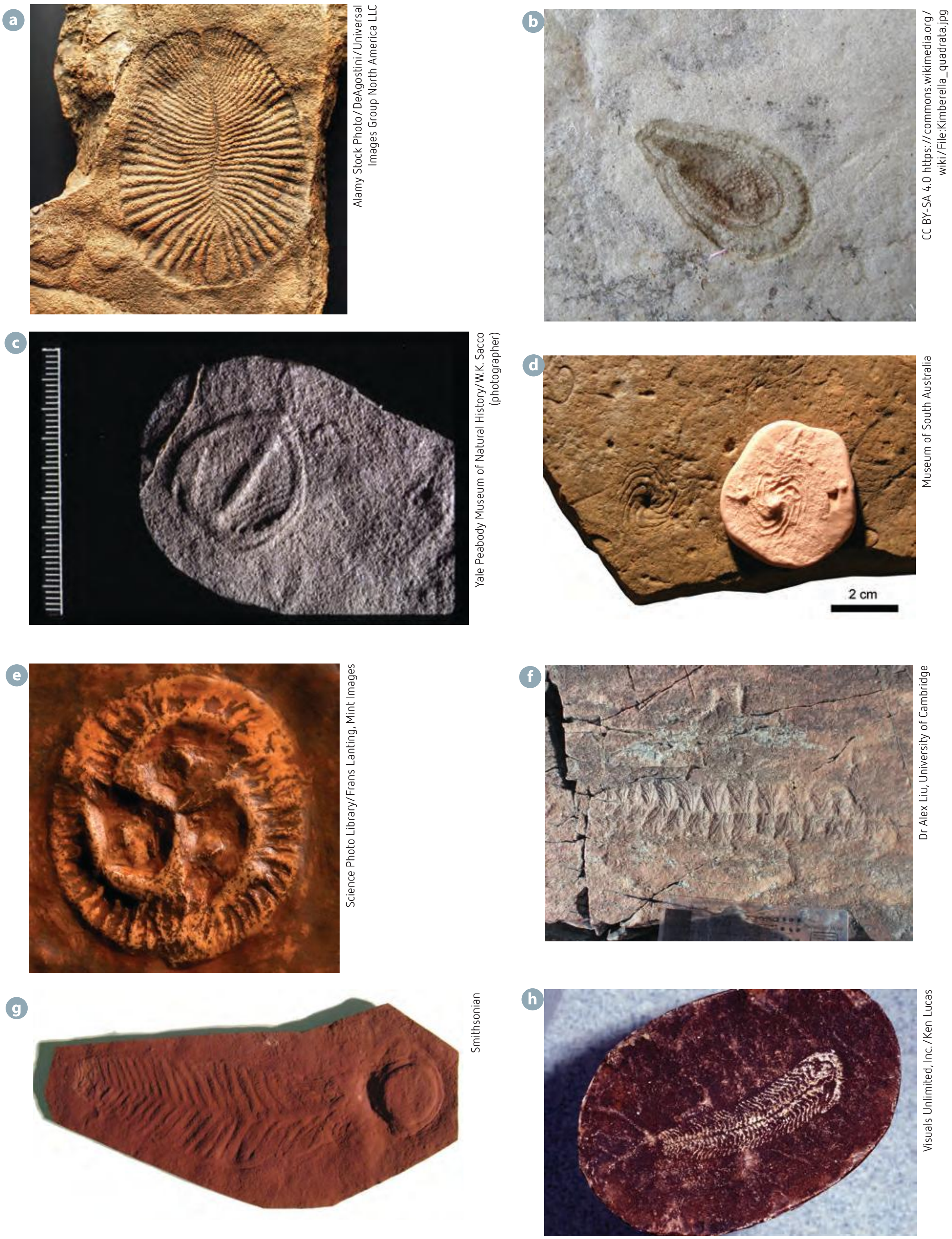

FIGURE 2.25 Examples of Ediacaran organism: **a** *Dickinsonia costata*, **b** *Kimberella quadrata*, **c** *Parvancorina minchami*, **d** *Eoandromeda octobrachiata*, **e** *Tribrachidium heraldicum*, **f** *Fractofusus misrai*, **g** *Charniodiscus arboreus*, **h** *Spriggina flounderisi*

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The evolutionary links between the fauna of the Ediacaran and Cambrian are still being studied. Fossil impressions generated by *Dickinsonia*, a flat sheet-like creature up to 50 cm long, suggest that it may have been capable of movement on the seabed. This would have required it to have an organised musculature and a simple nervous system to coordinate movement. Classification and understanding the lifestyles of the soft-bodied Ediacaran animals is difficult. Palaeontologists have demonstrated that these mostly immobile creatures died out quickly at the end of the Ediacaran. Their extinction was probably due to competition from the emergence of invertebrate animals. These bilaterians had evolved more complex body plans, including eyes and mouths and armour that enabled them to hunt and consume the Ediacarans.

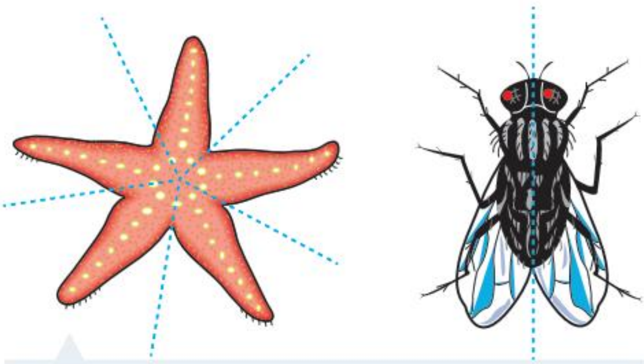


FIGURE 2.26 Radial symmetry and bilateral symmetry

Cambrian explosion

The first period of the Phanerozoic eon lasted from 542 million to 488 million years ago. It is called the Cambrian after the rocks found in Cambria, Wales, where the oldest fossils of invertebrate animals with hard shells and jaws and eyes were first identified. The abundance and variety of fossils that occur in the earliest Cambrian rocks increases dramatically, and by about 520 million years ago, all 34 phyla of animals that inhabit Earth today are represented in the fossil record. This sudden appearance of animals and the apparently extremely rapid diversification event that established the animal kingdom is so significant that palaeontologists call it the **Cambrian explosion**. Geologists and palaeontologists are not certain why and how it happened.

Cambrian explosion explained

Several events that occurred between 700 million and 542 million years ago, before the beginning of the Cambrian, are thought to have enabled the explosion of life to occur. These events significantly changed the nature of Earth's environments. First, about 650 million years ago, the supercontinent Pannotia began to break apart into two large continents, Laurasia and Gondwana. This rifting event continued well into the following Cambrian period. The temperature of the atmosphere significantly rose to an average of 22°C. Icesheets receded and ocean levels rose, which led to continental flooding and erosion and eventuated in a change in the chemistry of ocean water, including an increase in oxygen and vital nutrients such as phosphorus for ATP synthesis. An ozone layer formed, shielding Earth from harmful ultraviolet rays. The most important factor was probably oxygenation of the oceans and atmosphere because reliable high concentrations of oxygen are required to support the metabolisms of active animals.

Evidence from fossils also provides clues about the other main driver of the Cambrian explosion – competition between the evolving animals. Some of the very latest Ediacaran and earliest Cambrian fossils are placed in a group called the small shelly fauna. This includes the enigmatic *Cloudina* and fragments of hard silicate, calcite and phosphatic skeletal material produced by molluscs, brachiopods, sponges, echinoderms and proto-arthropods (Figure 2.27).

https://www. geoparquevilluercas.es/cloudina/

FIGURE 2.27 *Cloudina* was a small shelly animal of the late Ediacarna–early Cambrian.

WS
Ediacaran and Cambrian fauna

The function of the small shelly fauna's skeletal material is thought to have been protection from the environment and predators. It was a form of armour, which is one of the main functions of invertebrate shells and exoskeletons today. But the protection was only partly successful. Bored holes found in *Cloudina* suggest that predators were able to breach the armour.

Animals had begun to live in burrows as well. A surge in the complexity and depths of burrowing in the earliest Cambrian sediments suggests some animals were probably hiding from predators, while others were probably ambushing unsuspecting victims from camouflaged hides.

These, and many other evolutionary innovations and adaptations indicate that a major biological 'arms race' was underway. Lightly armoured animals became more robustly armoured and bigger. Predators developed larger jaws and stronger teeth. Many groups of animals developed sophisticated eyes. Life on the floor of the Cambrian oceans diversified rapidly, and by 525 million years ago, large and small armoured trilobites with savage protective spikes, thick-shelled molluscs and brachiopods and impressive apex predators such as *Anomalocaris* (Figure 2.28b) had occupied the complete range of the ecological niches recognised in today's marine environments. Vertebrates such as *Pikaia gracilens* (Figure 2.28a) were minor players in the Cambrian world, but the evolutionary arms race that has continued at a fast pace ever since would eventually see their descendants come to dominate Earth's ecosystems.

a

Shutterstock.com/Catmando

b

PaleoEquii/CC BY-SA 4.0 International https://creativecommons.org/licenses/by-sa/4.0/deed.en

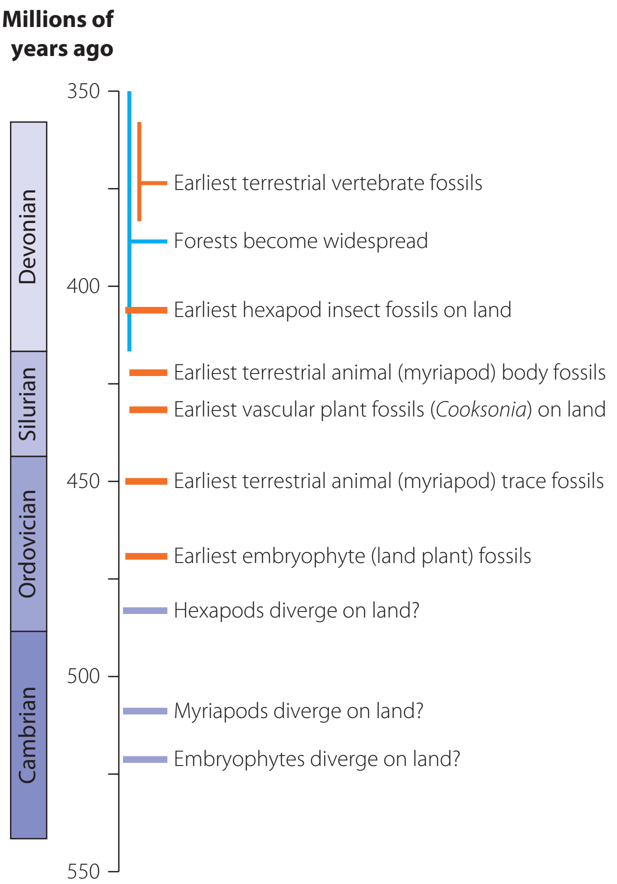
c

Shutterstock.com/MarcelClemens

FIGURE 2.28 **a** *Pikaia gracilens*, **b** *Anomalocaris* and **c** *Trilobite* are examples of animals that evolved during the Cambrian explosion.

Invasion of land

It was a surprisingly short period between the Cambrian explosion and the colonisation of terrestrial environments by plants and animals (Figure 2.29). It may have only been 50 million years before some groups of the large, complex invertebrate animals that appeared 520 million years ago during the Cambrian explosion started to explore the land. There is even some evidence to suggest that plants such as liverworts, mosses and pond scum began to exploit freshwater environments and permanently damp bogs and swamps at the same time as the Cambrian explosion. Some palaeontologists and biologists suspect that these plants were probably accompanied by groups of marine arthropods who spent short periods on land, escaping predators or feeding on the earliest terrestrial plants and algae in a similar way that modern-day mudskipper fish do today.

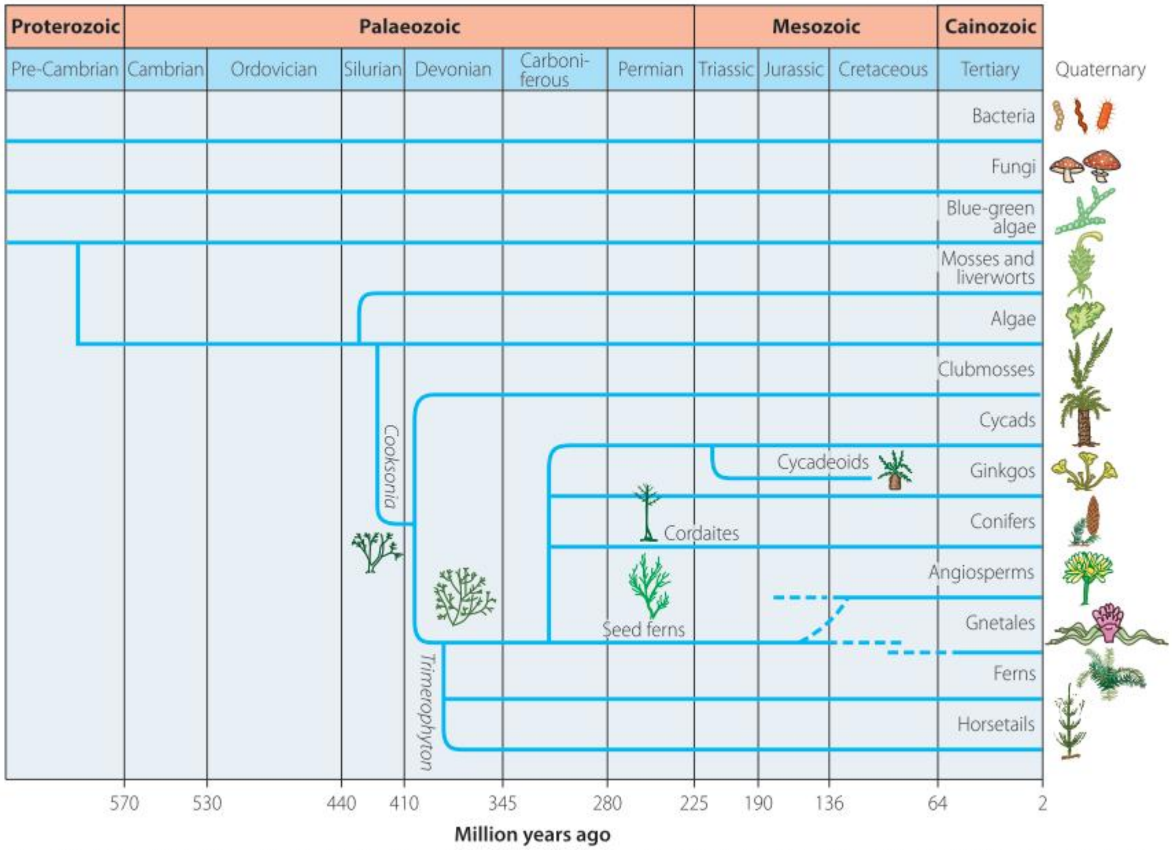


Current Biology, vol 23, issue 6, pp.443–542. 'Evolution: Out of the Ocean' by Casey W. Dunn

FIGURE 2.29 The timing of important events in the invasion of terrestrial environments by plants and animals

The earliest accepted plant fossils are 470 million years old (Figure 2.30, page 56). They are embryophyte spores, which suggests that the first terrestrial plants depended on fungi to obtain their nutrients and that symbiotic relationships were a key aspect of the early terrestrial colonisers. The first fossils of **vascular plants**, which have roots, such as *Cooksonia*, occur in rocks about 430 million years old in the late Silurian. Vascular plants diversified in the Devonian and the first forests and trees with root systems penetrating to depths of around one metre spread across the continents (Figure 2.31, page 56).

FIGURE 2.30 Plant lineages through geological time



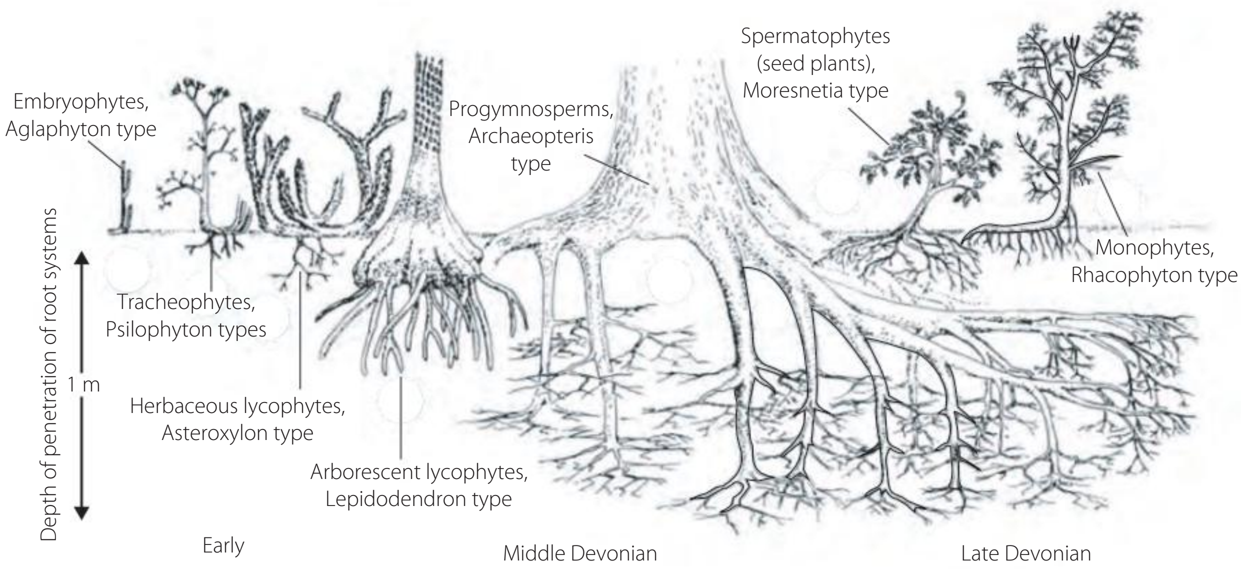


FIGURE 2.31 Increase in stem and root system size during the Devonian

As terrestrial forests became established on the continental landmasses, there were major changes to Earth's climate, the composition of the atmosphere and the geosphere by increasing the thickness of soil profiles and the depth of weathering profiles. Plants **transpire** large amounts of water from deep in the soil into the atmosphere and dramatically increase the amount of heat energy retained by Earth's surface by decreasing the amount of solar radiation reflected back out into space. Both these processes combine to increase average global temperature by about 5°C and significantly increase the amount and distribution of rainfall across Earth's surface.

The earliest accepted evidence for animals occupying terrestrial environments are the footprints and tracks of myriapods such as millipedes and eurypterids. These trace fossils become relatively common from about 450 million years ago and suggest that invertebrates colonised the land long before our vertebrate ancestors (Figure 2.31). The first accepted fossil of a land animal is for the lower Devonian species *Pneumodesmus newmani*, a millipede fossils that is 414 million years old (Figure 2.32). It is definitely a terrestrial myriapod because it has **spiracles**, tubes that deliver atmospheric oxygen to the internal tissues.

FIGURE 2.32 A reconstruction of *Pneumodesmus newmani,* the oldest fossil of a land animal

Terrestrial vertebrates

The first fossil evidence for terrestrial vertebrates dates from about 365 million years ago. This is long after the first arthropods and plants colonised the land in the Silurian period. Terrestrial vertebrates first ventured on land during the middle Devonian, which is often called the 'age of the fishes'.

During this period, vertebrate fish diversified and became a dominant group of oceanic animals. Jawed fish first appeared in the Silurian and had developed pelvic fins before they split into three main groups that diversified dramatically during the Devonian. The three groups are the heavily armoured placoderms, which went extinct at the end of the Devonian, the cartilaginous fish, including the sharks and rays, and the bony fish (Figure 2.34, page 59). The two main types of bony fish are the ray-fins, which dominate the oceans today, and the much less abundant lobe-fins.

The **tetrapod** (four-footed) descendants of the lobe-fins emerged from rivers and lakes and moved onto the land during the middle and late Devonian. This terrestrial group of lobe-fins includes the amphibians, followed by the reptiles and then the birds and mammals and they have dominated the other terrestrial species ever since their expansion during the Carboniferous.

It used to be thought that terrestrial vertebrates had evolved from a fish that had managed to survive on land after being stranded by a falling tide or a receding flood. But the transition from fish to the first tetrapods that walked on the land was much more gradual – it took 15 million years. When fossils linking the two groups of animals were found, the steps separating a fully aquatic vertebrate lifestyle from a mostly terrestrial one and the progression of vertebrates from ocean onto the land is much easier to understand (Figure 2.35, page 239).

The critical fossils include *Acanthostega* and *Icthyostega*, which are about 365 million years old. They were first found in Greenland in the 1930s but were not properly described and understood until the 1990s. The 'missing link' fossil *Tiktaalik* was found in arctic Canada in 2004 and is 375 million years old. Neck joints had allowed these animals to move their heads independently from the rest of their bodies. For this reason, these animals are sometimes referred to as fishibians. They were freshwater species that probably spent much of their time in the shallows of rivers and floodplain lakes, avoiding the ferociously jawed and strongly armoured placoderm predators that dominated the deep-water channels. To help them avoid predators, *Tiktaalik* and its forebears used strongly developed pectoral and pelvic lobe-fins as pudgy feet that could grasp the shallow bottom of fast-flowing streams. They could probably also clamber up onto the shore to escape aggressive predators or scrounge for food supplied by the abundant arthropods and plants thriving on land at that time.

Tiktaalik, *Icthyostega* and *Acanthostega* were really fish with legs rather than truly terrestrial animals. All three species had scales and gills as well as a special air sac or second stomach. This air sac was linked by a tube, called a spiracle, that passed through the skull and linked the primitive lungs to the atmosphere. *Icthyostega* was also probably more fish-like in its behaviour than later

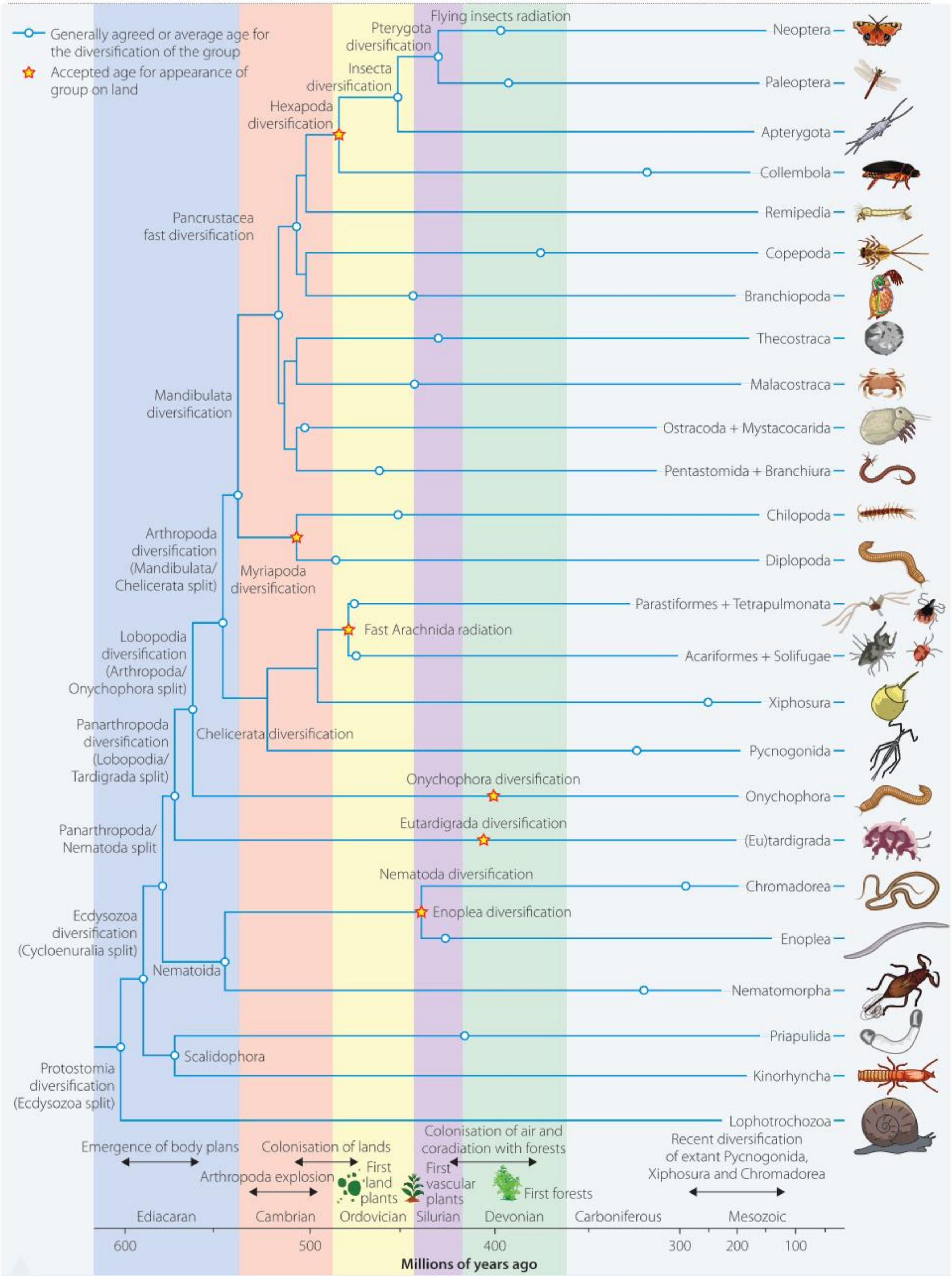


FIGURE 2.33 A timeline of the colonisation of terrestrial environments by invertebrates. The open circles are generally agreed or average ages for the diversification and appearance of that group of animals.

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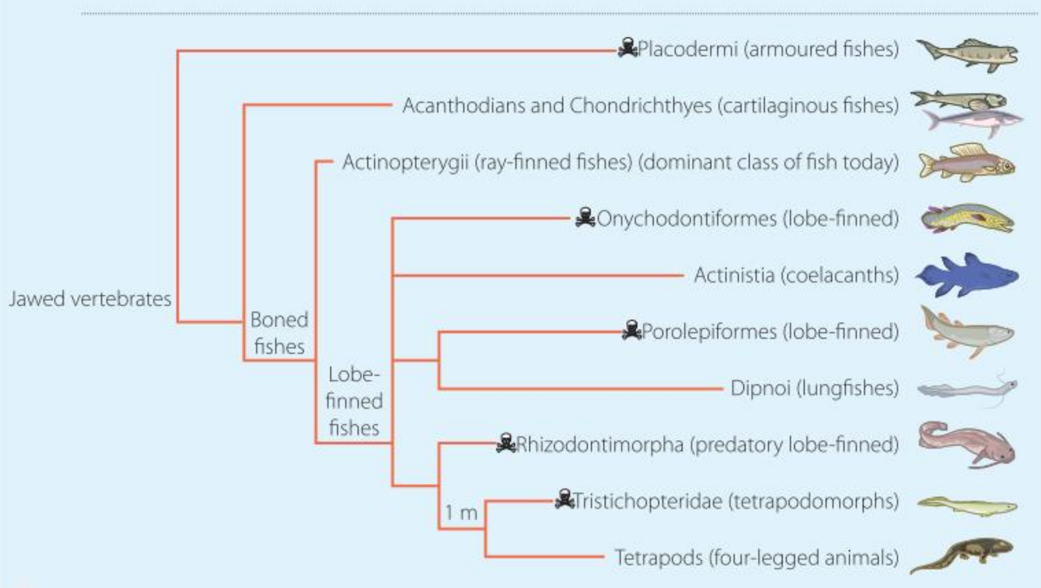

FIGURE 2.34 Evolution of fish during the Devonian period. A skull and crossbones indicates that the group died out during the Devonian mass extinction event.

land-living amphibians but it was better adapted for life on land than *Tiktaalik* and *Acanthostega.* Its limbs and rib cage were organised in such a way that it could probably walk fairly well and scurry about in brief bursts of activity on dry land.

By 355 million years ago at the end of the Devonian, fully terrestrial tetrapods were abundant, but these species all relied on water for reproduction. They had to lay their eggs in conditions where they wouldn't dry out. The first tetrapods that were fully terrestrial appeared about 315 million years ago during the late Carboniferous – they are called amniotes and they laid water-tight eggs.

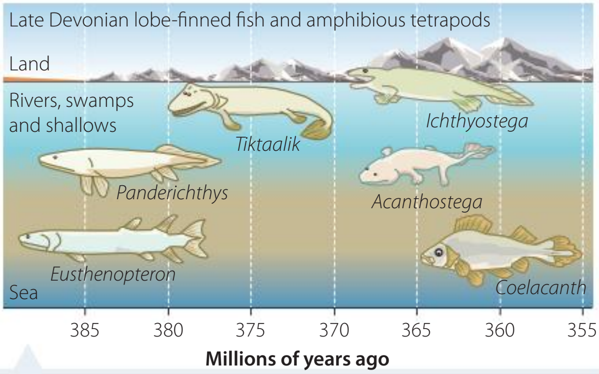

FIGURE 2.35 Evolution of fish to amphibians during the late Devonian period

KEY CONCEPTS

- The first fossil evidence for multicellular organisms is for the plant *Bangiomorpha*, which is 1200 million years old.
- Animal fossils appear about 635 million years ago about the same time that oceanic and atmospheric oxygen concentrations approached modern-day levels.
- Large soft-bodied Ediacaran animals such as *Dickinsonia*, *Charniodiscus* and *Spriggina* appeared about 565 million years ago. They dominated the latest Proterozoic ecosystems before their disappearance during the radiation of bilaterian organisms in the earliest Cambrian.
- All of the groups of bilaterally symmetrical animals recognised today diversified and became well established during the Cambrian explosion event that took place over about 20 million years. By about 523 million years ago, some of these animals achieved large sizes and had developed armour, eyes and teeth. Most, and possibly all, the predator–prey behaviours recognised today were established during this event.
- The oldest recognisable terrestrial plant fossils are 470 million years old. The oldest arthropod fossils are 414 million years old. The oldest terrestrial tetrapods appeared about 365 million years ago. There is good evidence that these groups evolved from aquatic species and the transition to the land was a gradual process that took several million years or possibly 10 million years or so.
- The colonisation of terrestrial environments by plant species in the Devonian probably stabilised soils by anchoring to the layer of bedrock underneath the soil as tree root systems reinforced soil profiles and reduced landsliding. This enabled thicker soil profiles to develop and probably increased the variety of minerals produced by weathering. This may have reduced rates of soil erosion and almost certainly protected river bank soils from erosion.

CHECK YOUR UNDERSTANDING 2.4

1 Construct a timeline to show when the following appeared in the fossil record: marine plants, animals, complex animals with armour and teeth.

2 What are Edicarans? List their characteristics.

3 What is the small shelly fauna?

4 Name or sketch three examples of the animals that appeared during the Cambrian explosion.

5 **a** What does the term 'Cambrian explosion' refer to?

b How long did this explosion take?

6 Outline the main characteristic of a bilaterian organism.

7 Which group of organisms dominated the middle Cambrian oceans?

8 When do land plants appear in the fossil record?

9 When did the first land animal live?

10 Outline the characteristics of the 'selection pressures' or 'evolutionary events' that are thought to have driven the diversification of marine animals during the Cambrian.

11 What is *Cooksonia*? When did it appear and why is it an important organism?

12 How did the size of plants and their root systems change during the Devonian? Outline the consequences of these changes for soil formation and erosion processes.

13 What is *Tiktaalik*? When did it live and why is it an important organism?

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2 CHAPTER SUMMARY

- Unmetamorphosed sedimentary rocks of early Archean age are very rare. This makes the search for the signs of ancient life very difficult. Nevertheless, there is good geological evidence for active microbial organisms being active on Earth 3.8 billion years ago.
- Stanley Miller and Harold Urey synthesised amino acids and other organic compounds by discharging electrical sparks through a gaseous mixture of CH_4, NH_3, H_2O and H_2, and demonstrated that amino acids, the precursor components of proteins, could have been generated from inorganic processes.
- Comets and carbonaceous meteorites commonly contain phosphorus and a variety of complex organic molecules that are precursor materials required for the development of microbial organisms.
- The panspermia hypothesis proposes that life occurs everywhere in the universe and that Earth's organisms could have evolved from organic material that was brought to Earth from space on meteorites or comets.
- Hydrothermal vents are features on the deep sea floor where jets of sea water are ejected. The jets of sea water contain dissolved sulfides and sulfates that support ecosystems in which chemosynthetic microbes produce carbohydrates and organic material that are consumed by browsers and filter feeders. In turn, these organisms are consumed by scavengers and predators.
- There are three common types of hydrothermal vents. Black smokers eject very hot (350°C) sea water rich in dissolved iron and copper sulphides. White smokers eject hot (250°C) sea water rich in calcium and barium sulfates. Alkaline vents eject warm (60°C) sea water rich in hydrogen and sulfur, dissolved silica as well as calcium, magnesium, nickel, iron and carbonates.
- Stromatolites are a type of layered organic sedimentary deposit formed by photosynthetic microbial colonies. Extracellular slime produced by the microbes traps layers of sediment and as the microbial colony grows towards the light, their layers of sediment develop very distinctive cone-shaped, dome-shaped, flat or wavy layered structures.
- The oldest known stromatolites formed 3.4–3.5 billion years ago and are known from deposits such as Western Australia's Strelley Pools. There is a continuous record of stromatolites from these very ancient examples through to the present day.
- Modern-day stromatolites are colonies of prokaryotic microbes. The upper layers are dominated by photosynthetic cyanobacteria and purple bacteria producers. The lower layers consist of consumer prokaryotes, including anaerobic bacteria, sulfate-reducing bacteria and methanogenic archea. Stromatolitic cyanobacteria generate oxygen as a photosynthesis by-product.
- Cyanobacteria are single-celled, photosynthetic prokaryotic microbes that occur in most Earth environments that receive sunlight. Modern cyanobacteria produce oxygen by photosynthesis using chlorophyll. Chloroplasts are a type of symbiotic cyanobacteria that have been incorporated into the cells of eukaryotic plants.
- The oldest known fossils of cyanobacteria are 2600 million years old. The first cyanobacteria probably evolved by 2700 million years ago, but this group of prokaryotes may have appeared even earlier in the Archean.
- Stromatolites are largely responsible for increasing the concentration of oxygen in the Archean atmosphere.
- Evolutionary events in the biosphere increased oxygen production by photosynthetic organisms and contributed to changing the composition of the atmosphere and surface conditions on Earth during the Great Oxidation Event and the Neoproterozoic Oxidation Event, and due to the proliferation of terrestrial plants during the Devonian and Carboniferous periods.
- The Great Oxidation Event occurred between 2500 million and 2000 million years ago. The proliferation of photosynthetic cyanobacteria at this time oxygenated the oceans and produced most of Earth's banded iron formations. Reduced atmospheric CO_2 also reduced the greenhouse effect, which cooled the planet and generated extensive continental icesheets and a major period of global glacial conditions.
- The Neoproterozoic Oxidation Event occurred between about 800 million and 600 million years ago. It is associated with global cooling, extensive continental glaciations and increased oxygenation of the oceans and the atmosphere to levels similar to those of the present day. This is one of the factors required for the evolution and survival of large marine animals.
- The colonisation of the land masses by plants in the Devonian and Carboniferous periods between 400 million and 350 million years ago also caused a significant increase in atmospheric oxygen and an associated reduction in atmospheric CO_2. This event contributed to global cooling and helped cause a globally significant extended period of continental glaciation.
- The characteristics and extent of chemical weathering of rocks changed due to the Great Oxidation Event and the Neoproterozoic Oxidation Event. Sulfide minerals ceased to be stable at Earth's surface after the Great Oxidation Event, and clay mineral production by chemical weathering increased during and after the Neoproterozoic Oxidation Event.
- The colonisation of terrestrial environments by plant species in the Devonian probably stabilised soils by anchoring to the layer of bedrock underneath the soil as tree root

systems reinforced soil profiles and reduced landsliding. This enabled thicker soil profiles to develop and probably increased the variety of minerals produced by weathering. This may have reduced rates of soil erosion and almost certainly protected river bank soils from erosion.

- The first fossil evidence for multicellular organisms is for the plant *Bangiomorpha*, which is 1200 million years old.
- Animal fossils appear about 635 million years ago about the same time that oceanic and atmospheric oxygen concentrations approached modern-day levels.
- Large soft-bodied Ediacaran animals such as *Dickinsonia*, *Charniodiscus* and *Spriggina* appeared about 565 million years ago. They dominated the latest Proterozoic age ecosystems before their disappearance during the radiation of bilaterian organisms in the earliest Cambrian.
- All of the groups of bilaterally symmetrical animals recognised today diversified and became well established during the Cambrian explosion event that took place over about 20 million years. By about 523 million years ago, some of these animals achieved large sizes and had developed armour, eyes and teeth. Most, and possibly all, the predator–prey behaviours recognised today were established during this event.
- The oldest recognisable terrestrial plant fossils are 470 million years old. The oldest arthropod fossils are 414 million years old. The oldest terrestrial tetrapods appeared about 365 million years ago. There is good evidence demonstrating that all these groups evolved from aquatic species and the transition to the land was a relatively gradual process that took several million years or possibly 10 million years or so.

2 CHAPTER REVIEW QUESTIONS

Qz Review quiz

1 Draw the Miller–Urey apparatus. Label the reactants and products of the experiment. Explain how this experiment provided evidence for the origin of organic life on Earth.

2 Outline why the scientific investigations of the Murchison meteorite and the 67P/Churyumov-Gerasimnko comet provide evidence to support the Panspermia hypothesis.

3 a Draw a sketch that shows how a high-temperature hydrothermal vent functions.

b What is the origin of the materials ejected by its seawater jet?

4 a Draw a simple food web for a hydrothermal vent community.

b Explain the relationships between the producers, consumers, scavenger and predator organisms.

5 Explain how Earth's physical, compositional and environmental conditions contributed to the evolution of organic life in the Archean.

6 Draw a sketch of a modern-day stromatolite colony that shows its internal divisions and the slime mat that traps inorganic sediment on the stromatolite's topmost growing surface.

7 Why are ancient late Archean cyanobacteria so similar to modern-day cyanobacteria?

8 a Outline the main characteristics of the two oxidation events of the Precambrian.

b Construct a three-circle Venn diagram to illustrate the consequences that resulted from the increased availability of atmospheric oxygen on the geosphere, biosphere and hydrosphere.

9 Explain the Neoproterozoic Oxidation Event's role in starting up the 'global clay mineral factory'.

10 Why are global glaciations associated with the Great Oxidation Event, the Neoproterozoic Oxidation Event and the Carboniferous atmospheric oxygen peak?

11 a What is *Bangiamorpha*?

b Why is it important?

12 Explain why some geologists think that the term 'Cambrian explosion' is somewhat misleading. (Hint: Consider how long the Cambrian explosion took to occur.)

13 a Outline the timeline of the emergence of terrestrial organisms (animals and plants).

b Provide an explanation for why arthropods successfully invaded the land so long before vertebrates made this important transition.

14 Outline why palaeontologists think that the colonisation of land was gradual rather than sudden.

15 Provide an explanation for why it is often suggested that the first land animals and plants probably migrated onshore from freshwater environments rather than directly from the oceans.

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3 The plate tectonic supercycle

OUTCOMES

In this chapter you will learn about:

- features of the plate tectonic supercycle CCT ICT
- effects of the plate tectonic supercycle on global sea level, climate and evolution. CCT ICT

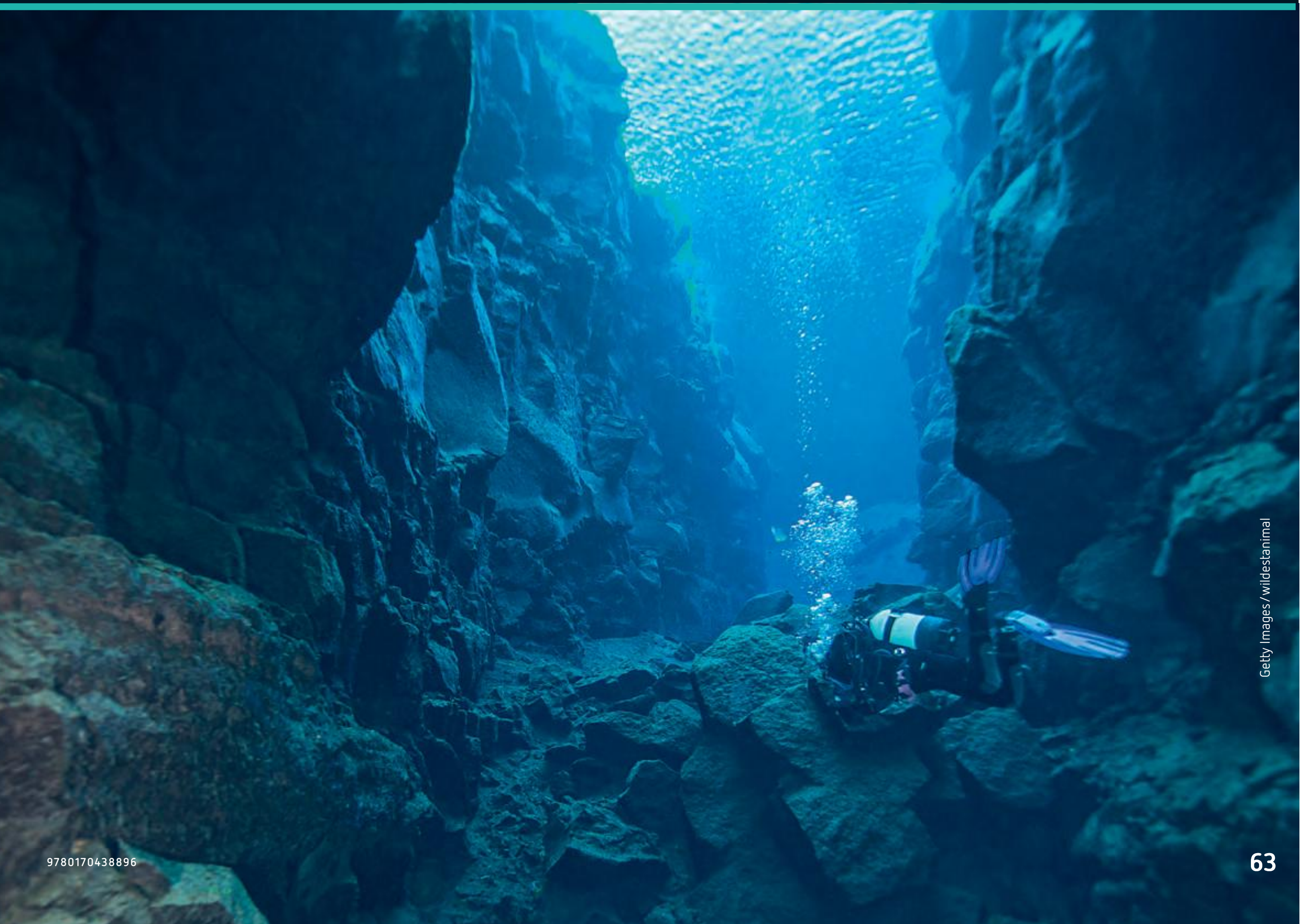

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FIGURE 3.1 Pangaea as it would have appeared 200 million years ago

The 1960s was a decade of change in many ways. The new theory of plate tectonics was one of these changes. It completely revolutionised the way geologists thought about Earth and the processes that formed it. In 1912, Alfred Wegener proposed the supercontinent of Pangaea (Figure 3.1). However, Canadian geologist Tuzo Wilson thought there had been several supercontinents. In the mid-1960s, he proposed that the continents gone through repeated phases of convergence, collision and mountain building followed by phases of divergence and separation due to sea-floor spreading. The continents had repeatedly separated and then recombined into a supercontinent and would probably continue to do so.

This model, which was initially known as the Wilson cycle, has been expanded and modified over the last 50 years. The plate tectonic supercycle has become one of geology's most important concepts. The construction of supercontinents followed by their break-up and dispersal has influenced the timing of major events in Earth's evolutionary and climatic history. This cycle has altered the composition of the geosphere, atmosphere, hydrosphere and biosphere over geologic time.

3.1 Features of the plate tectonic supercycle

You learnt about other forms of tectonics in Chapter 6 of *Earth and Environmental Science in Focus 11*.

Early Earth was a molten mass of rock that gradually cooled enough for a crust to form. This early crust was probably a single unbroken plate – like that of Venus. The first evidence of Earth's present type of plate tectonics comes from approximately 3 billion years ago in the Archeaneon. At this time, granite and greenstone belts formed the building blocks of today's continents. The rise of continents and beginning of subduction was the start of the plate tectonic **supercycle**.

Cratons, continents and supercontinents

Cratons are stable masses of ancient continental crust that were formed mostly in the Archean. Cratons consist of a shield, where ancient rock is near the surface, and a platform, where sedimentary rock covers the shield (Figure 3.2). The stable interiors of today's continents are built from cratons. Cratons can be thought of as continental building blocks.

Continents are areas of land often made up of several continental cratons as well as younger Phanerozoic fold belts that have been added through plate convergence and collision. If a large area of land does not contain a craton, it is considered a continental fragment. An example of this is Madagascar, which has broken off from eastern Africa.

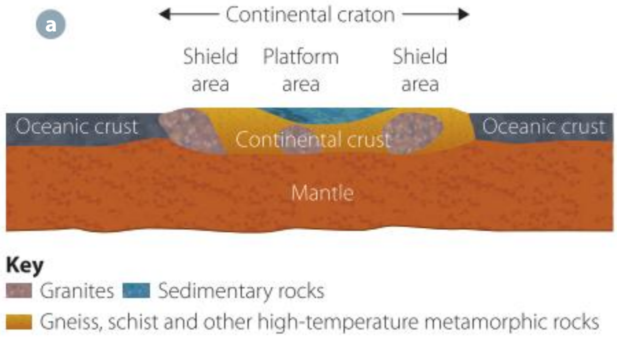

FIGURE 3.2 **a** A cross-section of a typical craton such as the Pilbara. **b** Banded iron-stone in the Hamersley Gorge is the platform portion of the Pilbara craton.

The present-day Australian continent consists of several Archean cratons, including the Pilbara craton, separated by Proterozoic platforms. The Thomson and Lachlan fold belts were accreted onto the continent during the Phanerozoic (Figure 3.3). Other continental cratons include the Congo and Kalahari cratons in Africa, the Amazonia craton in South America, and the Baltica and Siberia cratons in Eurasia.

You learnt about Wegener's evidence for Pangaea in Chapter 6 of *Earth and Environmental Science in Focus 11.*

Supercontinents are giant landmasses composed of all or most of Earth's continental continents. The most recent of these was Pangaea.

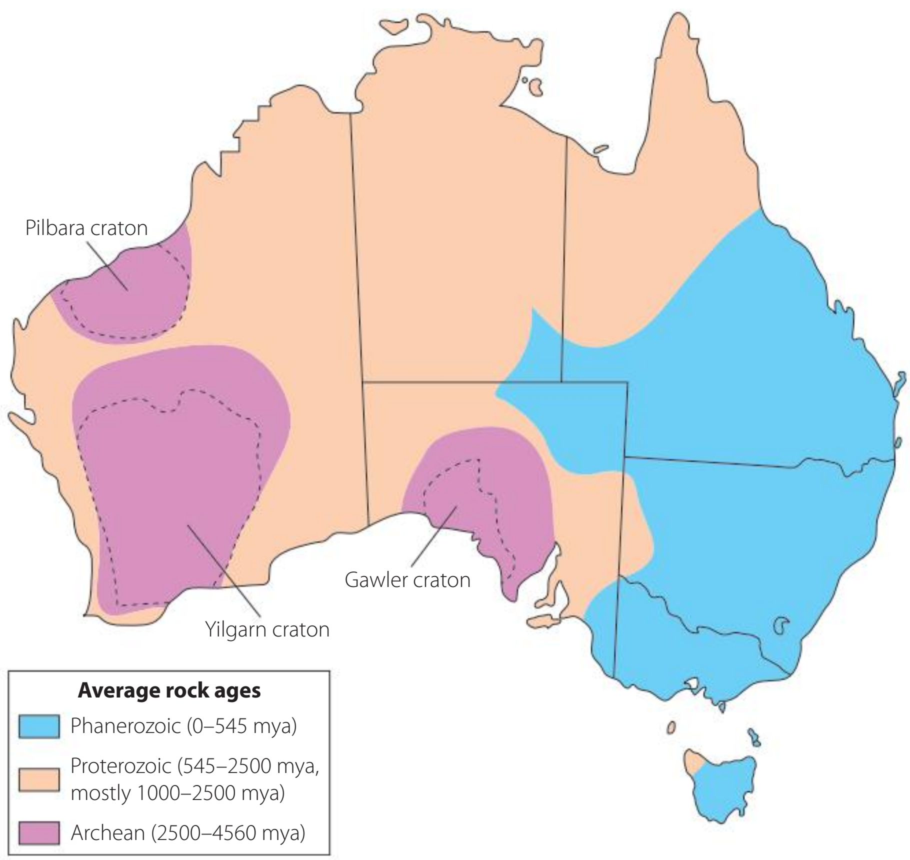

FIGURE 3.3 Australia's Archean cratons, Proterozoic platforms and Phanerozoic fold belts; mya = millions of years ago

Stages of the plate tectonic supercycle

Supercontinent formation is a repeating cyclic process. The cycle is generally pictured with a supercontinent as a starting point (Figure 3.4). Heat builds up under the supercontinent, causing doming and rifting that break the supercontinent apart. The resulting continents disperse as new ocean bases form and oceanic crust is subducted in other locations. The continents eventually reach maximum dispersal with wide oceans around the globe. The oceans eventually contract. Island arcs collide with continents and continents amalgamate, forming fold mountain belts such as the Himalayas. The result is a supercontinent, which is ready to begin the cycle again.

During each repetition of the plate tectonic supercycle, a supercontinent forms at the beginning of the cycle, breaks apart into several continents that separate from each other for a time and then recombine into a supercontinent at the end of the cycle.

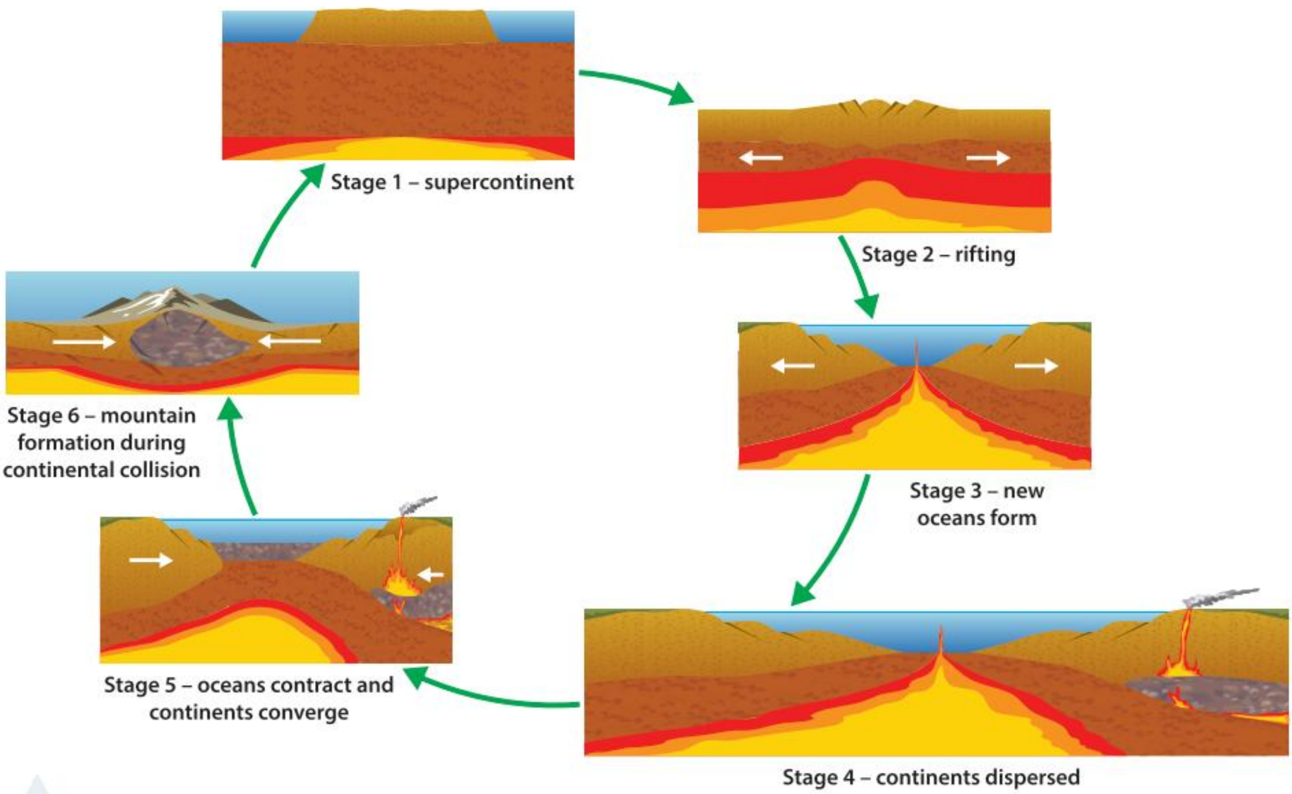

FIGURE 3.4 The basic stages of the plate tectonic supercycle

Each of the supercontinents that have formed during Earth's history have combined continental cratons in different arrangements and broken apart in different ways. Estimates of the time required for a full plate tectonic supercycle to occur range from 500 million to 700 million years. If these estimates are correct, this means that somewhere between six and eight supercontinents could have formed over the last 3 billion years since plate tectonics began in the Archean.

INVESTIGATION 3.1

Modelling the plate tectonic supercycle

Critical and creative thinking

Information and communication technology capability

The plate tectonic supercycle is a dynamic process that is often represented in small two-dimensional diagrams such as Figure 3.4. In reality, the cycle takes up to a billion years to complete and occurs on the spherical Earth.

AIM

To model the cyclic processes of the plate tectonic supercycle using stop-motion animation

MATERIALS

- Coloured playdough or plasticine
- A4 transparency or thin plastic cutting board
- Tape
- Thin spatula for lifting clay
- Digital camera or mobile phone camera
- Cable or card reader to transfer images from camera to computer
- Computer with movie editing software
- Small tripod or retort stand with ring clamp to hold camera or phone

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
If the camera is dropped, it will break.	Secure the camera with the tripod or carefully rest it on the ring clamp.

What other risks can you identify in this investigation? How will you manage them?

METHOD

1. Decide upon a colour scheme to represent cratons, fold belts, continental crust and oceanic crust.
2. Use tape to secure the plastic to the table or lab bench.
3. Mount the camera directly above the plastic to include most of the sheet in each photo.
4. In the middle of the plastic, construct a model supercontinent that includes two or three cratons and continental crust. Place oceanic crust around your supercontinent.
5. Take a photo of your supercontinent.
6. Use the spatula to trace thin line(s) across the continental crust where it will begin to rift.
7. Take a photo.
8. Continue to make small modifications to your model, photographing each step as you demonstrate rifting, the formation of oceans etc. The smaller the change in each photo, the smoother the final movie will look.
9. When you have finished modelling all stages of the supercycle, transfer the photos to the computer and insert into a movie program.
10. Experiment with different frame rates (less than 1 second) to determine the best speed to create your movie.
11. Add an explanatory soundtrack or captions to the movie.
12. Finalise the movie in a standard format (e.g. MP4) and share it with your class.

»

OPTIONS

- Different class members could film different stages of the cycle and join these together for the final product.
- Another camera could be set up to gain a side or cross-sectional view of the process.

DISCUSSION

1 What aspects of the supercycle were most difficult to show?
2 What does your model fail to demonstrate?
3 Evaluate your model as a representation of the plate tectonic supercycle, explaining the advantages and disadvantages of your modelling choices.

CONCLUSION

Write a suitable conclusion, stating the result of your stop-motion animation.

EXTENSION ACTIVITIES

- Create a split-screen animation showing both cross-sectional and surface views of the supercycle.
- Model the supercycle on a half sphere.
- Create a model using a different material such as paper or textiles.

Past supercontinents

WS
Supercontinent formation and breakup

Palaeomagnetic data show how the continental cratons have moved about Earth and where they were located at different points in time. This gives us an indication of the several supercontinents that formed and broke apart before Pangaea, the most recent supercontinent, came into existence.

The rocks offer evidence of events in the supercycle. Continental convergence at the end of the cycle leads to folded igneous and metamorphic rocks such as those on the Isle of Lewis in Scotland (Figure 3.5). Rifting during the break-up of a supercontinent leads to basalt dykes such as the columnar basalts of Mount Wellington (Figure 3.6) in Tasmania. The folded remains of mountain belts are 50–100 million years older than the basalt dykes because the supercontinent had to form (folds) before it could rift apart (dykes).

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FIGURE 3.5 These folded gneisses on the Isle of Lewis in Scotland were deformed during the amalgamation of North America and Europe into the supercontinent Pangaea.

From the palaeomagnetic and geological evidence, we know that at least five supercontinents formed in the past (Figure 3.7). From the most recent to the oldest, these are Pangaea, Pannotia, Rodinia, Columbia and Kenorland (Figure 3.7). The original continent, Ur, is not included in this list because it was smaller than Australia and many geologists do not consider it to be a supercontinent.

Watch the continents form

Alamy Stock Photo/David Wall

FIGURE 3.6 The Organ Pipes of Mount Wellington in Tasmania are columnar basalts formed during the break-up of Gondwana.

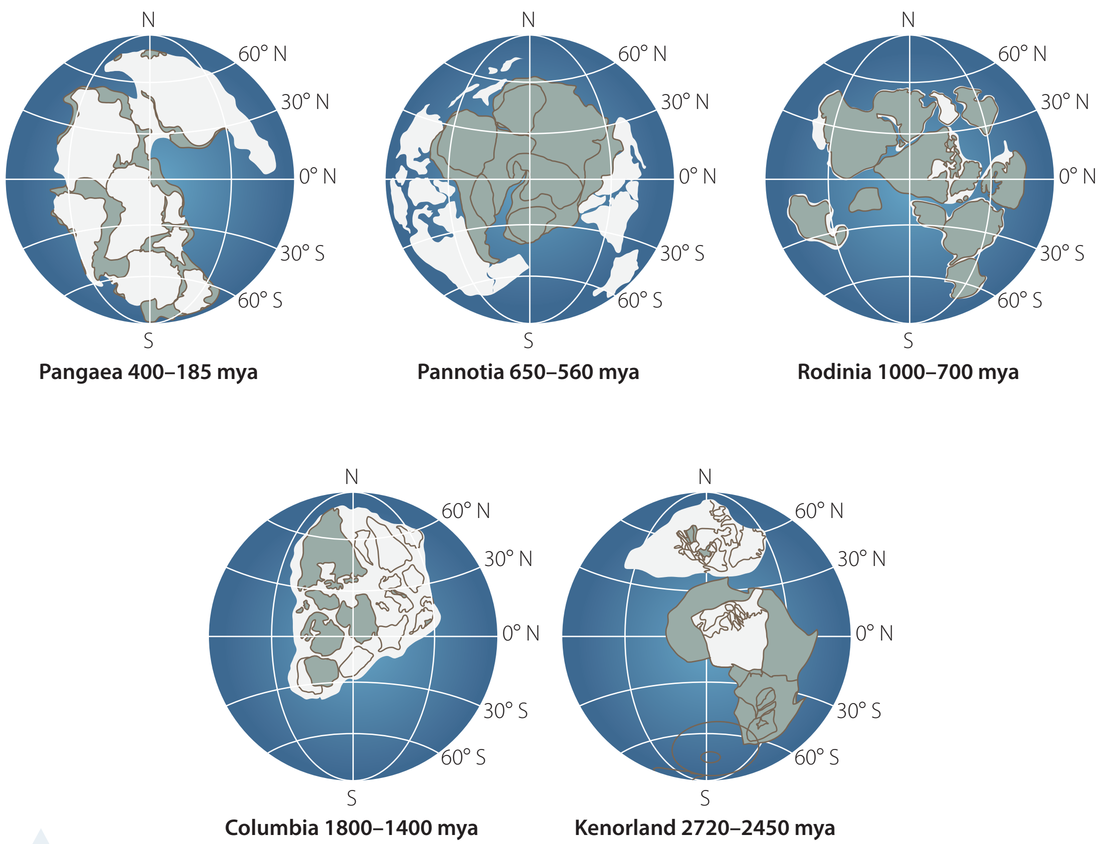

FIGURE 3.7 Relative positions of the continental cratons within the supercontinents and the approximate times that the supercontinents existed

KEY CONCEPTS

- The plate tectonic supercycle began approximately 3 billion years ago with the start of modern tectonic processes.
- Cratons are ancient continental crust composed of shield and platform areas.
- Continents are composed of several cratons joined by fold belts.
- A supercontinent is a single giant landmass that contains all or most of Earth's cratons.
- The formation and break-up of supercontinents occurs on a repeating cycle of 500 million to 700 million years – the plate tectonic supercycle.
- Past supercontinents, from youngest to oldest, are Pangaea, Pannotia, Rodinia, Columbia and Kenorland.

CHECK YOUR UNDERSTANDING 3.1

1 Why were there no supercontinents before 3 billion years ago?
2 Distinguish between the shield and platform portions of a craton.
3 Name four continental cratons and the modern continent on which you would find each of these.
4 What was Pangaea and when did it exist?
5 List the stages of the plate tectonic supercycle.
6 How do geologists identify mountains made during supercontinent formation?

3.2 Effects of the plate tectonic supercycle

When Tuzo Wilson proposed that oceans had opened and closed on a long-term cycle, geologists realised that this would affect sea level and climate. This was because the location of continents and construction of mountain belts would alter the way the atmosphere and oceans interacted with the landmasses. Biologists recognised the implications for evolution due to nutrient level fluctuation, changing climate and habitats that are joined or fragmented.

Sea level

Plate tectonics and sea level in action

The formation of a compressed high-standing supercontinent increases the total area of the global ocean. The supercontinent is high-standing because of both recent mountain range formation and uplift because it traps heat of the underlying mantle. Trapped heat causes the continental crust to expand, further elevating the supercontinent. At the same time, the older colder sea floor subsides into the mantle. These two effects can elevate the supercontinent so much that sea level is lowered by approximately 400 metres. Sea level at the coastline of the supercontinent is at a minimum (Figure 3.8a).

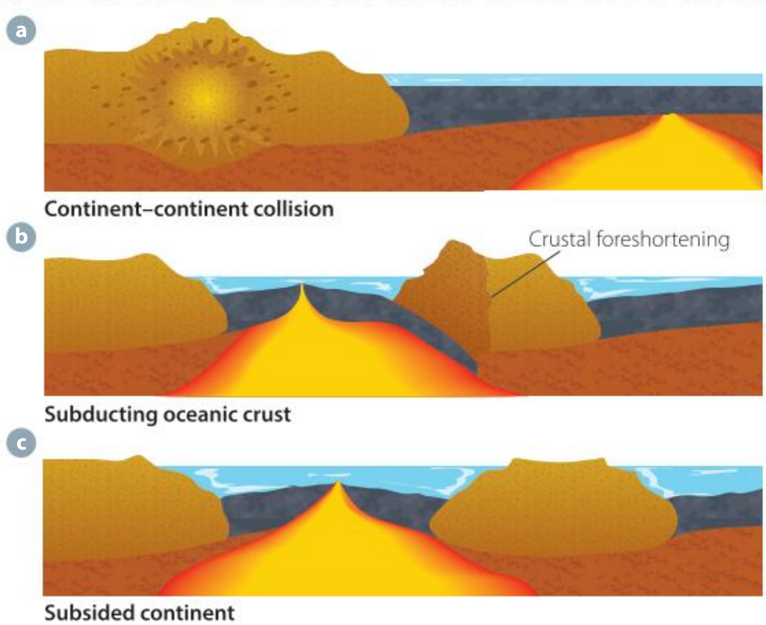

FIGURE 3.8 Sea levels vary at different stages of the supercycle.
a Supercontinent stage: lowest sea levels (small land area, large ocean basins).
b Supercontinent breaking up: intermediate sea levels (average land area, average ocean basins).
c Continents dispersed: highest sea levels (largest area of land, smaller ocean basins).

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Sea level during the intermediate stages of the supercycle would be between the maximum and minimum sea levels (Figure 3.8b). As a supercontinent breaks up, the continents are stretched by rifting and drift apart, decreasing the total area of the global ocean. The generation of young hot mid-ocean ridges also decreases the space that oceanic water can occupy. Thus, sea level at the coastline of the continents should be at a maximum (Figure 3.8c).

Climate

WS Supercontinents, climate, sea level and evolution

The effect of a supercontinent on climate was demonstrated when Pangaea drifted over the south pole during the late Carboniferous period (Figure 3.9). This large area of high-standing land at the south pole experienced a 3-month-long night every year. This led to the growth of a massive ice sheet, which was a key piece of evidence for Wegener's concept of continental drift. The positioning of a supercontinent over the north or the south poles is a significant contributing factor for ice-sheet growth.

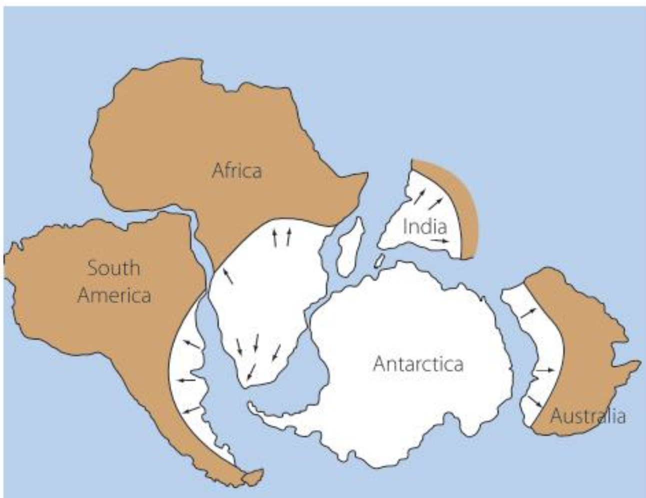


FIGURE 3.9 The extent of the Permo-Carboniferous ice sheet in the Gondwana segment of Pangaea

The break-up and dispersal of Pangaea at the end of the Permian period was accompanied by the eruption of enormous amounts of basaltic magma in Siberia and into the rifts where continental divergence would form the Atlantic Ocean. The release of vast amounts of carbon dioxide (CO_2) associated with this volcanic activity caused an extreme planetary warming event that completely disrupted marine and terrestrial environments across Earth – the end-Permian extinction.

The break-up and dispersal of a supercontinent does not normally have such catastrophic consequences, but it does change Earth's climate. This usually involves significant global warming and an extended period of greenhouse conditions replacing the icehouse conditions that prevail when the supercontinent is present.

Weathering and cooling

High-standing young mountains that result from continental collisions are rapidly weathered and eroded (Figure 3.10). The rocks are broken up in landslides and ground up in river channels, generating mineral fragments that are chemically weathered. The weathering releases large amounts of calcium, potassium, sodium, magnesium, phosphorus and trace elements into terrestrial and marine environments. The weathering products are mostly transported to the sea by rivers as fine-grained sediment or dissolved material.

Calcium eventually combines with carbonate in the oceans and is precipitated as calcite ($CaCO_3$) sediment on the sea floor. The oceanic carbonate is replenished by atmospheric CO_2. This sets up a feedback loop that affects Earth's climate (Figure 3.10). As the amount of CO_2 in Earth's atmosphere decreases over time, the atmosphere's ability to retain heat diminishes and Earth's climate cools. If enough CO_2 is removed from the atmosphere, ice sheets form near the poles, generating a global ice age.

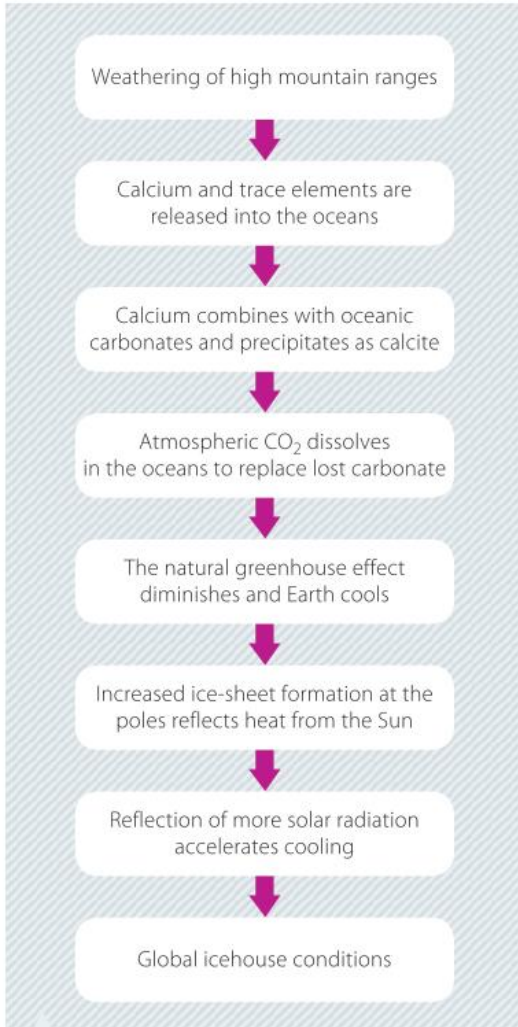


FIGURE 3.10 Increased weathering after supercontinent formation leads to icehouse conditions.

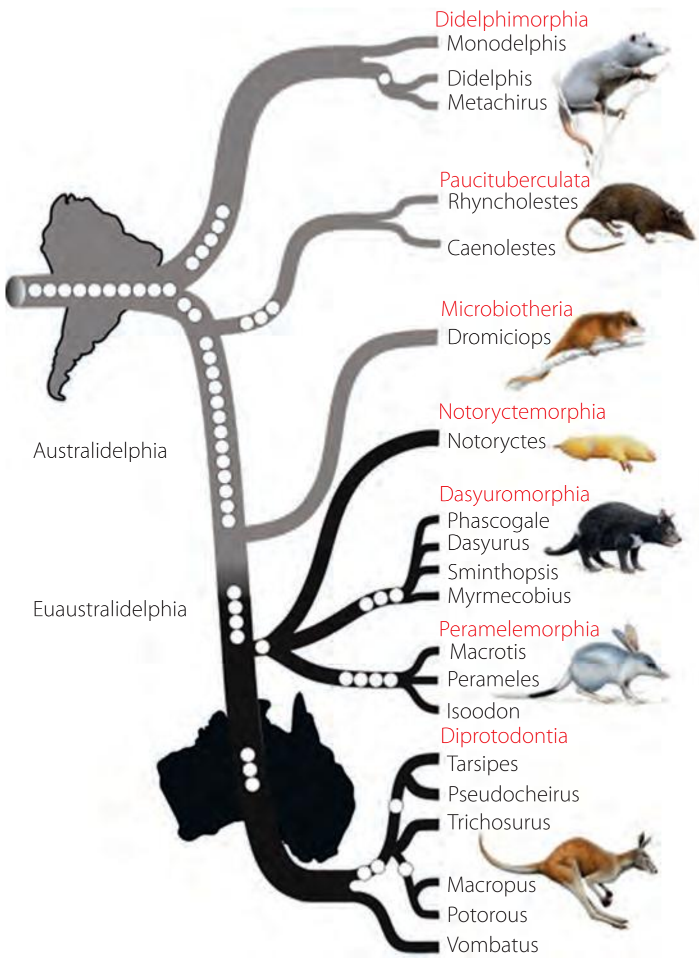
Evolution

Read about plate tectonics and life on Earth

The plate tectonic supercycle causes variations in the intensity of important global geologic processes. Long-term variations in Earth's climate, the amount of continental weathering, the availability of nutrients in the oceans and the composition of the atmosphere combine to influence the evolution of life on Earth. For example, low sea levels associated with a supercontinent and large ice-sheet formation significantly reduce the area of continental shelves and cause shallow inland seas to disappear. This environmental stress has been associated with several regional extinction events.

One direct consequence of the amalgamation of landmasses has become important since the advent of large plants and animals during the Phanerozoic. As continental landmasses converge and collide, their terrestrial flora and fauna directly compete with each other. This may lead to the extinction of some species and expanded territory for others.

Continental dispersal leads to a variety of environments and selective pressures. An ancestral species may give rise to many variations adapted to local environments, such as the marsupials of South America and Australia (Figure 3.11). This is called **adaptive radiation**. Conversely, new continental positions and conditions may drive regional extinction events, such as the extinction of large plants and marsupials on Antarctica after the break-up of Pangaea.



Nilsson et al. (2010) Tracking marsupial evolution using archaic genomic retroposon insertions. PLoS Biology 8(7) Figure 2, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2910653/

FIGURE 3.11 Continental dispersal led to the adaptive radiation of an ancestral species to give rise to marsupials in South America (grey lines) and Australia (black lines).

The rapid weathering associated with supercontinents increases the supply of essential biological nutrients. Geologists have demonstrated that a rapid rise in trace elements preceded the appearance the Ediacaran fauna about 650 million years ago and the Cambrian explosion – when many animal groups appeared in the fossil record. Other earlier major evolutionary events also coincided with supercontinent formation. These include the proliferation of cyanobacteria 2.5 billion years ago, the appearance of poriferans (sponges) 1.5 billion years ago, and the appearance of metaphytes (multicellular and multiorgan plants) about 1 billion years ago (Figure 3.12).

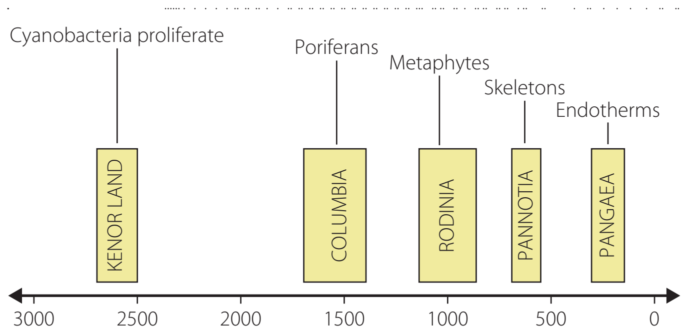


FIGURE 3.12 The relationship between supercontinents and major events in the evolution of life

KEY CONCEPTS

- Global sea level, weathering, climate and evolution are affected by the plate tectonic supercycle.
- Sea level is at a minimum when supercontinents form and at a maximum during dispersal.
- Climate tends to icehouse conditions when supercontinents form because CO_2 is removed into marine sediments and polar ice sheets reflect solar radiation.
- Basalt production during rifting releases large quantities of CO_2, leading to greenhouse conditions.
- Evolutionary events that can be associated with supercontinent formation include the proliferation of cyanobacteria, the appearance of metazoans and the evolution of skeletons.
- The break-up of supercontinents creates new habitats and can lead to adaptive radiation of species.

CHECK YOUR UNDERSTANDING 3.2

1. Explain the reasons for low sea level when there is a supercontinent.
2. Why is there increased weathering after supercontinent formation?
3. Identify three important evolutionary events and their links to past supercontinents.
4. How does supercontinent formation lead to the removal of CO_2 from the atmosphere?
5. Explain why the formation of a supercontinent is usually followed by the formation of a large continental ice sheet and an extended period of global icehouse conditions.
6. Outline one positive effect and one negative effect that supercontinent formation might have on marine habitats and organisms.
7. How can the break-up of a supercontinent cause speciation in one location and adaptive radiation in another?

3 CHAPTER SUMMARY

- The plate tectonic supercycle began approximately 3 billion years ago with the start of modern tectonic processes.
- Cratons are ancient continental crust composed of shield and platform areas.
- Continents are composed of several cratons joined by fold belts.
- A supercontinent is a single, giant landmass that contains all or most of Earth's cratons.
- The formation and break-up of supercontinents occurs on a repeating cycle of 500 million to 700 million years – the plate tectonic supercycle.
- Past supercontinents, from youngest to oldest, are Pangaea, Pannotia, Rodinia, Columbia and Kenorland.
- Global sea level, weathering, climate and evolution are affected by the plate tectonic supercycle.
- Sea level is at a minimum when supercontinents form and at a maximum during dispersal.
- Climate tends to icehouse conditions when supercontinents form because CO_2 is removed into marine sediments and ice sheets may reflect solar radiation from polar supercontinents.
- Basalt production during rifting releases large quantities of CO_2, leading to greenhouse conditions.
- Evolutionary events that can be associated with supercontinent formation include proliferation of cyanobacteria, the appearance of metazoans and the evolution of skeletons.
- The break-up of supercontinents creates new habitats and can lead to adaptive radiation of new species.

3 CHAPTER REVIEW QUESTIONS

Qz
Review quiz

1 Explain how the total length of continental coastline changes due to supercontinent break-up and dispersal.

2 Identify geological signs that would suggest that a supercontinent formed in the geological past.

3 How long does it take for a single cycle of the plate tectonic supercycle to occur?

4 **a** At which stage of the supercycle is Earth currently located? Justify your answer.
b Based upon this stage, will sea levels rise or fall over the next 50 million years?
c Explain how the supercycle will affect climate over this time.

5 Draw a series of diagrams showing a supercontinent with three cratons breaking up and re-forming into a different supercontinent during one full supercycle.

6 Examine the maps of the supercontinents shown in Figure 3.7. Identify and list the cratons and continents that were in contact with continental mass containing the Yilgarn, Pilbara and Gawler cratons for each supercontinent.

7 Explain how the supercontinent is affected by heat build-up in the underlying mantle.

8 Analyse the influence of calcium from the products of weathering upon Earth's climate.

9 Imagine that you are living in the Jurassic period. How many separate continents exist? Give them names based on their modern continental components.

10 Outline how global climate changes from icehouse to greenhouse conditions during the plate tectonic supercycle.

11 Evaluate the role of the plate tectonic supercycle in the evolution of life on Earth.

12 Predict some changes that might occur in the Australian biota as Australia converges with south-east Asia and the Eurasian continent over the next 20 million years.

13 Geologists agree about the timing and formation of Pangaea, but there is less certainty about older supercontinents. Explain why this is the case.

14 Figure 3.13 shows the origin and extinction of species during the Phanerozoic.

a Identify at least three times when mass extinctions appear to occur and three times when evolutionary radiations (many new species) appear to occur.

b Analyse the relationship between extinctions and radiations.

c Discuss the effect of formation of Pangaea (400–185 million years ago) on species diversity.

d Assess the role of the supercontinent cycle in driving extinction and radiation events.

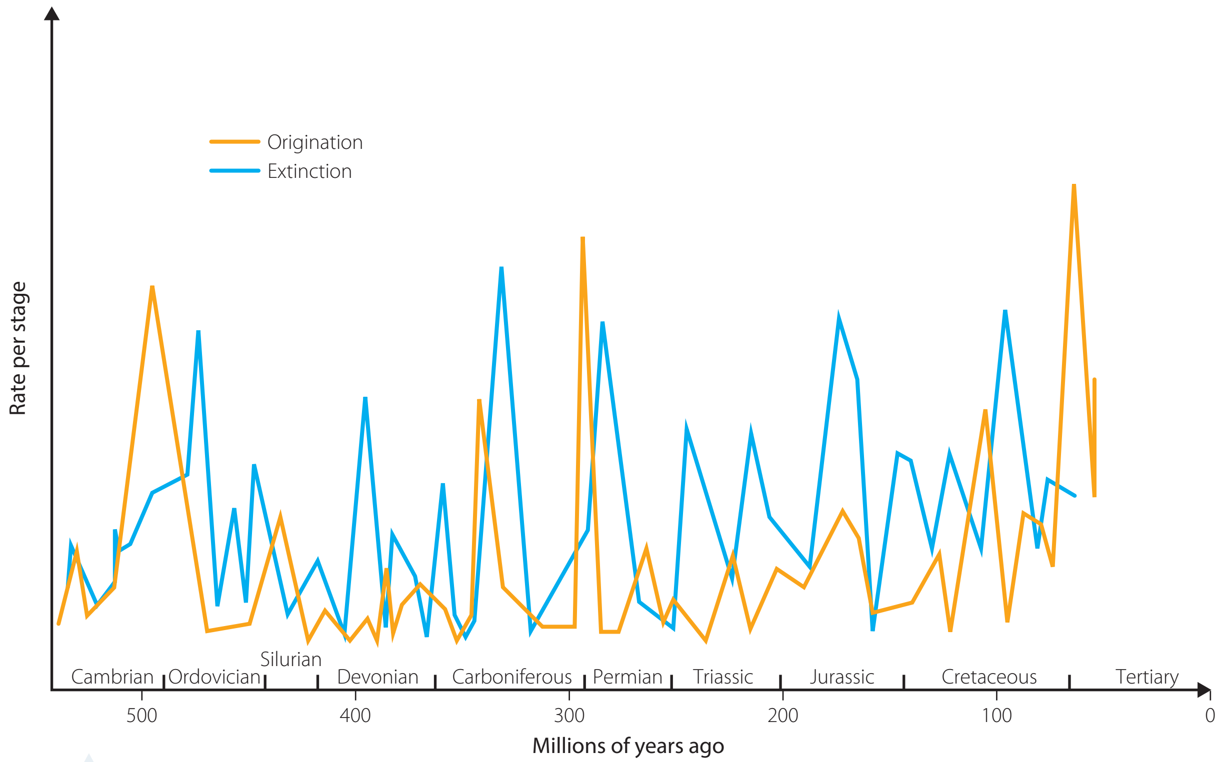


FIGURE 3.13 Origination and extinction of marine species in the Phanerozoic

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4 Fossils and stratigraphy

OUTCOMES

In this chapter you will learn about:

- processes of fossil formation, including fossil moulds, cast fossils and trace fossils ICT
- the significance of fossils in establishing the geological timescale, including extinctions, radiations and the geological periods, and index fossils L
- how fossils, absolute dating, the principle of uniformitarianism and the principle of superposition are used to date events of geological significance, including:
  - the evolution and appearance of the Cambrian fauna CCT ICT L
  - mass extinction events.

Getty Images/Reimer Gaertner/UIG

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Fossils are possibly the most important objects that palaeontologists and evolutionary biologists investigate. Fossils have enabled these scientists to establish the origins of all the living things on Earth and the evolutionary relationships between them. Fossils tell the story of where we came from, why we are and who we are.

Between the 17th and 19th centuries, Nicolas Stenson and French zoologist Georges Cuvier established that most fossils are the impressions and remains of once living, but now extinct, plants and animals preserved within sedimentary rock. Other geologists, palaeontologists and biologists then used these ideas to develop the principles of uniformitarianism and stratigraphy as they demonstrated the somewhat chaotic but generally ordered progression in the development of organisms throughout geological time.

Towards the end of the 19th century, Charles Darwin explained this order with his theory of evolution by natural selection. Biologists, geologists and palaeontologists have since used these concepts to tease out the details of Earth's geological and evolutionary history. The work done by these scientists, the detailed examination of sedimentary rock layers and the cataloguing of the fossils entombed within them, means that we can also use fossils to tell us the geological time. This is because most fossilised species occupy a short span of the stratigraphic record. Biostratigraphy is the branch of geology that determines the age of sedimentary rock layers and strata by identifying the fossils contained within the strata. Figure 4.1 shows a famous collection of fossils at the Gallery of Paleontology and Comparative Anatomy in Paris, France. It was started in the late 19th century.

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FIGURE 4.1 The permanent exhibition of fossil animals on display at the Gallery of Paleontology and Comparative Anatomy in Paris.

4.1 Fossils and their formation

Fossils are the preserved remains of once-living organisms (**body fossils**) or traces of the activities of organisms (**trace fossils**). You are probably familiar with the body fossils of ancient invertebrates (Figure 4.2) and the more easily recognised skeletal remains of large vertebrates, such as whale skeletons and humanoid skulls (Figures 4.3 and 4.4). Most fossils are found in relatively young rocks of the Phanerozoic eon, which is the relatively short period (542 million years) named for its record of visible life (*Phanero* means 'visible' and *zoic* means 'to do with life'). Tracks and trails of relatively large animals are another common and easily recognised fossil known as trace fossils. You can see a trace fossil in Figure 4.5, which shows footprints of the Cretaceous age *Allosaurid* dinosaur.

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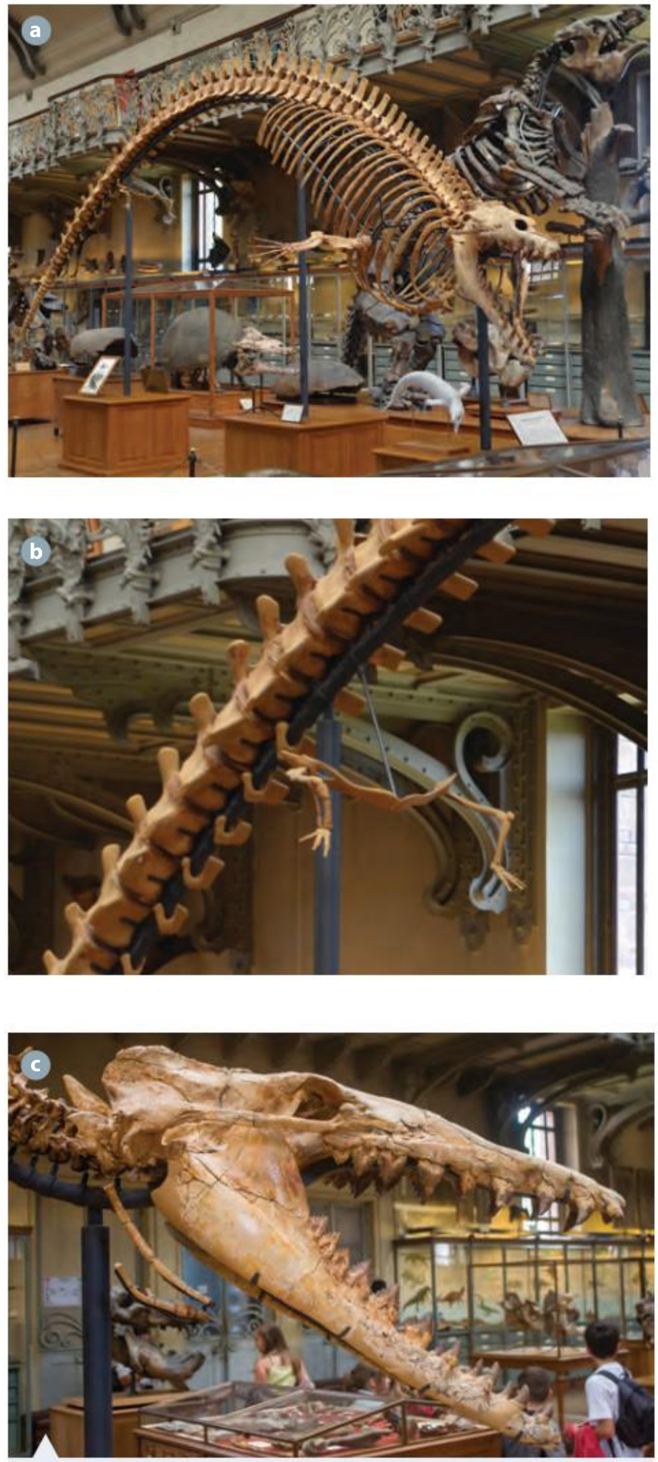
FIGURE 4.2 The Middle Cambrian, Burgess Shale arthropod *Sidneyia*. Note the exceptional preservation of this 10 cm long specimen.



Barbara Smith/Monceau

Barbara Smith/Monceau

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FIGURE 4.3 **a** An entire skeleton of the Eocene whale *Cynthiacetus peruvianus*. **b** Close-up views of its rear legs and **c** skull, which contains a set of teeth that indicate the animal's predatory nature. The pair of tiny hind legs clearly indicate the transitional evolutionary position of this extinct whale species between its wolf-like terrestrial tetrapod ancestors and modern whales that no longer possess or need rear limbs.

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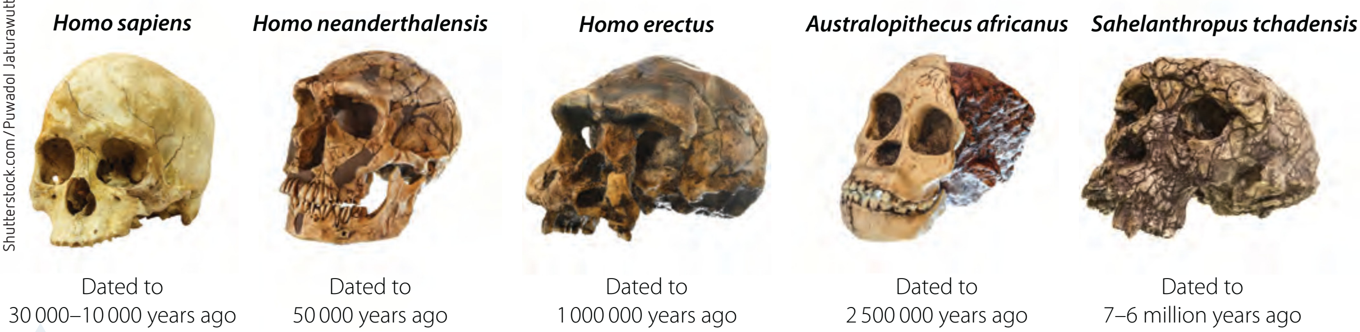

FIGURE 4.4 Fossil remains of our immediate primate ancestors

Tom Hubble

FIGURE 4.5 This *Allosaurid* footprint is at Broome, Western Australia. The central claw mark is obvious, the left and right claw marks are two hollow holes in the rock located at the top left and right corners of the footprint. In time, weathering will reveal them to view.

Fossilisation

The apparent appearance of abundant fossils at the beginning of the Phanerozoic is related to the evolution of exoskeletons and an increase in the size and complexity of organisms at this time. These evolutionary innovations were driven by several factors. The apparently sudden appearance of a diverse and complex fauna at the beginning of the Phanerozoic is known as the **Cambrian explosion**, which you investigated in Chapter 2. For many years, it was commonly thought that this event marked when the first living organisms evolved and arose from the primordial slime. However, since the 1950s, careful examination of Earth's older rocks has gradually revealed that the fossil record stretches back much further to the earliest Precambrian time (Figure 4.6).

It is difficult to recognise Precambrian fossils in the field because they are usually very small or microscopic soft-bodied animals, delicate plants or unicellular organisms that are difficult or impossible to detect without a microscope. Sometimes the presence of these older lifeforms in rocks is detected from their **biomarkers** – biological chemicals that they generated during their lifetimes. Biomarkers can be breakdown products of polymers that constructed plant cell walls and enzymes generated by living organisms. These materials are also considered to be part of the fossil record.

Scientists don't really know what the rate of fossilisation is. It is rare for an organism to be fossilised. The chance of any given organism being fossilised is probably much less than one in a million. This is because biomass is processed from one form into another. Plants and fungi are consumed by herbivores and omnivores. Carnivores consume the herbivores, omnivores and each other. Some animals and plants die from old age or disease and their remains are consumed by scavengers while the nutrient-rich residues are reprocessed by microbes. Natural acids in soil dissolve bones, and so on. This reprocessing of living things into other living things in ecosystems happens constantly.

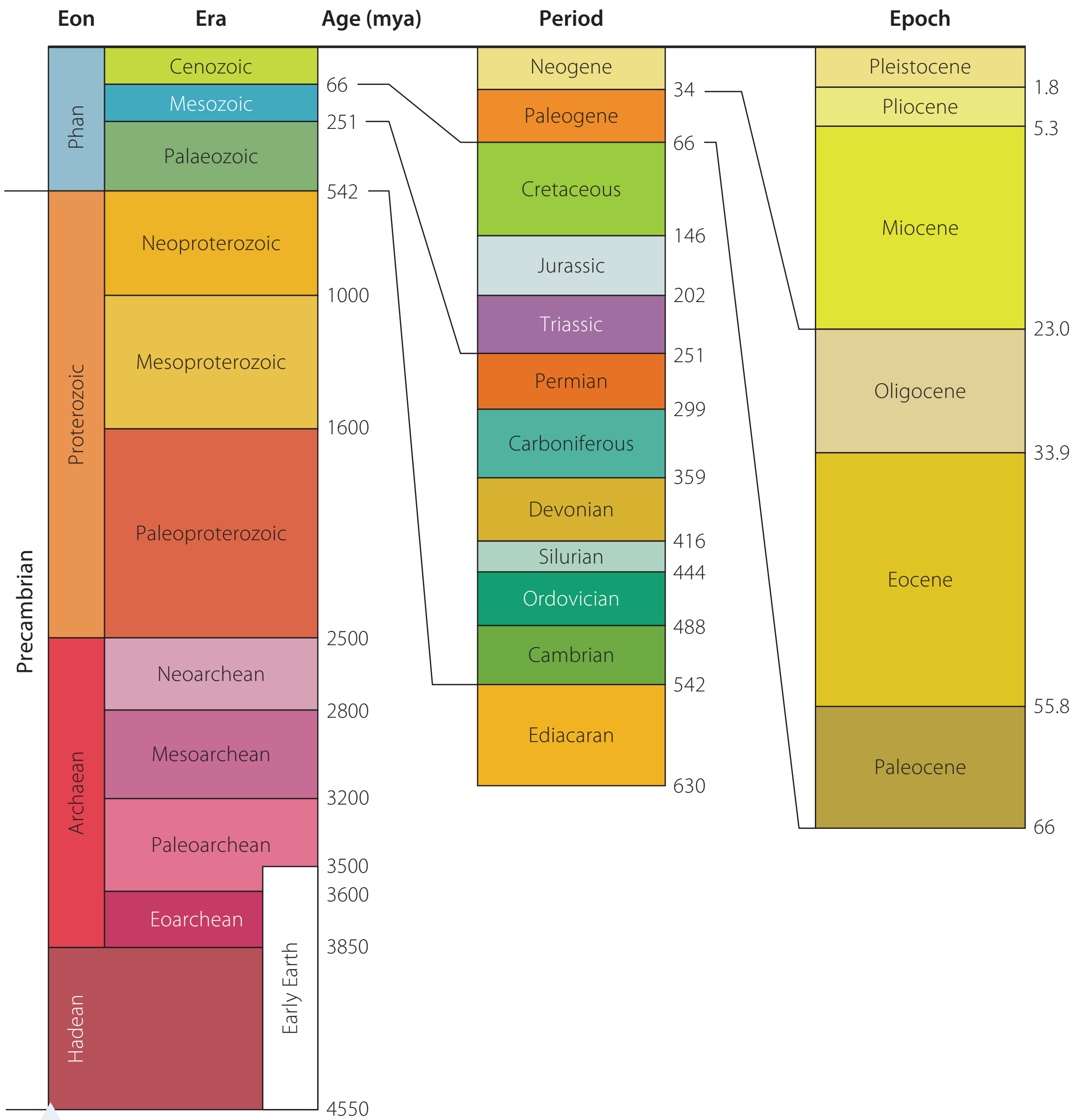

FIGURE 4.6 The geological time scale

For plants, animals and microbes to be preserved as fossils, a particular set of circumstances is required. Rapid burial of the organism by sediment is the most common factor that enables fossilisation. This is because burial in sediment protects the remains of the organism from physical processes that might break it apart and organisms that might consume it. Burial also reduces the availability of oxygen for oxygen-powered respiration, which is more efficient and rapid than **anoxic** processes. Therefore, burial in sediment isolates an organism from the oxygen required for respiration and reduces access to animals and microbes that could feed on and consume the animal or plant remains.

Other conditions that produce well-preserved fossils include the entombment and mummification of whole animals, plant fragments, spores and pollen in tree sap, tar or ice. Tree sap becomes amber, tar solidifies into asphalt and accumulating snow refrigerates and freezes organic remains. These materials are like natural traps for animals and some extraordinarily well-preserved fossils have been recovered from them. Examples include the Eocene insect fauna preserved in amber deposits at various sites around the Baltic Sea (Figure 4.7), the Late Pleistocene vertebrate fauna recovered from the La Brea tarpits in Los Angeles (Figure 4.8), and mammals and birds recovered from melting glaciers (Figure 4.9).

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FIGURE 4.7 An Eocene scorpion fossilised by entombment in Baltic amber

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FIGURE 4.8 Fossilised Late Pleistocene mammalian and reptilian bones preserved in the tar deposits of Rancho La Brea in Los Angeles, California

Dreamstime.com/Massimo Gherardi

FIGURE 4.9 A reconstruction of Otzi the Iceman, who was entombed by ice in Austria's Otzal Alps. He was born about 3400 BCE and apparently died from blood loss due to an arrow wound when he was about 50 years old. Otzi's tattooed, mummified body was discovered by hikers in September 1991.

More on types of fossil formation

Rapid burial of organisms is common in areas around large intermediate and silicic volcanoes that erupt large amounts of ash, riverine floodplains and river deltas, shallow seas, continental shelves and reef systems that experience frequent large storms, and the abyssal plains of deep oceans and floors of lakes. Large floods can deposit huge amounts of sand and mud on riverine floodplains that entomb the flora and fauna that live there as well as any aquatic organisms removed from their river and stranded on the floodplain.

Over the course of two or three days, cyclonic storms can mobilise layers of sea-floor mud and sand deposited 50 metres or so below the surface of a shallow sea. It can redeposit this material in layers that are tens of centimetres, or even a few metres, thick. The plants and animals that previously lived there are buried in the newly deposited sediment. The bottom of lakes and the deep-ocean sea floor often receive sudden influxes of mud and sand mixtures from landslides that flow over these surfaces like a very fluid cement. Sediment transported in this way often traps and buries organisms living on the bottom of the lake or the floor of the sea even if they live in burrows below the sea floor (Figure 4.10). The famous Cambrian age Burgess Shale fossils occur in sediment deposits of this type (Figure 4.2). The landslide sediment is commonly dislodged from a nearby slope by large earthquakes, which liquefies the sediment and enables it to flow downslope.

More layers of sediment are deposited on top of the fossil-containing layer over time. Eventually these layers become part of a geological unit and sequence. As the soft sediment is **lithified** (converted into rock), the organic remains are often preserved by **petrificaction**. This can preserve the organic material in its original state (e.g. the calcite shell of a brachiopod fossil (Figure 4.11)) or in a modified form, such as the carbonised wood in Figure 4.12.

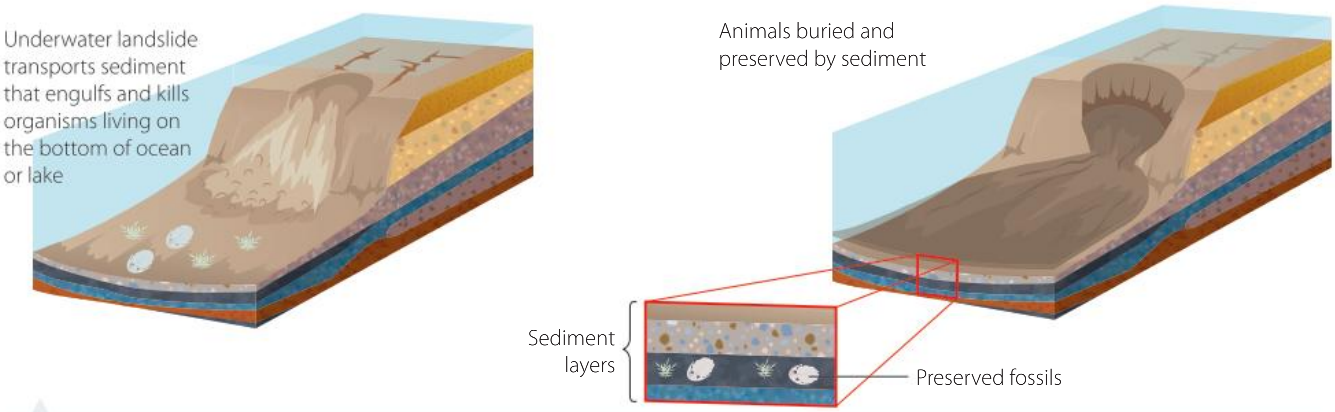

FIGURE 4.10 Sedimentary environments where rapid burial and fossil formation is common

FIGURE 4.11 Petrified Ordovician Rhynconellid brachiopod specimens (*Platystrophia acutilirata*) in which the original calcite shells are preserved. They are external cast fossils.

FIGURE 4.12 Petrified Early Triassic wood, species unknown, from North Narrabeen, New South Wales. The original plant material has been carbonised and converted to coal. Small patches of native copper that has crystallised and replaced the original carbon compounds on the surface of this cast fossil are also visible.

FIGURE 4.13 These petrified Ordovician Graptolite specimens have been preserved by carbonisation as kerogen-rich films within layers of marine mud.

Fossilisation by replacement occurs when organic material is replaced by inorganic minerals such as quartz (silicification), calcite (calcification) or pyrite (pyritisation). Carbonisation is the process that converts the organic structures into carbon-rich films composed of kerogen, which is a material similar to tar (Figure 4.13).

FIGURE 4.14 **a** A mould of the exoskeleton as the impression made by the animal in the surrounding mud. **b** The external cast of the exoskeleton is like a true copy of the animal.

Casts and moulds

Fossils can be referred to as **casts** or **moulds**, depending on how they formed. Moulds and casts are three-dimensional impressions of the organism. When organisms are buried in sediment and slowly decompose, they leave a cavity that contains an exact imprint of the organism's features (Figure 4.14a). This hollow space is a mould. If this hollow space fills with sediment, the material can take the exact shape of the original organism and form a cast (Figure 4.14b). So, a cast is a copy, and moulds make casts. For example, when jewellers make rings, they pour molten silver into a ceramic mould to cast a solid metal ring. Sediment such as wet mud or fine sand that encases an organism is a natural moulding material. Fine sediment such as volcanic ash (Figure 4.15) or marine mud (Figure 4.16) can make an extremely detailed impression of the organism's characteristic features. The appearance, shape and the anatomy of organisms (their morphology) is preserved in such good detail that palaeontologists can determine how the organism functioned and how its physiology operated.

WS
Types of fossilisation

Trace fossils

Trace fossils are the tracks, trails, impact marks and footprints that organisms made when they were alive. A trace fossil is a mark that was preserved when an organism moved across or burrowed through a layer of sediment. Figure 4.17 shows a set of dog-paw impressions preserved in a concrete pavement slab.

FIGURE 4.15 Petrified dinosaur eggs preserved in volcanic ash.

Trace fossils provide a record of simple everyday events that provide clues about how animals lived and moved. They preserve moments in time,' such as the footprints shown in Figure 4.18. These trace fossil footprints capture an event that only lasted a few seconds and that occurred about 100 million years ago. They show what happened when a 10–20 tonne sauropod dinosaur walked across a sand bar exposed at low tide. The weight of the animal caused the layers of mud and sand underneath to fluidise and deform as the animal rolled through its footstep. Nearby, several similar sets of parallel lines of footprints are preserved in the sedimentary rock strata. This suggests a small herd of sauropods moved across the sandflat together. Trace fossil footprints can also be seen in Figure 4.19.

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Getty Images/Field Museum Library

FIGURE 4.16 A complete cast of a 2.5-metre-long Mesozoic *Ichthyosaur* skeleton preserved by a mixture of petrification and permineralisation in marine mud

Tom Hubble

Thomas Hubble

FIGURE 4.17 **a** Teddy the Wonder Dog inspecting Anthropocene age trace fossils, canine footprints. **b** Close-up of the trace fossils.

Tom Hubble

FIGURE 4.18 These Cretaceous sauropod footprints (the flat grey oval areas) with underlying deformed layers of fluidised sediment were found near Broome, Western Australia.

Shutterstock.com/servickuz

FIGURE 4.19 This Ordovician horseshoe crab fossil (cast) has trace fossil footprints visible on both sides of the animal's tail.

INVESTIGATION 4.1

Creating and interpreting trace fossils

Information and communication technology capability

Simulation experiments can be used to understand the formation of ancient features preserved in the rock record.

AIM

To determine how a group of animals were moving (running, walking or foraging) from the tracks they made by creating different sets of trace fossils and analysing them in a similar way to how palaeontologists and biologists analyse ancient fossil trackways

MATERIALS

- Long-jump sandpit at school or local park
- Rake
- People of various sizes and ages. Ideally, some junior school, some middle school and some senior school students (otherwise, just the members of your class)
- 5 distance marker posts or large witches' hats
- Digital cameras with video function (or mobile phones)
- Small whiteboard and markers, to provide details about photographs you take. The whiteboard and details should be prominent and visible in the photograph.
- Stopwatches, measuring tapes or metre rulers
- Wrapped treats or objects to scatter about randomly in the test area to represent food
- Stepladder or elevated viewing platform from where an overhead view of the paved area can be obtained (optional, but very helpful for acquiring good video and photograph data)

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
You might trip, slip over or collide with other people or be injured. Other potential injuries may be similar to those that might be sustained during a game of netball or soccer.	Perform the experiment in a space that is sufficiently large, well ventilated and separated from traffic. Obtain signed permission slips from parents of all test subjects.
This is an outside activity so there is a risk of sunburn.	Apply sunscreen – follow Slip, Slop Slap protocols.
Younger students may become overwhelmed by mixing with older students.	Take care as you perform the experiment because this will generate better and more realistic results
There may be a lot of noise generated by the participants.	Make sure your experimental area is distant from other classes and people who might be distracted by the noise.

What other risks can you identify in this investigation? How will you manage them?

METHOD

1. Gather 5–10 subjects of different sizes and ages.
2. Set up your long-jump sandpit track by placing six distance markers 2 metres apart from the start to the end of the sandpit.
3. Set up a digital camera in video mode so that the test track is in view for recording the passage of the subjects through the test area.
4. Get the subjects to individually walk slowly across the track. Video their passage and record the time required for them to move between the marker posts. Record your results.
5. Photograph the area in which the tracks were made and make sure that you have recorded useful details about this photograph on the whiteboard and include it in the photograph's field of view.

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6 Measure the distance between the footstep (stride length) directly on the sand or from the photograph. Record and tabulate your stride-length data and the size of the footprints.

7 Rake the sand and repeat for a variety of possible scenarios. For example, transits across the track could include walking slowly in the same direction, walking quickly in the same direction, jogging, running, aimless ambling and talking, collecting treats (i.e. feeding), being chased by a wolf, and so on. Rake the sand in between each scenario.

8 Keep good records of your experimental scenarios so that you can compare and cross-check your photographs and data for each scenario with each other if required.

RESULTS

1 Order your photographs into appropriate groups according to the number of individuals involved and by the scenario activity. Tabulate your measured data.

2 Describe the characteristics of the photographs of the sets of tracks generated in your test scenarios. Your description could say whether it is possible to identify the number of individuals that made the tracks and the direction that they were moving in.

3 If you can identify a particular individual's track in a given photograph you should try to determine their average stride length for the type of motion. For example, what is the distance between steps for Individual A when they are walking, jogging and running. Tabulate this information (or graph stride length against speed).

SUBJECT NAME(S)	STRIDE LENGTH WHEN			
	WALKING SLOWLY	WALKING QUICKLY	JOGGING	RUNNING

ANALYSIS OF RESULTS

1 Examine the photographs and determine if there are similarities or differences between the sets of tracks generated in each scenario. For example, compare the tracks generated by an individual or a group walking slowly in the same direction to tracks generated by that person or group running in that direction.

2 Compare the tracks of a group moving in the same direction to those of a group ambling about and talking or collecting treats. Describe the similarities and differences between the tracks generated in your different scenarios.

3 Describe the relationship between an individual's speed and their stride length. Is it possible to estimate how quickly someone is moving from the distance between their footsteps?

CONCLUSION

Write a short summary that presents a brief outline of your findings and a statement about the potential usefulness of trace fossils in determining what an animal was doing when they made the trace.

EXTENSION

Palaeontologists who study dinosaurs often use stride lengths measured from trackways and the average, known hip height of particular species to determine how fast the animals were moving when they made the trace fossils.

Design a follow-up experiment that would enable you to determine a person's size, mode of motion and an estimate of the speed that they were moving from a set of tracks. Hint: there is a very approximate relationship between the height or hip height of individuals and the size of their feet (juveniles to adults), as well as a relationship between stride length and speed. Try collecting a data set of foot size, height, stride length and speed for a range of several small-to-large individuals. Plot stride length (y-axis) versus speed (x-axis) for each of your subjects on the same graph.

KEY CONCEPTS

- Fossils are the preserved remains of once-living organisms or the traces of their movement. Both groups of fossils are usually found in sedimentary rocks.
- Body fossils are remains of body parts of dead animals and plants.
- Trace fossils are preserved marks such as tracks and trails that organisms make when they move across or burrow through a layer of sediment.
- Most fossils form when an organism is rapidly buried in sediment. This process isolates the body of the organism from the oxygen supply that other organisms and some microbes require to consume and break down the dead organism's remains.
- Some fossils are formed by entombment and mummification of whole animals, plant fragments, spores and pollen in tree sap, tar or ice.
- A fossil cast preserves an impression in rock that copies an organism's features exactly as they appeared in real life.
- A fossil mould produces a reversed impression of an organism's features that could be used to cast a copy of the organism in the same way that we might use a mould to cast a ring or a plastic toy.

CHECK YOUR UNDERSTANDING 4.1

1 What is a fossil?
2 Outline why natural scientists regard fossils to be important.
3 What is the main difference between a body fossil and a trace fossil?
4 Draw a sketch that shows the difference between a fossil cast and a fossil mould.
5 Explain why fossil formation is a rare occurrence.
6 Describe a set of circumstances that would probably produce extremely good body fossils.
7 Examine the photograph of the concrete paving slab shown in Figure 4.17. Determine the directions that the dog(s) that made the paw prints were going and decide whether the dog(s) were running or walking. Determine how many organisms are represented by trace fossils or body fossils on this concrete surface.
8 The word 'Phanerozoic' means 'visible life'. Explain why geologists use this word to name the youngest of Earth's four eons of geological time.

4.2 Fossils and the geological timescale

Use this timescale to scaffold your learning

In the 19th century, naturalists slowly worked out the significance of the fossil record and how it could be used to provide a relative timescale for geological events. This realisation developed along with the idea that Earth might be incredibly old.

William Smith developed, and Georges Cuvier used, the law of faunal succession to explain the fascinating observations that particular groups of fossil organisms appeared in, and then disappeared from, vertical sequences of sedimentary rocks in a particular order. Every fossil always appeared at a lower level in the stratigraphic sequence and then disappeared at a higher level in the stratigraphic sequence.

By the 1880s, European and North American geologists and palaeontologists had established most of the named Phanerozoic geological periods that we use today. These periods divided up what these naturalists interpreted to be a gradual progression from strange, ancient and apparently primitive lifeforms towards familiar, modern and advanced organisms. These geological periods were named on the basis of their recognisably different sets of fossils. The names were often determined from the geographic areas where the rocks were well exposed and the vertical sequence of their layers was easily determined.

Ancient organisms preserved in the older sequences of rocks weren't necessarily as primitive as the 19th century naturalists considered them to be. They were probably as well adapted to their ancient environments as most modern lifeforms are to their present-day environments. Similarly, modern-day organisms aren't necessarily advanced just because they are extant and are abundantly present today. Simplicity in body form can be an excellent adaptation for long-term survival in a particular environment.

We are quite familiar with most of the periods these names signify in one way or another. For example, the Jurassic was named in 1799 about 40 years after the term Tertiary became commonly used for the uppermost layers of sedimentary rocks of Europe and North America. The Carboniferous and Cretaceous were named in 1822, the Quaternary in 1829, the Triassic in 1834, the Silurian and Cambrian in 1835, the Devonian in 1839, the Permian in 1841, and the Ordovician in 1879. These geological periods all relate to sets of rocks that contain recognisably different sets of fossils. Figure 4.20 shows the major evolutionary innovations recognised in the fossil record through geological time. Each period is characterised by the animals and plants that flourished during that time and examples of these are shown in Table 4.1 (pages 90–91).

The geological periods that were recognised in the 19th century belong to the Phanerozoic. The named periods were also grouped into longer time divisions known as eras. These are the Palaeozoic (the era of ancient lifeforms), the Mesozoic (the era of middle life) and the Cenozoic (the era of modern life), which is also called the Cainozoic. Initially, the fossil record provided the only system of determining the relative timing of events in Earth's history. Geologists have subsequently been able to date some boundaries and points in time during these periods by absolute dating methods all the way back to the beginning of the Hadean.

Two major changes in the fossil record mark the boundaries between geological periods. Below a boundary, there is a sudden disappearance of apparently widespread and thriving groups of animals or plants. Above the boundary, there is a gradual appearance of similar but different groups of animals or plants.

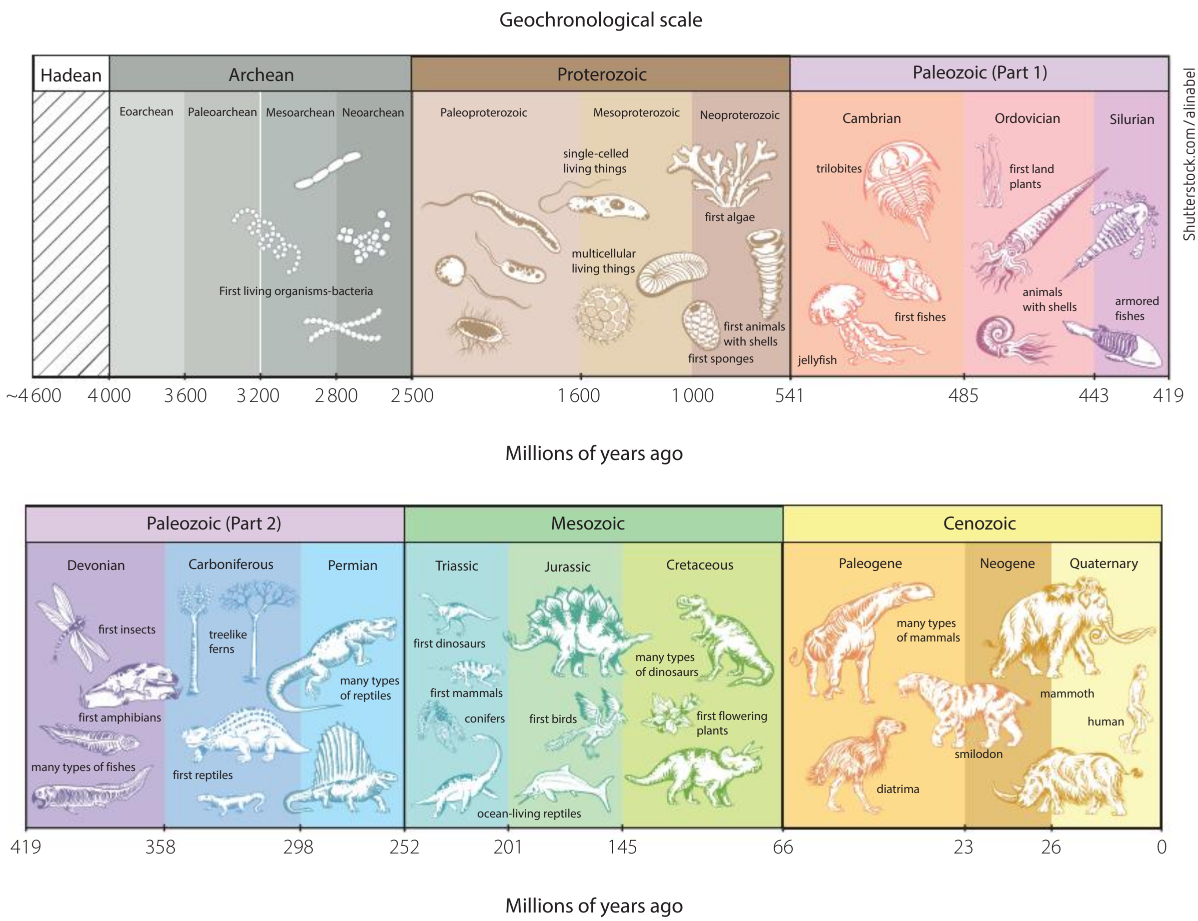

FIGURE 4.20 Each major division of the geochronological scale had characteristic fossils.

TABLE 4.1 Typical post-Proterozoic marine ecosystems and post-Silurian terrestrial ecosystems

PERIOD	ORGANISMS ALIVE AT THAT TIME	
Quaternary	 Shutterstock.com/Dotted Yeti	 Shutterstock.com/wildestanimal
Neogene	 Shutterstock.com/Estaban De Armas	 Shutterstock.com/Catmando
Paleogene	 Shutterstock.com/AuntSpray	 Shutterstock.com/Ferenc Cegledi
Cretaceous	 Shutterstock.com/Catmando	 Shutterstock.com/Catmando
Jurassic	 Shutterstock.com/ Daniel Eskridge	 Shutterstock.com/Catmando
Triassic	 Shutterstock.com/Catmando	 iStock.com/Daniel Eskridge
Permian	 Shutterstock.com/Catmando	 Shutterstock.com/AuntSpray

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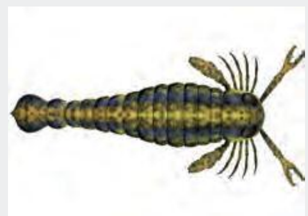
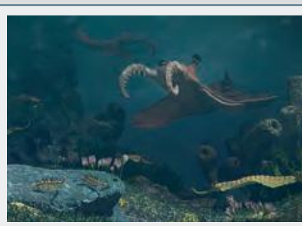
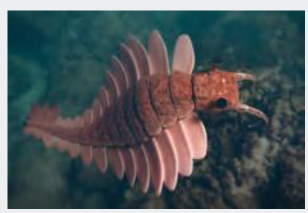
Carboniferous	 Shutterstock.com/Juan Gaertner	 Science Photo Library/Sebastian Kaulitzki
Devonian	 Shutterstock.com/Nicolas Primola	 Shutterstock.com/AuntSpray
Silurian	 Shutterstock.com/Alena Hovorkova	 Shutterstock.com/Catmando
Ordovician	 Shutterstock.com/AuntSpray	 Shutterstock.com/AuntSpray
Cambrian	 Shutterstock.com/Dotted Yeti	 Shutterstock.com/Dotted Yeti

Palaeontologists and geologists currently interpret the disappearances at the end of the geological periods to be extinction events or mass extinction events. The appearances of new lifeforms are interpreted to be radiation events. Mass extinction events are geographically widespread events that affect the majority of the species alive at the time. They are usually quick compared with the radiations – mass extinctions take less than a million years. The radiations that follow extinction events are much slower because it usually requires several million years or even tens of millions of years for lifeforms to evolve, diversify and refill the vacant ecological niches with new organisms.

Table 4.1 shows typical post-Proterozoic marine ecosystems and post-Silurian terrestrial ecosystems, in particular the impressive **apex predators**.

Index fossils

Most animals and plants are adapted to the areas in which they naturally live. They are adapted to a range of annual temperatures and average annual rainfall, as well as landscape or seascape conditions. The organisms adapt to local conditions and exploit them more or less successfully. Some species become very successful (e.g. the ecosystem's apex predator) and evolve traits that make them highly adapted to a particular ecological niche within an ecosystem.

Highly specialised animals and plants tend to live in relatively small areas that present a particular set of environmental conditions. If these species leave behind any fossils, they tend to be at one or two special sites. The fossils of these species aren't particularly useful as geological time markers because they are so few and far between.

Fossils that are good for determining the geological time are those of animals or plants that are not highly specialised but are wide ranging. These are species that can thrive in a variety of terrestrial or marine conditions. These organisms are said to be ubiquitous. It is also useful that the species is very abundant. This means that there are enormous numbers of individuals extant at a point in time so that large amounts of their remains can be entombed in rocks as fossils.

The other characteristic that makes a fossil species good for determining the age of a rock is if the species only lived for a short geological period. A species that was present on Earth during one of the named geological periods is reasonably useful for indicating the age of a rock because it specifies the time to be within a particular 50-million-year-long geological time. A species that enjoyed 10 million years of successful existence is a better time marker for geologists. Five million years is really good and species that were extant on Earth for 1 million years (or less) are very good and accurate geological time markers.

These widespread, abundant and short-lived species are called **index fossils** and the geological periods are sometimes divided into zones that bear their names. An example of an index fossil is a coccolith called *Emiliania huxleyi* that appeared about 270 000 years ago and became abundant about 70 000 years ago, shown in Figure 4.21. It is a tiny, unicellular, planktonic marine organism that can live in water at temperatures of 1–30°C. This means it occurs almost everywhere in the global oceans. When conditions are suitable, this species forms giant oceanic blooms more than 100 000 km^2 in extent. Finding this microfossil in marine sediment indicates that the material is geologically young, and identifying the level in a deep-sea sediment core at which this fossil first appears dates that layer to being 270 000 years old.

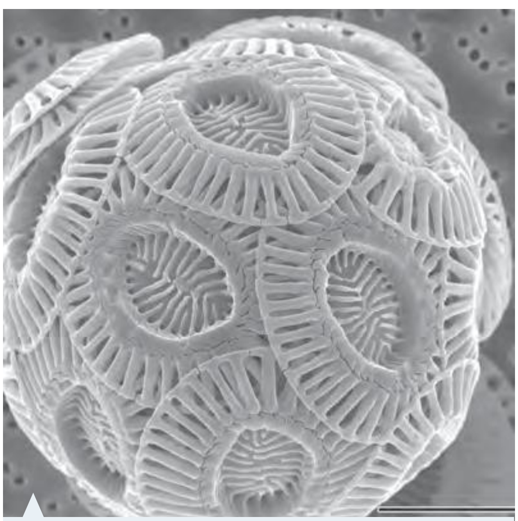


FIGURE 4.21 The index fossil *Emiliania huxleyi*

Another widely used index fossil is *Argopecten gibbus*, which indicates a Quaternary age between 2.3 million years and the present for sediments it is found within. Other index fossils are *Paradoxides davidis*, which is abundant in rocks of middle Cambrian age, the Devonian brachiopod *Mucrospirifer mucronatus* and the Jurrassic ammonite *Perisphincties virguloides*. Figure 4.22 shows a geological chart depicting the common index fossils that are useful for determining the period of a Phanerozoic. Other examples of fossils are shown in Figures 4.23–4.25.

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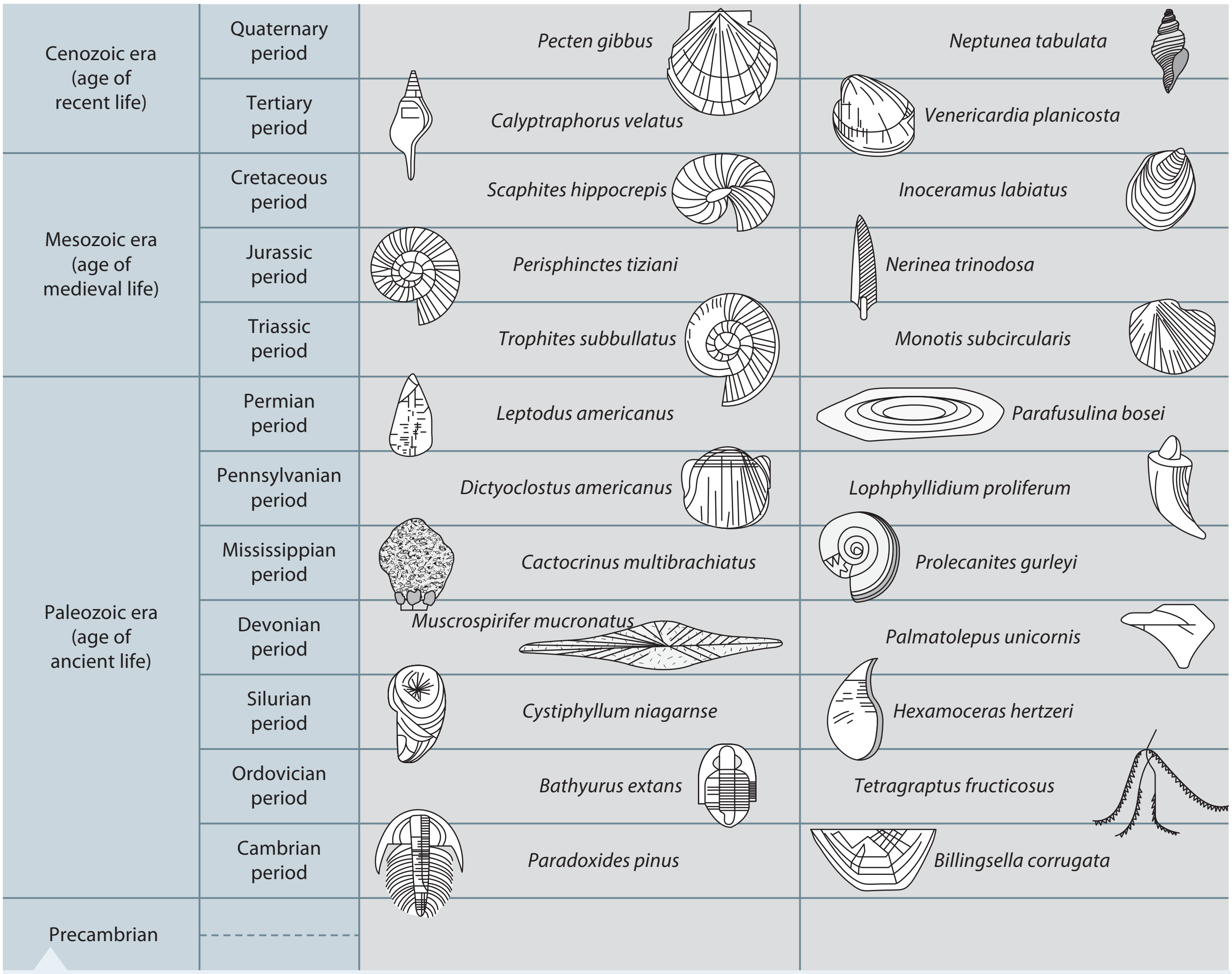

FIGURE 4.22 A geological chart of commonly found index fossils

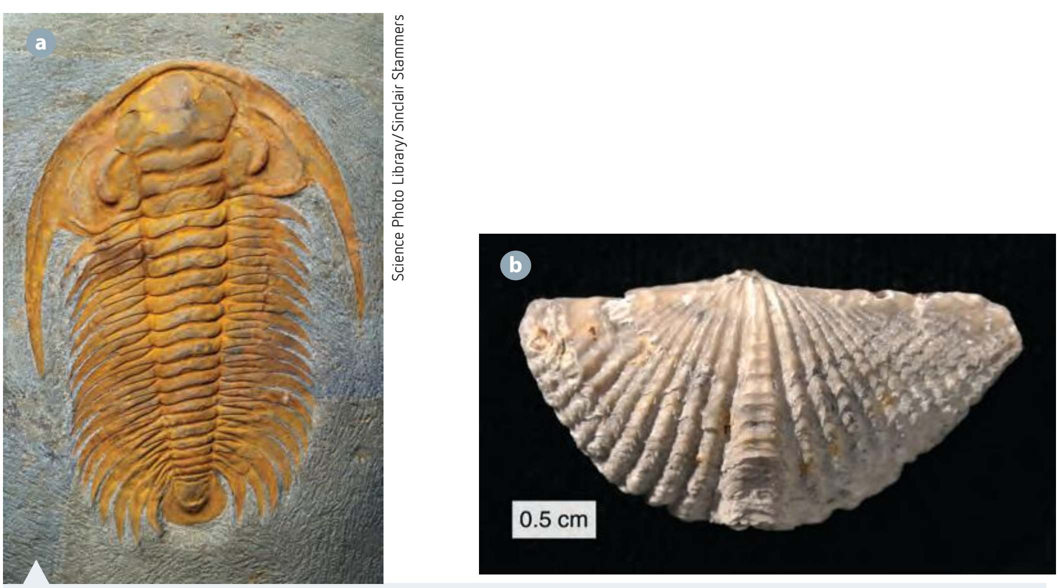

FIGURE 4.23 **a** *Paradoxides davidis* (Middle Cambrian) and **b** *Mucrospirifer mucronatus* (Devonian) are index fossils.

FIGURE 4.24 The Jurrassic ammonite *Perisphincties virguloides* lived in oceans all over Earth.

FIGURE 4.25 *Argopecten gibbus* or the Atlantic scallop is a Quaternary index fossil for the circum-Atlantic continents.

KEY CONCEPTS

- The named periods of geological time that make up the Phanerozoic were identified because they contain recognisably different and distinct groups of fossils.
- Boundaries between the named geological periods are identified by the disappearance of large numbers of fossil groups at the boundary. These groups are replaced by different groups of fossils above the geological boundary.
- The disappearance of large numbers of fossil groups at a geological boundary is thought to indicate that an extinction event occurred at that time. The emergence and proliferation of new groups of organisms is called a radiation event.
- The Phanerozoic is subdivided into three eras – the Palaeozoic, Mesozoic and Cenozoic – on the basis of the apparently ancient, intermediate and modern fossil animals that lived through these periods.
- Index fossils are species of fossil organisms that were geographically widespread, numerically abundant and lived during a relatively short geological time.
- Index fossils are very useful for dating the rocks in which they are found. The presence of an index fossil in a sedimentary rock usually indicates that it formed during a particularly short geological period.

CHECK YOUR UNDERSTANDING 4.2

1. List the geological periods of the Phanerozoic in order from oldest to youngest.
2. Name one organism that is typically associated with the periods of the Phanerozoic.
3. Name the geological divisions of time that are included in the:
   - a Cenozoic
   - b Mesozoic
   - c Palaeozoic.
4. What is an index fossil?
5. What characteristics make a species a good index fossil?
6. Why do geologists think that index fossils are very useful?
7. You examine fine-grained mudstones exposed in a rock platform during an excursion. They contain abundant trilobites and graptolites.
   - a Name which of the three Phanerozoic eras that the rocks probably belong to.
   - b What is oldest possible age of this mudstone?
   - c What is the youngest possible age for the mudstone?
   - d You take pictures of the fossil species and show them to a palaeontologist who identifies the graptolite fossil to be *Tetragraptus fructicosus* and the trilobite to be *Bathyurus extans.* Name the geological period during which the mudstone formed.
8. What is the ecological and evolutionary significance of the boundaries that separate the geological periods?

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4.3 Dating major geological and evolutionary events

Major events in the evolutionary and geological history of Earth are commonly identified because of the appearance or disappearance of groups of fossil organisms and sometimes the combined appearance and disappearance of groups of organisms. The principles of **stratigraphy** and **superposition**, in combination with **relative dating** methods based on fossils and index fossils, enable scientists to determine that an event occurred at a particular point in geological time as well as its geological significance. Scientists use **absolute dating** methods to determine the age of these events and to date when they occurred in numerical terms. For example, the end of the Cretaceous period and the beginning of the Cenozoic era is marked by the disappearance of dinosaurs and ammonites from the fossil record and a major increase in the diversity of mammals and birds.

You learnt about stratigraphy and superposition in chapter 4 of *Earth and Environmental Science in Focus Year 11*.

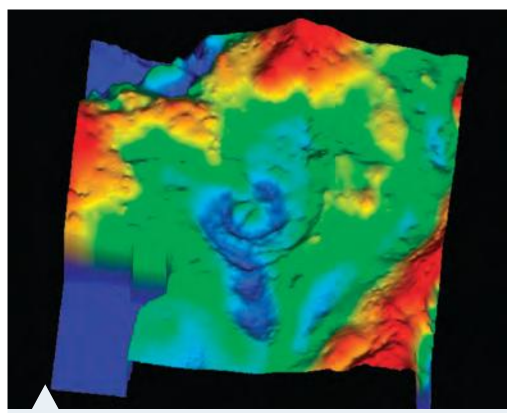
You learnt about relative and absolute dating techniques in Chapter 4 of *Earth and Environmental Science in Focus Year 11*.

The **principle of uniformitarianism** is fundamental to interpreting these geological facts. The idea that was proposed by Scottish geologist James Hutton towards the end of the 18th century. Hutton proposed that geological changes were the result of observable and measurable natural processes that caused gradual change over vast periods of time. The idea can be expressed as 'the present is the key to the past'.

An alternative idea at the time, catastrophism, was developed by French naturalist Georges Cuvier. Catastrophism proposes that most geological change is the result of major catastrophic events.

Cretaceous–Paleogene mass extinction

A good example of how the principle of uniformitarianism was used to identify and date a major catastrophe is the Cretaceous–Paleogene mass extinction event (also known as the Cretaceous–Tertiary extinction or the K/T boundary event). This was a widespread extinction event, the demise of the dinosaurs, which was followed by an important evolutionary radiation event, the rise of the mammals. It was caused by the collision of the Chicxulub bollide comet with Earth 66 million years ago. The bollide was 10–20 km wide and impacted Earth near Chicxulub in eastern Mexico.



Science Photo Library/Geological Survey of Canada/Mark Pilkington

FIGURE 4.26 This is a computer-generated gravity map image of the Chicxulub crater in eastern Mexico, where a comet impact led to the extinction of dinosaurs.

This event was a mass extinction and catastrophic for dinosaurs, large (more than 25 kg) terrestrial animals generally and many groups of invertebrate organisms. Conversely, it was also the event that enabled bird and mammal species to become the dominant groups of terrestrial vertebrates. This event is the most recent and the best understood of the big five extinction events recognised by palaeontologists.

About 75% of species living at the time died out during the Cretaceous–Paleogene mass extinction event. The other four mass die-offs are the Ordovician–Silurian mass extinction when more than 60% of species went extinct, the Devonian mass extinction when about 70% of species went extinct, the end-Permian mass extinction, the most devastating with 90–95% species extinction, and the end-Triassic mass extinction with about 70% species extinction. Other smaller mass extinction events are recognised as well (Figure 4.27).

Mass extinction slideshow

The Ordovician, Devonian, Permian and Triassic mass extinctions are thought to have been ecological or biotic crises caused by rapidly changing environmental conditions driven by tectonic events, massive large igneous province eruptions of basalt, extraterrestrial bollide impacts and several other rare catastrophes. Earth's ecosystems collapsed and vast numbers of species went extinct in a relatively short geological period – somewhere between 100 000 years and a few million years. These events punctuated a gradual but accelerating increase in the diversity of organisms during the Phanerozoic (Figure 4.27).

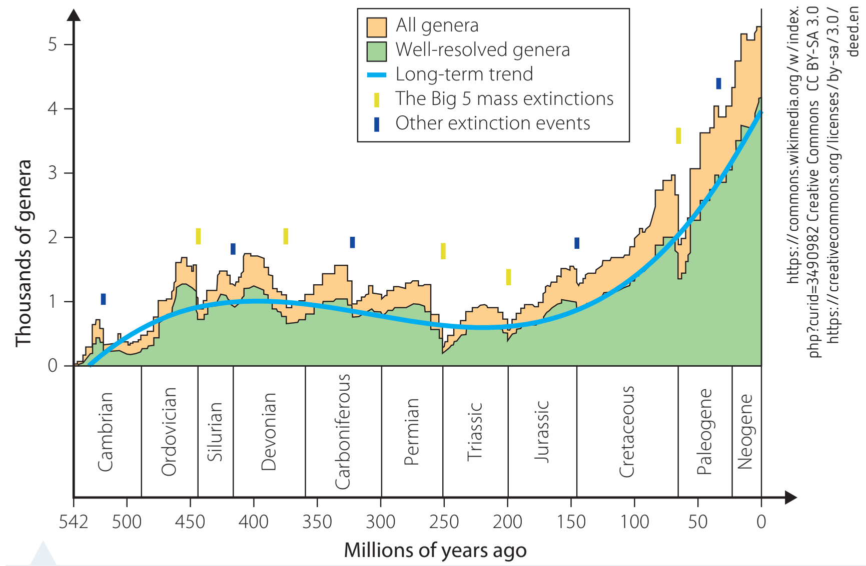


FIGURE 4.27 Increasing biodiversity during the Phanerozoic was punctuated by extinction events.

Dating the Chicxulub bollide collision event has involved investigations of the Cretaceous–Paleogene sequences at different locations and combining the results of the investigations. It has been difficult to identify sites that contain a continuous sequence of undisturbed fossil-bearing sediments that span the boundary as well as the necessary layers of volcanic ash located just above and just below the boundary. Remember that it is this ash layer that can be dated by absolute dating methods; therefore, the sedimentary fossil-bearing rock layers between the ash layers can be dated relatively.

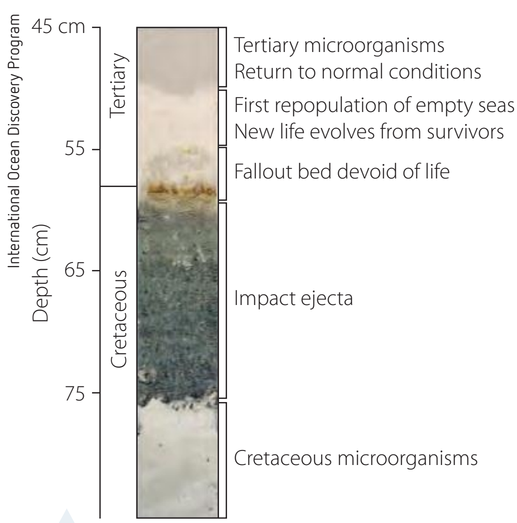


FIGURE 4.28 Deep marine sequences containing the Cretaceous–Tertiary boundary impact layer with its characteristic iridium-containing grey clay, tektites and shocked quartz grains

The change in animal species represented in the fossils (**faunal overturn**) at some point in a sedimentary sequence are the characteristics required to meet the principles of stratigraphy, superposition and uniformitarianism that identify the Cretaceous–Paleogene mass extinction event boundary. At sites close to the Chicxulub crater, the violence of the collision event eroded and disturbed the last of the Cretaceous sedimentary sequences so that they are missing. At sites distant from the impact site, the boundary layer material may not be easily identified.

The Chicxulub bollide impact layer is quite commonly preserved in deep marine sediments (Figure 4.28). These layers usually contain tiny globules of meteorite impact glass, high-pressure shocked-quartz crystals, carbon molecules called fullerenes (which were generated by high-temperature combustion of carbon) and a famous layer of green clay that contains unusually high levels of the element iridium.

These unusually high levels of iridium are the bollide-impact time marker. Iridium is rare in Earth's surface materials but abundant in comets. The glass meteorite impact globules, which are called tektites, should yield very accurate isotopic dates because they are like volcanic glass and were formed instantaneously during the impact. Unfortunately, tektite glass weathers easily and breaks down into clay and other minerals. This resets these potentially precise isotopic clocks due to loss of the parent **isotopes** or decay products. They do not give precise dates, yielding ages as either older or younger than the actual event.

You learnt about U/Pb dating in Chapter 4 of *Earth and Environmental Science in Focus Year 11*.

Nevertheless, there are two sites where a continuous sedimentary sequence through the K/T boundary has been identified. These sites also present volcanic material that can be dated reliably. One site is the Messadit marine limestones in Morocco. This site contains volcanic ash layers above and below the Cretaceous–Paleogene mass extinction event boundary layer and have returned an age of about 66.0 million years for this event.

The other site is the Hauso Flat Coals in the Hell's Creek region of Montana in the western United States. Zircon-bearing bentonite volcanic ash layers have been found. One of these layers occurs a few centimetres above the iridium anomaly layer and within the zone of a carbon isotope anomaly generated by the global forest fires that were started by the comet's impact. The uranium/lead (U/Pb) ages measured on these zircon crystals are also about 66.0 million years (Figure 4.29).

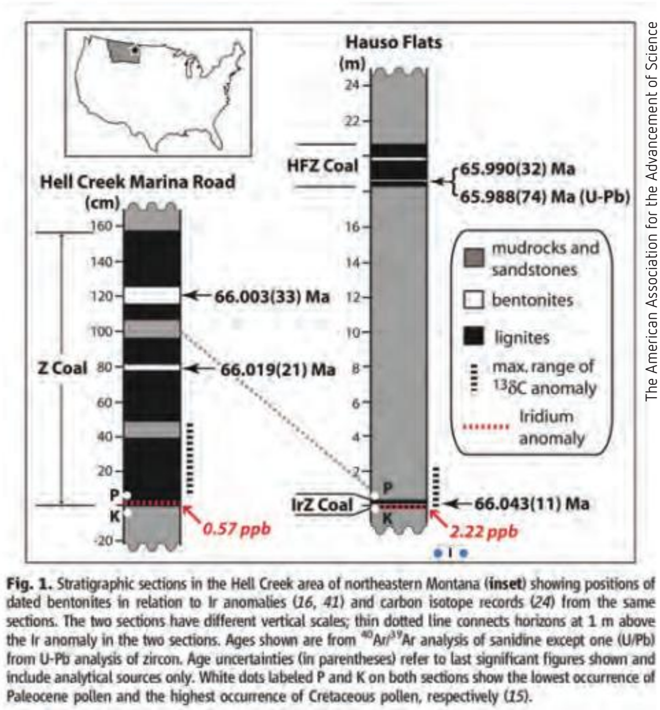


FIGURE 4.29 Dating the Cretaceous–Paleogene boundary by using the principles of stratigraphy, uniformitarianism and isotopic dating methods

Permian–Triassic mass extinction

The Permian–Triassic mass extinction is recognised as the largest and most devastating of the Big Five extinction events. It represents a catastrophic collapse of the Permian ecosystems. Up to 95% of species went extinct with almost 85% of genera and nearly 60% of biological families disappearing from Earth's seas and land masses. The event is generally accepted to have occurred in a short period – probably less than half a million years and quite possibly in less than 100 000 years.

Whole groups of organisms disappeared completely from the geological record at this stratigraphic level. All the major groups of organisms were affected and all Earth's ecosystems were completely disrupted. Marine invertebrates were most affected, especially those that attached themselves permanently to the sea floor. New Triassic genera appeared and the ecosystems recovered gradually over the next 20 million years. The new Mesozoic marine and terrestrial fauna and flora that replaced their Palaeozoic predecessors were distinctly different.

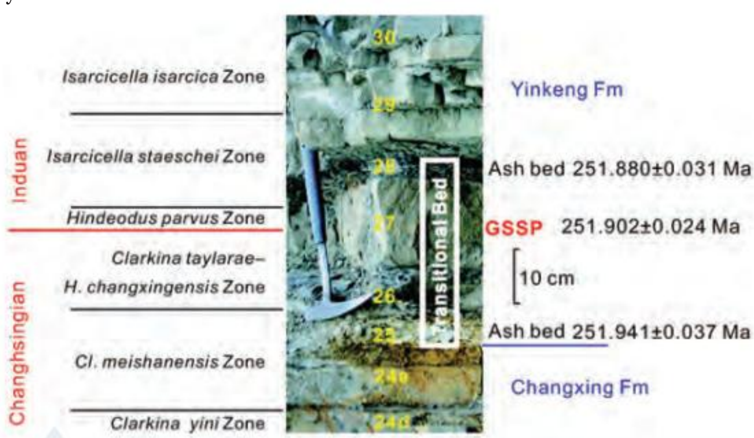


FIGURE 4.30 The Permian–Triassic boundary sediments at Meishan, Zhejiang Province, China

It took intense effort from a large group of geologists and palaeontologists to date the Permian–Triassic mass extinction. They dated 550 individual zircon grains using the SHRIMP ion probe microscope at the Australian National University. The zircon grains were extracted from a latest Permian to earliest Triassic sequence of marine sedimentary rocks found near Meishan in central China (Figure 4.30). The layers of marine mud and sand contained index fossils identifying the Permian–Triassic extinction event, as well as numerous layers of zircon-containing volcanic ash.

The stratigraphic boundary between the Permian and Triassic was identified from the succession of index fossils associated with the boundary using the laws of stratigraphy and uniformitarianism. The index fossils are the teeth of small eel-like animals called conodonts (Figure 4.31). The appearance of the fossil teeth of the conodont *Hindeodus parvus* above those of the *Hindeodus changxingensis* identifies the Permian–Triassic boundary and the zircon dates from ash bed 25 and ash bed 28 (yellow numbers, Figure 4.30) were used to determine the age of the boundary to be 252 million years.

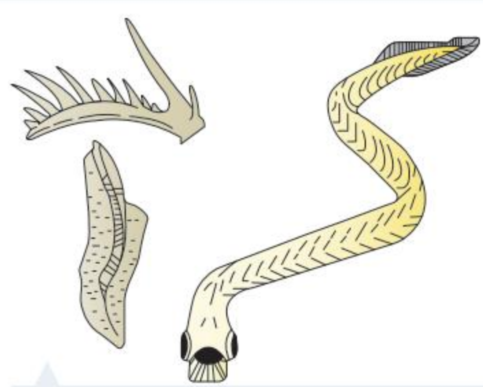


FIGURE 4.31 Conodonts are eel-like marine animals. Fossil teeth and jaws are shown on the left.

Cambrian explosion

The Cambrian explosion was the extraordinary proliferation of complex organisms at the beginning of the Phanerozoic. This is regarded as an extremely important event in the evolution of life on Earth. It is when most of the major animal phyla appeared in the fossil record. This included the first large, armoured and sighted invertebrate marine animals that possessed the first jaws.

The appearance of teeth, jaws and armour provided hard parts that fossilised easily. This change in the nature of the fossil record makes the Cambrian explosion such a distinctive event. Some palaeontologists have suggested that the evolution of eyes and sight was another very important development that occurred at this time. This is because animals with eyes could see, which made predators better hunters and prey more able to detect and avoid danger. Eyes encouraged the development of more complex brains to process images and make decisions about whether to chase and eat something or evade danger and hide. This generated fierce competition and an evolutionary arms race that drove this radiation of marine animals.

Most of the groups of complex multicellular organisms that dominate Earth's ecosystems today appeared during the Cambrian explosion. They displaced the soft-bodied, unsighted large animals that we know collectively as the Ediacaran fauna that had been developing during the preceding 150 million years.

The Cambrian explosion is possibly one of the most important phenomena that has been considered by biologists and geologists. Along with all of the other 19th-century naturalists, Charles Darwin was fascinated by the apparently sudden appearance of large recognisable animals above the lower layers of what was thought to be sterile organism-free layers of sediment. This is where the concept of life somehow arising from the primordial slime comes from.

Below the Cambrian boundary, very few obvious organisms are present in the rocks of Europe. Just above the boundary, life is abundant, and a hierarchy of brutal life-and-death struggles is obviously well established with bigger, faster, stronger predators chasing after their smaller, slower weaker prey. It is the sudden change from a relatively small number of simple soft-bodied species to a vast number of diverse complex animals that prompts palaeontologists to use the term 'Cambrian explosion'. It was not a sudden event as the term implies, but took between 10 million and 30 million years. This could represent between 10 million and several hundred million generations in which the evolutionary changes took place.

When Darwin was working on his theory of evolution by natural selection and the how and why of the Cambrian event, the age of Earth had not been determined and was a subject of great argument and dispute. Today, the determination of numerical ages for particular events in the geological past is a routine component of geological investigations.

Determining the ages of these important evolutionary events consists of a few simple stages. First, the principles of stratigraphy and superposition are used to identify the stratigraphic level of the geological event of interest. In the case of the Cambrian explosion, this is the layer of sedimentary rock in which the first widespread appearance of complex invertebrates is observed. The next step is to find a place where this sediment layer of interest can be dated accurately by isotopic methods.

The best materials for this purpose are volcanic ash layers that contain zircon crystals that formed in a volcano's magma chamber just before it erupted. These crystals can be dated using the very accurate U/Pb **isotopic dating** method. It helps if the volcano providing the ash was reasonably active so that there are lots of ash layers interspersed with the important fossil bearing layers. The third step is identifying several to a dozen zircon-bearing ash layers above and below the sediment layer of interest.

In the case of the Cambrian explosion, there is an excellent site in the southern African country of Namibia where all the factors required to date this event are present. A site within the Late Proterozoic to Cambrian includes a segment of the Nama Basin sediments. It presents a 200-metre-thick sequence of sedimentary rocks in which six, zircon-bearing volcanic ash beds are interlayered with the key fossil-bearing layers (Figure 4.32).

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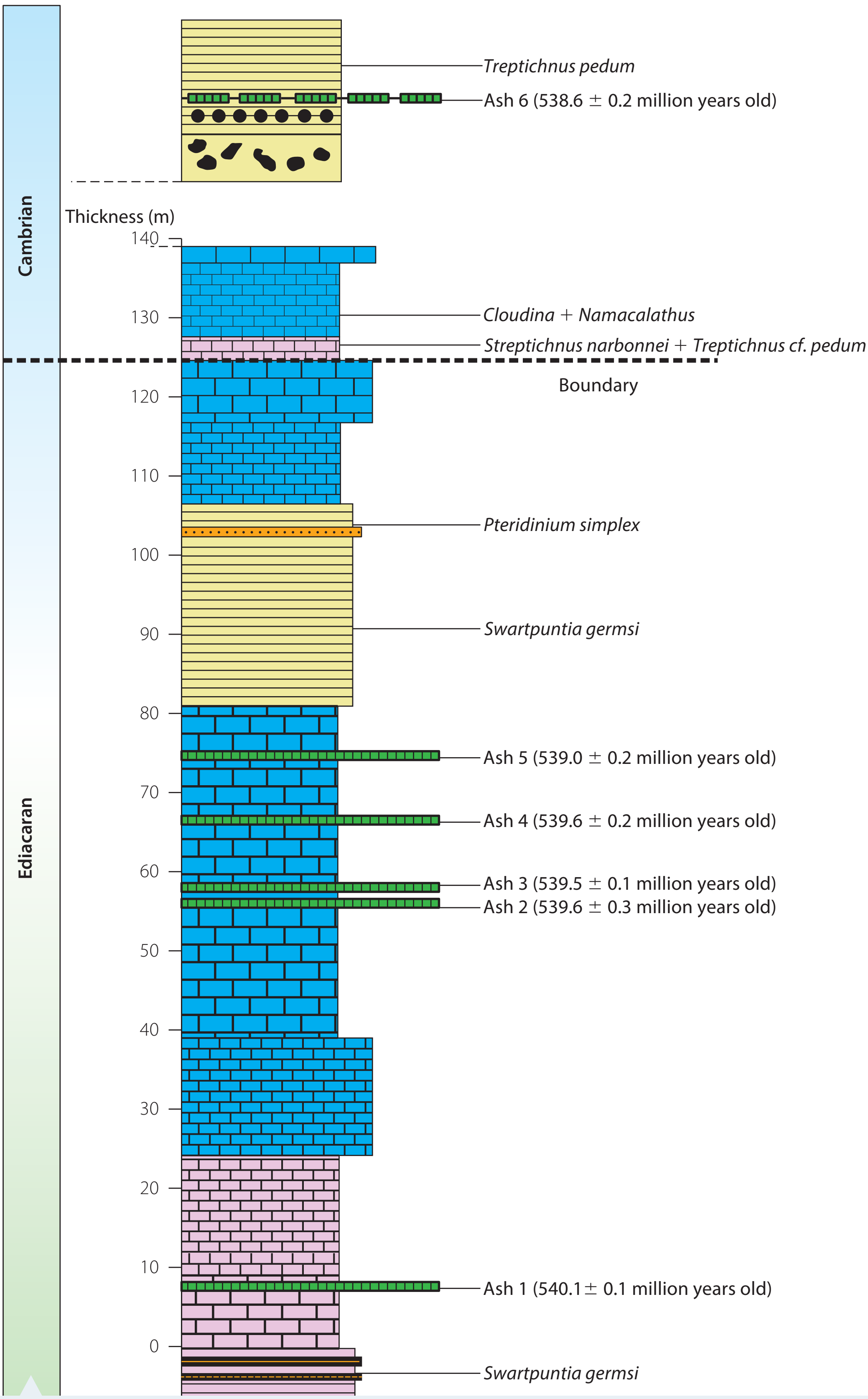

FIGURE 4.32 Dating the Ediacaran–Cambrian boundary and the start of the Cambrian explosion – the Witputs boundary section of Namibia. The site consists of six volcanic ash beds between key fossil-bearing layers. The different coloured sections represent different rock sections.

WS

Geological age from fossils

The oldest of the six ash layers is 540.1 ± 0.1 million years old and the youngest is 538.6 ± 0.2 million years old. Late Ediacaran body fossils are found in the lower parts of the section along with the tiny shells of the Ediacaran animal *Cloudinia*, which is an index or marker fossil. This animal went extinct at the very beginning of the Cambrian. Trace fossils of the earliest Cambrian animals are found just beneath the youngest volcanic ash layer. These trace fossils are named *Treptichnus pedum* and they were made by large soft-bodied animals – they are trace fossils of complex feeding patterns.

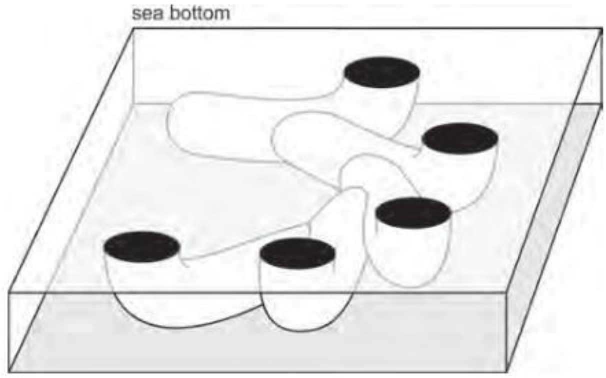

FIGURE 4.33 **a** The trace fossil *Treptichnus pedum* marks the beginning of the Cambrian period. **b** A diagram of the distinctive sea burrows formed by these large, soft-bodied animals.

INVESTIGATION 4.2

Period dramas and dioramas

AIMS

- To gather, process and analyse primary or secondary source information about the fossil fauna and flora that dominated during one of the geological periods of the Phanerozoic
- To outline how the ages of the beginning and end of the geological period were determined
- To produce a summary poster that outlines the key global evolutionary, geological and climatic events that occurred during that geological period

METHOD

1. Gather information about one of the Phanerozoic's geological periods.
2. Identify several major groups of organisms that dominated the period's marine and terrestrial environments.
3. Determine the important evolutionary and geological events that took place during the period.
4. If possible, determine the location of the key sites where materials were collected that enabled the beginning and the end of the geological period to be determined.
5. Use a variety of primary and secondary sources in your investigation, such as scientific journals, websites, textbooks, encyclopaedias, popular science magazines, newspaper articles and the information provided in this chapter.
6. Produce a cross-referenced list of your sources of information, using appropriate headings, and assess the significance of those sources.

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» RESULTS

Produce a poster (A1 or A0 sized) that summarises your chosen geological period. Include:

- images and descriptions of two or three of its major groups of organisms, and dioramas showing typical ecosystems of the period
- a list of the major evolutionary events or changes that occurred during the period
- an outline of the geological or environmental events that are thought to have brought the geological period to an end
- information about how the interval of geological time assigned to that period was determined.

KEY CONCEPTS

- Events of geological significance are dated by a combination of the principles of stratigraphy, superposition and uniformitarianism, fossils and absolute dating methods.
- The principle of uniformitarianism states that geological changes are the result of observable, measurable natural processes that usually cause gradual change over long periods. The principle can be summarised by the phrases 'the present is the key to the past' and 'the past is the key to the future', which broaden the concept of gradual uniformitarianism to include rare, but normal cataclysmic natural events that produce enormous changes suddenly.
- The geological boundaries between the Phanerozoic's geological periods and the Cretaceous were identified from major changes in the groups of fossils present in the sediments from before and after each of the boundaries.
- The age of 66 million years for the Cretaceous–Paleogene mass extinction event and 252 million years for the Permian–Triassic boundary were determined by using the principle of superposition and isotopic dates determined for volcanic sediments deposited just before and just after these events.
- The Cambrian explosion is the name given to the event when the first large armoured and sighted invertebrate marine animals appeared in the fossil record.
- The apparently sudden appearance of large recognisable animals in layers of sediment located immediately adjacent to sterile organism-free layers of sediment prompted geologists to describe this impressive proliferation of many different animal groups at the beginning of the Cambrian period as explosive.
- The dating of zircon crystals sampled from volcanic ash layers that bracket the first appearance of the fossils of the earliest Cambrian animals enabled geologists to determine that the Cambrian explosion started about 540 million years ago. (Note that previous dates for this boundary are slightly older at 541 ± 1 million years – these ages are refined from time to time as better sites are discovered.)

CHECK YOUR UNDERSTANDING 4.3

1. Name the geological technique usually used to determine the age of important geological events.
2. Name the geologist who first proposed the principle of uniformitarianism.
3. State a phrase that is used to outline the principle of uniformitarianism.
4. Name the geological concept that competed with the uniformitarianism and the naturalist who proposed this concept.
5. Name the five recognised mass extinctions of the Phanerozoiceon.
6. What percentage of species went extinct during the end-Cretaceous mass extinction.
7. Explain why the end-Cretaceous mass extinction is generally thought to the best understood of the five mass extinctions.
8. Outline the steps involved in identifying when the Cambrian explosion took place.

4 CHAPTER SUMMARY

- Fossils are the preserved remains of once-living organisms or the traces of their movement. Both groups of fossils are usually found in sedimentary rocks.
- Body fossils are remains of body parts of dead animals and plants.
- Trace fossils are preserved marks such as tracks and trails that organisms make when they move across or burrow through a layer of sediment.
- Most fossils form when an organism is rapidly buried in sediment. This process isolates the body of the organism from the oxygen supply that other organisms and some microbes require to consume and break down the dead organism's remains.
- Some fossils are formed by entombment and mummification of whole animals, plant fragments, spores and pollen in tree sap, tar or ice.
- A fossil cast preserves an impression in rock that copies the organism's features exactly as they appeared in real life.
- A fossil mould produces a reversed impression of the organism's features that could be used to cast a copy of the organism in the same way that we might use a mould to cast a ring or a plastic toy.
- The named periods of geological time that make up the Phanerozoiceon were identified because they contain recognisably different and distinct groups of fossils.
- Boundaries between the named geological periods are identified by the disappearance of large numbers of fossil groups at the boundary. These groups are replaced by different groups of fossils above the geological boundary.
- The disappearance of large numbers of fossil groups at a geological boundary is thought to mean that an extinction event occurred at that time. The emergence and proliferation of new groups of organisms is called a radiation event.
- The Phanerozoic is subdivided into three eras – the Palaeozoic, Mesozoic and Cenozoic – on the basis of the apparently ancient, intermediate and modern fossil animals that lived through these intervals of time.
- Index fossils are species of fossil organisms that were geographically widespread, numerically abundant and lived during a short geologic period.
- Index fossils are very useful for dating the rocks in which they are found. The presence of an index fossil in a sedimentary rock usually means that it formed during a particularly short geological time.
- Events of geological significance are dated by a combination of the principles of stratigraphy, superposition and uniformitarianism, fossils and absolute dating methods.
- The principle of uniformitarianism states that geological changes are the result of observable, measurable natural processes that usually cause gradual change over long periods. The principle can be summarised by the phrases 'the present is the key to the past' and 'the past is the key to the future', which broadens the concept of gradual uniformitarianism to include rare, but 'normal' cataclysmic natural events that produce enormous changes suddenly.
- The geological boundaries between the Phanerozoic geological periods Cretaceous were identified from major changes in the groups of fossils present in the sediments from before and after each of the boundaries.
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4 CHAPTER REVIEW QUESTIONS

Review quiz

1 What does the word 'Phanerozoic' mean?

2 Name the event that occurred at the beginning of the Phanerozoic.

3 Explain why the statement that 'one-in-a-million animals becomes a fossil' is considered to be a very rough estimate.

4 Name three materials that can entomb and mummify organisms.

5 What is the common factor generally required to enable fossilisation?

6 Identify the mould and cast fossils of the ammonites preserved in mudstone shown in Figure 4.34.

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FIGURE 4.34 Moulds and casts of two ammonites

7 What is a trace fossil?

8 What information can we gather from the examination of trace fossils?

9 Name the periods of the Phanerozoiceon.

10 Name the eras used to divide the Phanerozoic into its three intervals of geological time.

11 Name a group of organisms that palaeontologists identify to have been abundant and dominated the fossil record of each Phanerozoic period.

12 Why do geologists search for index fossils when they examine sequences of sedimentary rocks?

13 What is the significance of the disappearance of large numbers of species at the end of a geological period?

14 What percentage of species extinction is commonly used to identify a mass extinction?

15 When did the so-called 'Big Five' mass extinctions occur?

16 Name the evolutionary event that usually follows a mass extinction.

17 Explain how 19th century geologists and palaeontologists used the fossil record to create a relative geological time scale that they used to 'date' major geological events.

18 Outline how geologists and palaeontologists established that the Cretaceous–Paleogene (K/T) mass extinction occurred 66 million years ago.

19 Why do natural scientists consider the Cambrian explosion to be one of the most important events in Earth's evolutionary history?

20 Explain why palaeontologists and evolutionary biologists consider fossils to be very important natural objects.

MODULE 5: EARTH'S PROCESSES

Answer the following questions.

1 Experiments similar to those performed by Miller and Urey have demonstrated that amino acids and organic molecules can be generated by abiotic processes, while studies of the Murchison meteorite have identified that it contains a large number of life's so-called precursor materials.

- **a** What is abiotic synthesis?
- **b** Why are amino acids important organic materials?
- **c** Name three organic molecules found in the Murchison meteorite and describe their role in a biological process.
- **d** Explain why abiotic synthesis and the naturally occurring organic materials found in the Murchison meteorites provide support for the panspermia hypothesis.

2 The table shows the three main types of hydrothermal vents and the minerals and nutrients they are associated with.

VENT TYPE	BLACK SMOKER	WHITE SMOKER	ALKALINE
Minerals	Pyrite Chalcopyrite Sphalerite Barite Anyhydrite	Barite Anyhydrite Gypsum	Calcite Dolomite Magnesite Siderite Brucite Silica
Nutrients	H_2S CO_2 CH_4	H_2S CO_2 CH_4	H_2S CO_2 CH_4 H_2

- **a** At what temperatures do the three different types of hydrothermal vent eject their seawater jets?
- **b** Determine and list the chemical compositions of the minerals that commonly occur at deep-sea hydrothermal vents.
- **c** Name the type of organisms that utilise the nutrients ejected at deep-sea hydrothermal vents.
- **d** Write an example of the chemical reaction that generates carbohydrates at a deep-sea hydrothermal vent.
- **e** Draw and label a simple food web for the organisms that live at a hydrothermal vent.

3 Draw examples of conical, domical and wavy stromatolites and briefly describe how and why these different shapes form.

4 Outline the relationships between the appearance and proliferation of cyanobacteria, the timing of the Great Oxidation Event and the deposition of most of Earth's banded iron formations.

5 Describe and discuss a significant example of how a change in the biosphere caused major changes in the geosphere, atmosphere and hydrosphere.

6 'The Cambrian explosion is an inaccurate description of the evolution and proliferation of bilaterian organisms.' Assess this statement and comment on its accuracy and usefulness.

7 Draw a sketch that outlines the stages of the supercontinent cycle and shows the relationships between supercontinent formation and supercontinent dispersal to deep mantle processes.

8 Why is supercontinent assembly associated with lower global sea levels, a larger ocean area and the formation of extensive ice sheets?

9 Outline the possible consequences of the break-up of a supercontinent for sea level, climate and evolution.

10 Outline how the appearance of multicellular plants and animals as well as the oxygenation of the atmosphere during the Proterozoic oxygenation event can be linked to the supercontinent cycle.

11 Outline why fossils are not very useful for determining when the major geological events of the Archean and Proterozoic occurred.

12 Explain how the stratigraphic column has been calibrated by absolute dating methods to produce the geological timescale.

13 Trace fossils are the tracks, trails, impact marks and footprints that organisms made when they were alive. Explain why palaeontologists and geologists find trace fossils to be an extremely useful type of fossil.

14 The timing of major events in Earth's history is established by absolute dating techniques that mostly use zircon crystals, which are often extracted from volcanic ash horizons. Identify how absolute dating has been used to determine the age of the following events in Earth's geological and evolutionary history.

- **a** The appearance of stromatolites in the Archean
- **b** The Cretaceous–Palaeongene boundary
- **c** The Permo–Triassic boundary
- **d** The Ediacaran–Cambrian boundary
- **e** The assembly of the supercontinent Rodinia
- **f** The break-up of the supercontinent Columbia

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DEPTH STUDY SUGGESTIONS

- Investigate the search of organic materials and life on the solar system's extra-terrestrial (non-Earth), moons, comets and planetessimals.
- Create a chemical garden and monitor the growth of its chimney and tower structures for two weeks.
- Explore the three main types of oceanic hydrothermal vents (black, white and alkaline) and the communities of organisms that utilise the nutrients expelled within their jets of heated sea water.
- Investigate the natural history of stromatolites through geological time.
- How are index fossils used to date important geological events?
- Investigate one or several of the five Phanerozoic mass extinction events and their aftermaths.
- Explore the evolution of lungs and other modes of air breathing developed by arthropods and vertebrates.
- Investigate the Cambrian explosion and the early history of the evolution of bilaterian organisms.
- Investigate the Permo–Triassic mass extinction and assess the evidence for this event being predominantly due to a very extreme and rapid global warming event.
- Investigate the supercontinent cycle and the impacts of supercontinent assembly and dispersal on global sea level and climate.
- Investigate the Carboniferous oxygen peak and appearance of this period's giant arthropods and insects.
- Explore the invasion of terrestrial environments by unicellular and multicellular organisms.

» MODULE SIX

HAZARDS

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5 Geological disasters

OUTCOMES

In this chapter you will learn about:

- how to use data to predict the locations of earthquakes and volcanic eruptions and their relationships with the different types of plate boundaries AAEA CCT ICT N
- the changing depth of earthquake foci at divergent and convergent plate boundaries AAEA CCT ICT N
- the hazards associated with earthquakes AAEA CCT ICT N
- the hazards associated with volcanic eruptions CCT ICT N
- different magma chemistries and how volcanic eruptions can be influenced by magma chemistry
- how a geological hazard can become a geological disaster. AAEA

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The eruption of Mount Vesuvius in 79 CE was witnessed by the historian Pliny the Younger. He described a giant branching eruption, flames sprouting from Vesuvius, ash blacking out the Sun and frequent earthquakes. It is the earliest first-hand account of an explosive volcanic eruption. The event destroyed the cities of Pompeii and Herculaneum by covering the cities in hot volcanic ash. It is estimated that 30 000 people died in this disaster.

NOAA

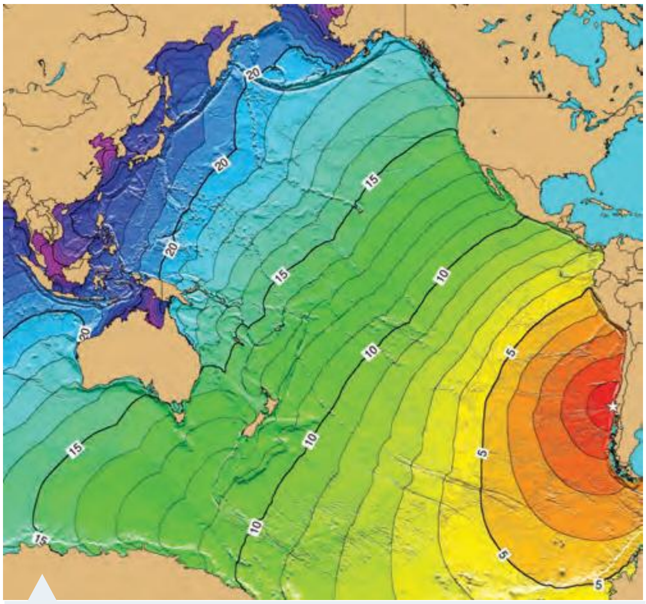


FIGURE 5.1 The tsunami travel time of the earthquake of Valdivia, Chile, 22 May 1960. Contours are 1-hour intervals.

The largest earthquake ever recorded occurred in Chile on 22 May 1960 when a magnitude 9.5 earthquake was caused by the subduction of the Nazca plate beneath the South American plate (Figure 5.1). Tsunamis triggered by the earthquake affected the Chilean coast with waves as high as 25 metres and extended from the epicentre as far as Hawaii, Japan, China and the Philippines. Tsunami waves of 1 metre were recorded on Australia's eastern coast, causing damage to boats in Sydney, Eden and Newcastle harbours. Estimated fatalities in Chile and the associated tsunami-affected areas were between 490 and 5700, with a further 2 million left homeless. Damage costs reached approximately $US550 million.

The links between earthquakes, volcanic activity and plate tectonic theory are an important advance in our understanding of Earth's processes. Contemporary **seismologists** and **volcanologists** cannot change Earth's geological activity; however, by studying the signs and hazards associated with this activity, they help to preserve human life.

5.1 Plate boundaries and geological hazards

Figure 5.2 is a map of tectonic plate boundaries, earthquakes and volcanic activity. The occurrence of seismic and volcanic events at plate boundaries is clearly evident. This is explained by our understanding of plate interactions.

Earthquakes and volcanoes tend to occur at plate boundaries. As tectonic plates move relative to each other, energy is stored in the rock and released as earthquakes. Earthquakes can also be caused by magma moving through Earth's crust. Increasing earthquake activity is often predictive of a volcanic eruption.

You will learn more about using seismic activity to predict volcanic eruptions in Chapter 7.

You will learn more about the differences in volcanoes in section 5.3.

Volcanic activity occurs where the crust thins at divergent boundaries, producing effusive volcanic eruptions. Subduction zones are characterised by explosive volcanic activity. Tectonic hazards are most frequent where plates interact. However, earthquakes and volcanoes can occur away from plate boundaries. For example, most **hotspot** volcanoes are not associated with plate boundaries. The Hawaiian Islands are a well-known series of hotspot volcanoes in the Pacific plate. Hotspot volcanoes are very different from those at subduction boundaries.

KEY CONCEPTS

- Earthquakes and volcanic activity occur mainly at plate boundaries.
- Relative plate movement stores energy that is released as earthquakes.
- Volcanoes may occur at rifting zones, subduction zones or hotspots.

CHECK YOUR UNDERSTANDING 5.1

1 Why do earthquakes occur at plate boundaries?

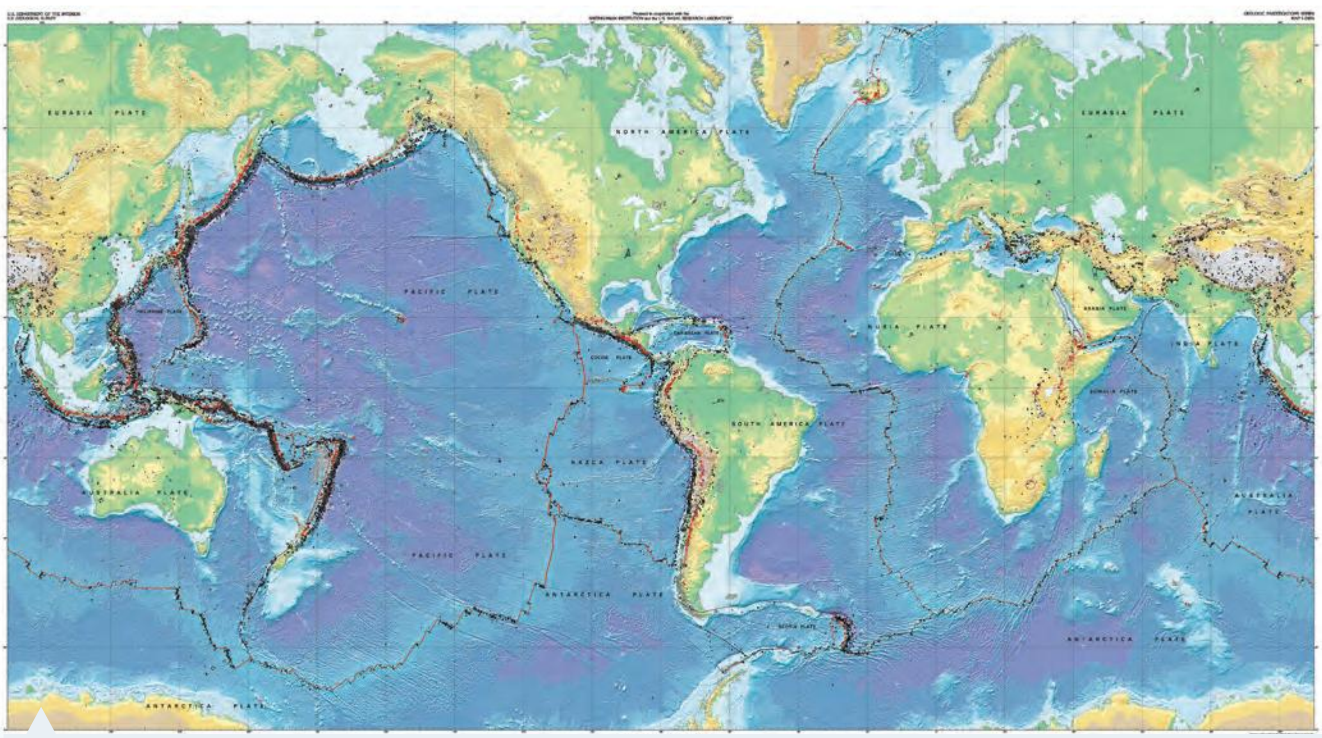
2 What type of volcano is generally *not* found at a plate boundary?

5.2 Earthquakes

Movement of plates grinding, crumpling, stretching or subducting beneath a neighbouring plate results in continual elastic energy storage that is inevitably followed by energy release. Small releases of energy are frequent and have little effect on Earth's surface. In some locations, huge tension built up over hundreds of years can suddenly release energy in forceful jolts of earth movement that can kill or injure thousands of people within minutes.

Earthquake locations

As shown in Figure 5.2, earthquake locations generally cluster around lithospheric plate boundaries. Differences in size, magnitude, frequency and depth of foci of earthquakes relate to geographical location



Courtesy of the U.S. Geological Survey, Smithsonian Institution, and U.S. Naval Research Laboratory

FIGURE 5.2 The location of the major and minor lithospheric plates and the distribution of earthquakes and volcanic activity between 1960 and 2006 . The black dots indicate earthquakes and the red dots indicate active volcanoes.

and plate movement. The type of plate boundary, potential energy storage of different types of rocks and dynamic activity in Earth's mantle all influence earthquake frequency and magnitude. Despite this variation, a knowledge of plate boundaries can help us predict the depth and location of earthquakes. Conversely, the type of boundary can be inferred from the pattern of earthquakes.

Earthquakes at divergent plate boundaries

Earthquakes at divergent plate zones are the result of the injection of magma from the partially molten upper mantle into thin oceanic crust or by the resulting movement of tectonic plates away from the boundary (Figure 5.4).

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FIGURE 5.3 The city of Port-au-Prince, Haiti, was devastated by an earthquake in January 2010.

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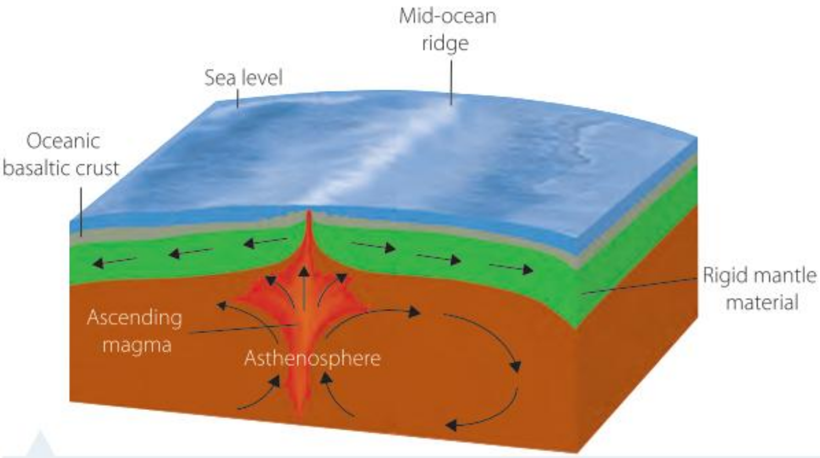

FIGURE 5.4 Divergent plate boundary showing upwelling of magma

As magma emerges, it pushes the crust apart, causing cracks and faults to occur. This movement causes frictional stress as the upwelling magma stretches, thins and breaks the overlying plates. Because the oceanic plate is thin and being stretched even thinner, the depth of earthquake foci very rarely exceeds 50–70 km. These are classed as **shallow-focus earthquakes**.

The pattern of very shallow earthquakes has been used to map the divergent plate boundaries with a high degree of accuracy. These earthquakes define a very narrow zone either side of the plate boundary (Figure 5.5). Most of these earthquakes have a small Richter magnitude. Of the 500 000 earthquakes estimated each year by the US Geological Survey, approximately 400 000 of these have Richter magnitudes of less than 5.

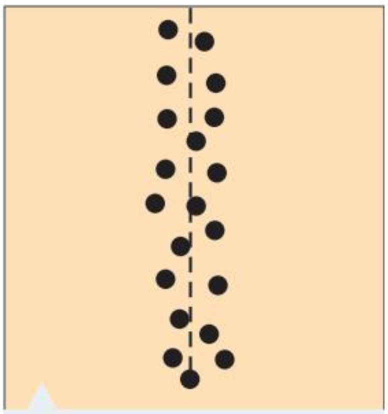

FIGURE 5.5 Shallow-focus earthquakes are evenly distributed on both sides of a divergent plate boundary.

Although most divergent boundaries are oceanic, they also occur when continents break apart. Continental crust is brittle and fractures easily, resulting in small earthquakes. These can be seen around the east African rift valley in Figure 5.2. This is the most active continental rift on Earth today.

Earthquakes at transform plate boundaries

Transform faults describe the movement of two plates moving past one another in opposite directions. The movement of the faults and energy exchange causes strike-slip faults, where the rock strata can split and be carried in opposite directions in parallel with the fault. Continental transform faults are generally active only in the upper 20 km, resulting in shallow earthquakes with a distribution similar to that around a mid-ocean ridge. Oceanic transform faults offset mid-ocean ridges and are also characterised by shallow earthquakes. Although shallow, earthquakes at continental transform boundaries frequently reach high magnitudes.

USGS

FIGURE 5.6 An example of fault creep

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The most well-known transform boundary is the San Andreas fault (Figure 5.6), which extends 1300 km along the western coastline of California and down to the north of Mexico and is the delineation of the North American and Pacific plates. The fault line is a horizontal transform fault with three main portions that contain several parallel fault lines. Each is characterised by differences in plate motion and physical rock type, creating different types of earthquake risks along the fault. The plates move past each other at a rate of 3.5–4.5 cm a year, and in parts are characterised by **fault creep**. Fault creep describes the movement of two plates that are not locked together to creep past one another in the absence of earthquake activity but can show displacement on the fault's surface.

There have many significant earthquakes along the San Andreas fault. The most devastating was the April 1906 San Francisco quake measuring 7.8 in magnitude. It caused 3000 deaths and countless injuries. Some areas, such as Parkfield, regularly experience large magnitude earthquakes. The Parkfield area has been the site of a long running experiment attempting to find predictors of large magnitude earthquakes.

San Andreas fault

Learn more about the San Andreas fault from the US Geological Survey.

Earthquakes at convergent plate boundaries

Convergent plate boundaries are boundaries where plates collide, often resulting in one plate being subducted by another, as shown in Figure 5.7. Dense oceanic plates sink beneath less dense continental plates. An oceanic plate is cold and brittle compared with the overriding continental plate. The subducting slab of oceanic crust fractures and compresses as it is exposed to increasing temperature and pressure while descending into the mantle. The friction of plate subduction produces earthquakes at ever increasing depths beneath the overriding plate (the Benioff–Wadati zone). The resultant energy release may produce earthquakes with large magnitudes that have devastating consequences for human structures and life. Studying earthquakes has helped scientists to map plate depth and the relationship to earthquake foci that occur as deep as 670 km (Figure 5.8).

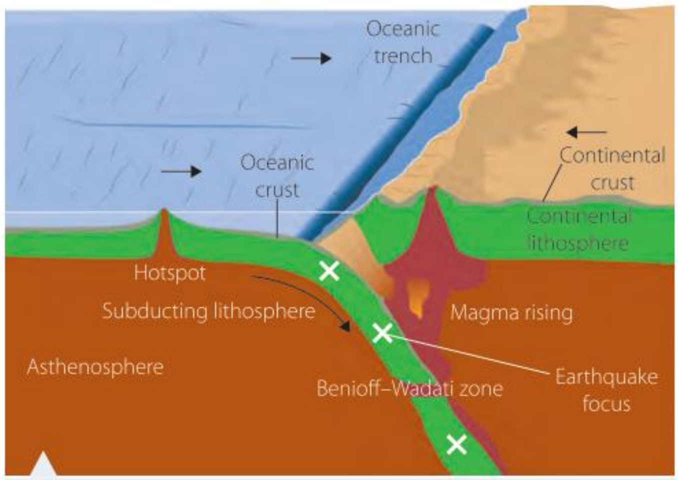


FIGURE 5.7 Ocean and continental plates converge, creating a subduction zone of seismic and volcanic activity.

Earthquakes and plate boundaries

Explore types of plate boundaries and the relationship to earthquake magnitude.

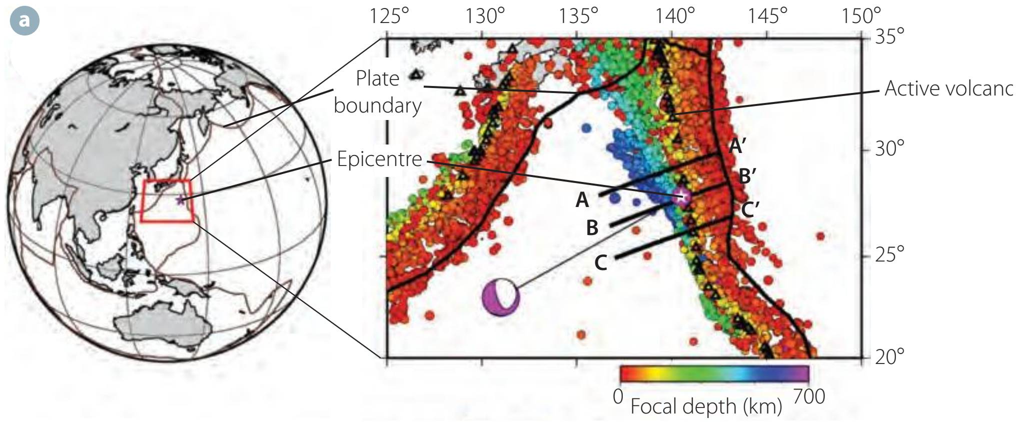
The large area of interacting plate surfaces leads to frequent large earthquakes in subduction zones. In fact, 80% of Earth's earthquakes occur around the Pacific Ocean Ring of Fire. This zone extends from New Zealand, then north and then west through Papua New Guinea, the Philippines, the island arcs of the western Pacific, across the Aleutian Islands then south along the west coast of the Americas. This area is apparent in Figure 5.2 because of the high density of earthquakes and extensive volcanic activity.

Converging boundaries also occur where two continental plates collide and produce some of Earth's highest mountain ranges. Of all earthquakes, 18% occur in the Alpine–Himalayan mountain belt (known as the Alpide Belt) running north from Myanmar and then west to the north of India, through Pakistan, Afghanistan, Turkey and into the European Alps (Figure 5.9, page 112). The collision zone between plates creates folding and faulting within the highly compressed rocks. Although there is a large area of plate interaction, seismic activity is shallow in focus but can be large in magnitude. The 2015 Gorkha earthquake in Nepal had a magnitude of 7.8 and depth of 8.2 km. The shaking and subsequent avalanches killed nearly 9000 people and injured approximately 22 000.

Earthquake locations and depth

Explore earthquake locations and depth of focus with the Exploring Earth interactive.

FIGURE 5.8 **a** On 30 May 2015, the deepest earthquake ever recorded occurred 670 km deep off the coast of Japan. The red box shows the area that was studied. The focal depth is indicated by the colours shown on the scale bar. **b** Seismologists use data from this earthquake and other earthquakes in the region to construct a map of the torn subducting slab. The red star represents the focus of the earthquake.



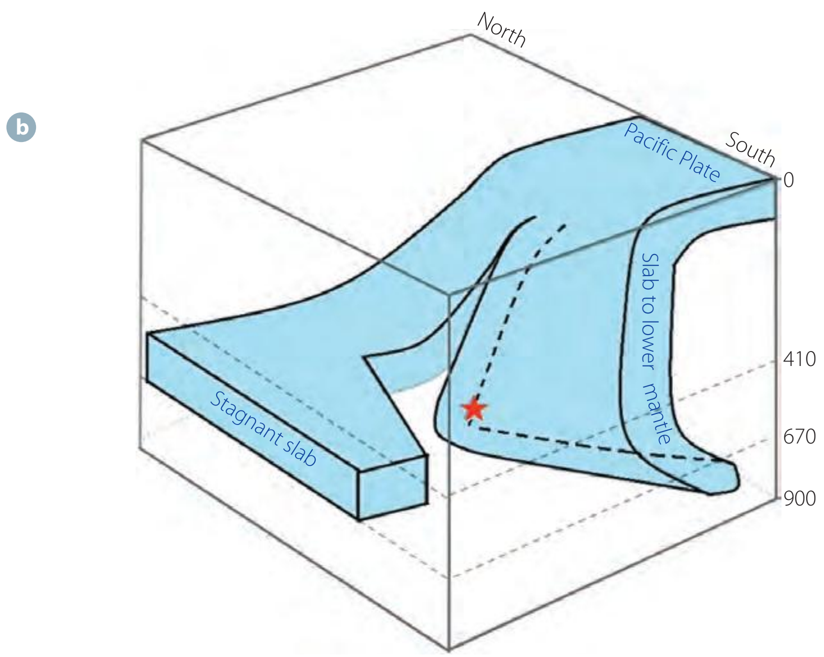
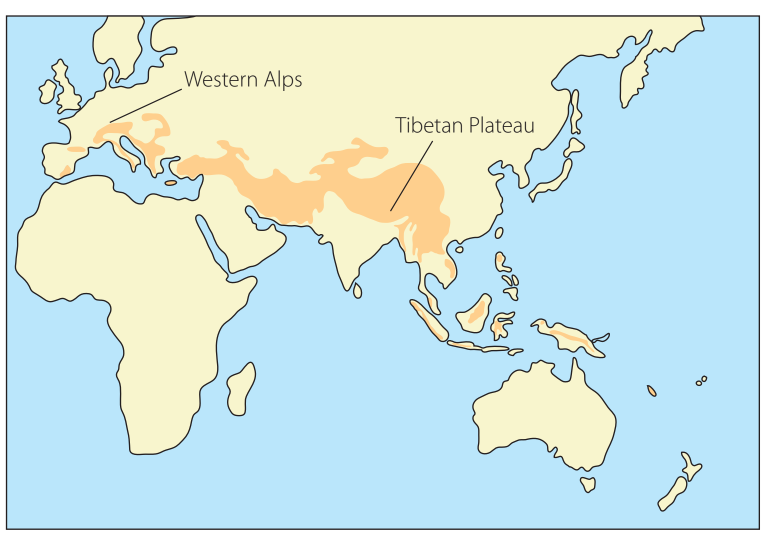


FIGURE 5.9 The Alpine–Himalayan mountain belt is an extended area of continental collision.



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INVESTIGATION 5.1

Earthquake depths at convergent and divergent plate boundaries

Approximately 50 earthquakes are recorded every day by seismometers around the world, and hundreds more are so small that they remain unrecorded. Tremors strong enough to be felt are much less common. The theory of plate tectonics helps us to explain the occurrence and pattern of earthquakes at different types of boundary.

Critical and creative thinking

Asia and Australia's engagement with Asia

Information and communication technology capability

AIM

To use an online model to determine the relationship between earthquake depth and type of plate boundary

METHOD

1 Open the weblink *IRIS Earthquake Browser* and in the upper right corner, change the Maximum earthquakes option to 3000 and click the orange Apply button.
2 Turn on the Show plate boundaries option.
3 Use the hand tool to navigate around the map, noting any relationships between earthquake location, depth and plate boundaries.
4 Place Australia in the centre of the map as you answer the analysis questions. You may wish to zoom in on areas to explore earthquake patterns and find place names.

IRIS Earthquake Browser

ANALYSIS

1 Which plate boundary type(s) had shallow-focus earthquakes?
2 Are shallow-focus earthquakes mainly located on boundary lines or not?
3 What type of boundary has a variety of earthquake depths? Give an example of this pattern located near Australia.
4 Identify two earthquake locations that are well away from a plate boundary. Note the depth of these earthquakes.

DISCUSSION

1 Describe the relationship between depth of earthquake focus and distance from a convergent plate boundary in Indonesia.
2 When looking at the earthquake browser, what clues allow you to determine the overriding plate at a convergent boundary?
3 Where did you notice the greatest concentration of earthquakes? Does this relate to a particular type of plate boundary?

»

CONCLUSION

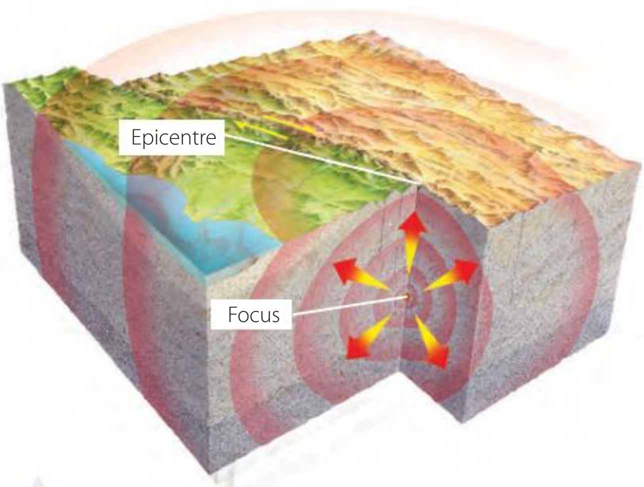
Write a conclusion about the depth of earthquakes at convergent and divergent plate boundaries.

Earthquake hazards

WS Earthquake magnitude and frequency

Historically, seismologists have measured the energy released in earthquakes using the Richter magnitude scale. This scale measures the amplitude of waves recorded by seismographs. The Richter scale is logarithmic – an increase of 1 on the scale equates to 10 times more energy released by the earthquake and an increase of 2 on the scale equates to 100 times more energy released. The Richter scale is only valid for certain frequencies of earthquake waves, so other magnitude scales were developed for different frequencies. Today, semiologists use the moment magnitude scale (Mw), which applies to all frequencies of earthquake waves and gives the most reliable estimate of the force released in very large earthquakes. The moment magnitude scale is equivalent to the Richter scale in the valid frequencies.

When news items report large magnitude earthquakes, the devastation usually correlates with the strength of an earthquake. Buildings are flattened, roads are split, and humans may be trapped beneath or killed by falling rubble. A large earthquake usually triggers aftershocks, a sequence of smaller tremors that occur in the days following the main shock earthquake. Aftershocks are smaller in magnitude but can be just as damaging because structures and landscapes have already been damaged by the force of the mains earthquake. Earthquakes can also come in swarms, a series of similar-sized tremors occurring in a limited area within a short timeframe.



Alamy Stock Photo/Science Photo Library

FIGURE 5.10 The position of the focus (deep underground) and the epicentre (directly above, on the surface) of an earthquake

Ground motion

The magnitude of seismic waves relates to the intensity and displacement of Earth's surface during an earthquake. These waves vibrate from an earthquake's focus in a circular fashion like the ripple from a rock hitting the still water of a pond (Figure 5.10). Typically, there are three types of waves: primary (P), secondary (S) and surface (L) waves. P-waves and S-waves are body waves that travel through the body of Earth. L-waves only travel along the surface of Earth, close to the earthquake epicentre.

L-waves are made of two component wave types – Love waves and Rayleigh waves. A Love wave produces a rolling motion of the ground, while a Rayleigh wave causes a sideways movement that is at right angles to the ground's surface. Built structures, such as buildings, bridges, roads and dams, are not usually designed to move sympathetically with the earth in all directions simultaneously and it is this ground motion that causes human-built structures to fail (Figure 5.11).

iStock.com/superjoseph

FIGURE 5.11 Building damage in Christchurch, New Zealand, after the 2011 earthquake

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Ground movement can make the ground unstable for a large area around an earthquake's epicentre. The greater the magnitude of an earthquake, the greater the intensity of ground motion triggered. In China in 2008, the Sichuan earthquake of 7.9 Mw was followed by strong aftershocks measuring up to 6 Mw. About 200 000 **landslides** were triggered, creating 800 new **quake lakes** and displacing several metres of earth. Buildings were tipped over or destroyed by ground **subsidence**. It is estimated that 15 million people lived in the affected area. Landslides and other geological hazards from the quake were responsible for at least a third of the death toll of 690 000. Millions were left homeless.

Alamy Stock Photo/Keystone Press

FIGURE 5.12 The collapse of earthquake-proof apartment blocks in Niigata, Japan, in 1964 was caused by liquefaction of reclaimed land.

Liquefaction

The propagation of waves through loose, saturated silty and sandy soils shakes them and causes a collapse of their granular structure, which throws the load from a structure directly onto the incompressible water between the particles. The soil then has no shear strength and is unable to support the structure, which sinks into it. The structure is sitting on a dense fluid and promptly settles, usually unevenly, as in Fig 5.12. Road pavements can suffer the same fate. This is a completely separate process from that which forms quicksand.

Landslides

Landslides are generally caused by the pressure of ground water in the slope increasing due to percolation by rain, causing the water table to rise to a level at which the contact stress between the soil particles is reduced sufficiently to bring the shear strength of the soil below what can support the slope. Even before this point is reached, the lateral stresses in the slope caused by horizontal acceleration of the ground will be enough to overcome the remaining soil strength and cause a slip. It is unlikely that the water pressures will be increased by the ground motion, as most slopes subject to instability consist of clay soils which have a high internal cohesion and a non-collapsing structure.

Fire

In the San Francisco earthquake of 1906, fire consumed the city for 3 days afterwards. Significant upheaval of earth damages not only buildings but also power lines, gas mains, water pipes and communication wires. Damaged powerlines and gas mains easily set structures alight, disrupted mains water supplies hinder fire-extinguishing efforts, and upheaval of roads interrupt and delay access to buildings under fire threat. Approximately 250 000 people were left homeless after the fire in San Francisco.

Floods

Excessive ground shake can damage dams, reservoirs and levees. The flow of water cannot be halted and the resulting flooding of urban areas damages structures and endangers human life. Delayed flooding may occur when natural or artificial dams are damaged by an earthquake and fail some time after the event.

Tsunamis

Tsunamis pose substantial risk to many coastal communities across the world. Tsunamis occur when displacement of the sea floor (uplift and subsidence) displaces the water above it, forming large waves that propagate from the source of the ground shake. This can be caused by:

- an earthquake on the ocean floor (2004 Boxing Day tsunami, 2011 Japan tsunami)
- an asteroid hitting the ocean surface (possibly 9000 years ago around Jervis Bay, New South Wales)

- an explosive volcanic eruption on an island volcano (Krakatoa 1883)
- a medium-to-large underwater sediment slide (erosion) (Palu, Indonesia 2018; Papua New Guinea 1998).

The causes of tsunamis are shown in Figure 5.13. The edge of an overriding plate in a subduction zone may become locked and be pulled several metres downwards over an area of thousands of square kilometres. When the plate edge releases and springs back, the water is uplifted, causing a wave that can reach several storeys high. A tsunami wave can travel at speeds up to 800 $km\,h^{-1}$, which is as fast as a jet plane.

Shutterstock.com/udaix

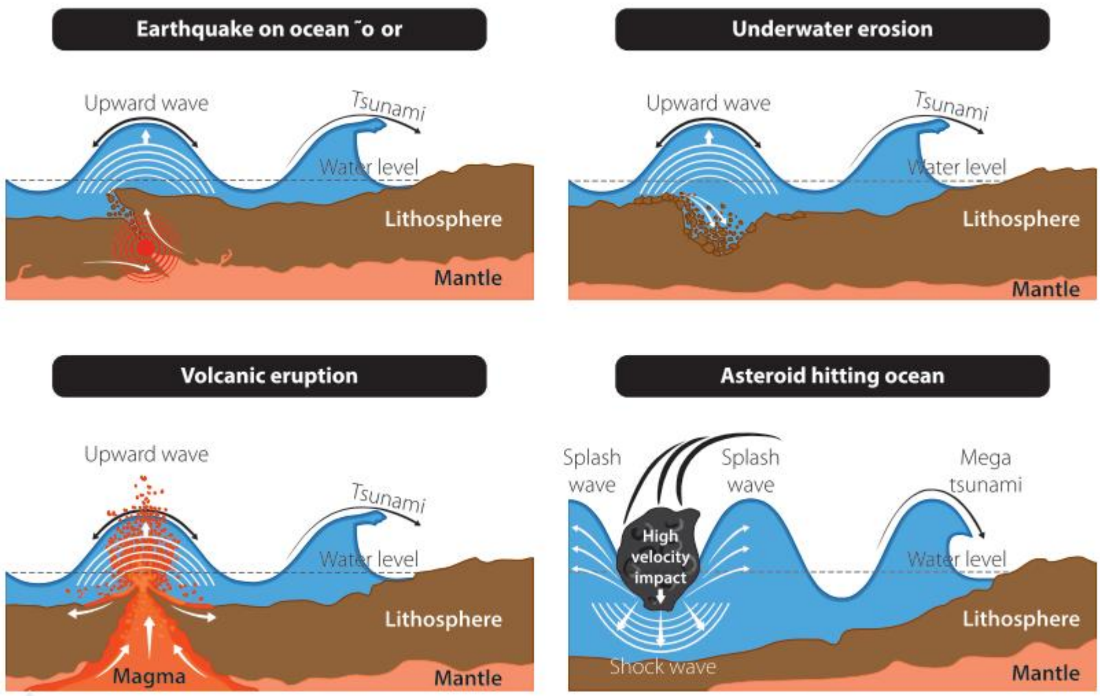

FIGURE 5.13 Tsunamis have different causes.

The damage caused by a tsunami is due to the ocean rising and flooding across the land. Any loose materials can be pushed along by the water and act as battering rams on structures. The more material that is moved by the water, the greater the battering ram effect. Flat land near the coast is most susceptible to the effects of a tsunami, while inlets and rivers allow the ocean surge to move far inland.

INVESTIGATION 5.2

Critical and creative thinking

Information and communication technology capability

Asia and Australia's engagement with Asia

Tsunamis

There is a lot of online video material for both the 2004 Indian Ocean tsunami and the 2011 Sendai tsunami in Japan.

1. Find videos online of the 2004 Indian Ocean and 2011 Sendai tsunamis.
2. Describe the shape of the waves as they approach the coast.
3. Is there evidence in the videos of how many waves struck the coast during the Boxing Day tsunami? If there is, describe it.

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4 Compare the responses of people who have encountered tsunamis before (the Japanese) with those of the tourists and locals of other countries as seen in the Boxing Day footage.

5 Explain how coastal communities can be better prepared for a tsunami threat.

6 Describe the likely effects of a large (>5 metre) tsunami hitting the eastern side of Australia. Explain, using secondary sources, how a large coastal city such as Sydney, Newcastle or Wollongong might be affected by a tsunami of this size.

KEY CONCEPTS

- All types of plate boundary may have shallow-focus earthquakes.
- Subduction zone earthquakes may occur as deep as 670 km.
- Earthquake foci are mainly on the overriding plate at a subduction zone.
- Most earthquakes occur at convergent boundaries, especially around the Pacific Ocean.
- The main causes of damage during earthquakes are ground motion, landslide and ground liquefaction.
- Ground liquefaction only occurs in waterlogged soils.
- Tsunamis can be caused by ocean floor earthquakes, asteroid strikes, volcanic island eruptions or underwater sediments slides.

CHECK YOUR UNDERSTANDING 5.2

1 Contrast the pattern of earthquake epicentres at divergent and subduction zone boundaries.

2 Explain why most earthquakes occur around the Ring of Fire.

3 Outline features of the San Andreas fault.

4 Define 'ground motion', 'ground liquefaction' and 'tsunami'.

5 Explain how ground liquefaction can damage buildings.

6 Which earthquake hazard is unique to populated areas?

7 What topographic features can make a tsunami more damaging?

5.3 Volcanoes

A **volcano** is a vent to the depths of Earth through which molten rock, known as **magma**, moves. When magma reaches Earth's surface, it is called lava. Volcanic zones are found on the surface of Earth, but 60% of volanoes are in the depths of the ocean at diverging or converging tectonic boundaries. Other volcanoes are found away from plate boundaries where Earth's crust is thin and stretched. Eruptions from volcanoes may be effusive or dramatically explosive, depending upon the chemistry of the magma in the volcano and its interaction with water near the surface.

Geochemists classify magma chemistry as ultramafic, mafic, intermediate or felsic, depending upon the percentage of SiO_2 (silica) they contain (Table 5.1).

TABLE 5.1 Magma chemistry and silica percentage

MAGMA TYPE (CHEMISTRY)	SILICA PERCENTAGE
Felsic	>63
Intermediate	55–63
Mafic	45–55
Ultramafic	<45

You can review magma formation in Chapter 9 of *Earth and Environmental Science in Focus Year 11.*

Shutterstock.com/sirtravelalot

FIGURE 5.14 Lava fountains at Eyjafjallajökull in Iceland indicate a high-temperature, low-viscosity lava.

Effusive eruptions

The upper mantle has an ultramafic chemistry with a very low silica percentage. The partial melting of parts of the upper mantle at divergent plate boundaries produces magma that is mafic in chemistry. As magma rises through a vent from the depths of the mantle, dissolved gases of water vapour, carbon dioxide, sulfur, chlorine and fluorine are released as pressure decreases. This makes the magma's chemical composition less reactive and of low viscosity. Large volumes of high-temperature (1000–1200°C) low silica (45–55%) lava flow steadily from the volcano, often following fire fountains that have released a low amount of dissolved gases just before the lava reaches Earth's surface. This is termed an **effusive** eruption (Figure 5.14).

INVESTIGATION 5.3

Modelling an effusive eruption

AIM

To model the formation of an effusive eruption over a hotspot

MATERIALS

- 500 mL Pyrex beaker
- Heat mat
- Bunsen burner
- Tripod
- Wire gauze
- Red candle wax
- Sand

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Beakers can break and cause injury.	Take care when handling glassware and do not leave it near the edge of the bench. If the beaker cracks, immediately turn off the Bunsen burner and inform your teacher of all breakage.
Hot wax, sand and water can burn.	Ensure you wear eye protection and handle the hot glassware with care. Allow the beaker to cool before removing it from the tripod

What other risks can you identify in this investigation? How will you manage them?

METHOD

1. Melt the candle wax and pour it into the beaker so that it forms a layer approximately 2 cm thick. Let the wax cool overnight.
2. Cover the wax with a layer of sand of approximately the same thickness.
3. Three-quarters fill the beaker with water. The wax represents mantle material that melts to become magma. Wax that sets in the cold water represents intrusive igneous rock. The sand and water represent the crust of Earth.

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4 Set up the heat mat, tripod, wire gauze and Bunsen burner.
5 Place the beaker on the wire gauze and adjust the Bunsen burner so that the heat is concentrated on one side of the beaker.
6 Observe the sand and wax as the contents of the beaker heat up.
7 Turn off the burner as soon as the eruption finishes. Notice any changes to the contents, particularly the wax.
8 Allow the beaker to cool before removing it from the tripod.

RESULTS

1 Record your observations as the wax begins to melt and as it cools.
2 Draw a labelled diagram that explains your 'eruption'.

DISCUSSION

1 Describe the way that the wax moved through the sand and water.
2 Analyse the movement in terms of the different densities of the wax, sand and water.
3 How has this model assisted you in understanding how effusive volcanoes are formed?
4 How would you change this model to improve it?

CONCLUSION

Write a conclusion evaluating this model of a volcanic eruption.

EXTENSION

You can decrease the viscosity of your wax by mixing it with vegetable oil when molten. Repeat the experiment with melted candle wax mixed with oil in a ratio of 3:1 and 2:1 for medium and low viscosity magmas. How does a lower viscosity change the result?

Volcanoes at divergent plate boundaries

iStock.com/Matt Palmer

FIGURE 5.15 The mid-Atlantic Ridge is visible on land in Thingvellir National Park, Iceland.

Effusive volcanism occurs at divergent plate boundaries, most commonly on the sea floor where two plates are moving away from each other. This tectonic movement and upwelling of magma from the asthenosphere results in sea-floor spreading, rift valleys and the formation of the mid-ocean ridge systems. Rift valleys can be up to 2 km deep and ridge systems up to 74 000 km long. Their physical characteristics are determined by the rate of plate movement. At slow (1–5 cm year^{-1}) spreading centres, the ridge is tall and narrow. Fast (10–20 cm year^{-1}) spreading results in wider rifts with more gentle slopes.

Mid-ocean ridges are usually submerged, but the unique tectonic setting in Iceland allows geologists to study this system on land. Iceland is located on the plate boundary between the North American and Eurasian Plates along the mid-Atlantic Ridge (Figure 5.15). This slow spreading centre forms a rift valley similar in size to the Grand Canyon in the USA. Iceland is also directly over a hotspot, which has contributed large amounts of lava and pushed Iceland up into a dome shape. This hotspot magma from the melting of oceanic crust is more viscous and has formed some intermediate rocks (rhyolite and diorite) that would not be found at a typical mid-ocean ridge.

Volcanoes that emerge in the depths of Earth's oceans are known as **submarine volcanoes**, upwelling approximately 75% of Earth's magma. Once the upwelling basaltic, low-viscosity magma reaches sea water, the lava cools rapidly and solidifies forming spherical-shaped structures called pillow lava (Figure 5.16). The outer layer or crust of these bulbous structures, often up to 1 metre in diameter, is made up of volcanic glass because the lava has had little time to crystallise due to the substantially cooler water surrounding it. Crystal size is larger in the centre of pillow lava where cooling is slower. Mostly made of basalt, pillow lava is typically dark grey in colour with a lower percentage of silica and a higher percentage of iron and magnesium.

In deeper waters, at pressure up to 200 times greater than at sea level, water can no longer boil around the surface of the hot magma and gases remain in solution. Deep water eruptions are always effusive because of high confining water pressure.

It is easier to observe the type of lava produced in continental divergent zones such as the East African rift that features both dormant (Mount Kilimanjaro) and active (Mount Nyiragongo and Ol Doinyo Lengai (Figure 5.17)) volcanoes. As magma rises and the continental rock splits, some magma bodies are trapped in the continental crust, melting the surrounding sedimentary rock and forming a unique volcano with carbonatite (more than 50% carbonate minerals) lava, such as at Ol Doinyo Lengai in Tanzania. Carbonatite lava is molten at only 600°C, making it the coolest lava in the world. In comparison, the temperature of a basaltic flow may reach 1200°C. Other areas of the rift erupt mafic magmas that are similar to those at mid-ocean ridge systems. The interaction of continental rock and upwelling mantle material leads to a variety of explosive and effusive volcanic eruptions at continental rift zones.

Alamy Stock Photo/Doug Perrine

FIGURE 5.16 Pillow lava erupting underwater from Kilauea volcano, Hawaii

Alamy Stock Photo/Stocktrek Images

FIGURE 5.17 Effusive eruption of Ol Doinyo Lengai, Tanzania, in July 2004. The volcano erupted explosively in 2007.

Hotspot volcanoes

Hotspot volcanoes can occur anywhere on Earth's surface. A hotspot is a large stationary magma source deep within Earth that rises as a thermal plume. Thermal plumes may originate from as deep as the core–mantle boundary. Heat rises to Earth's surface over many millions of years, producing mafic magma as the high heat and lower pressure at the base of the lithosphere allows mantle rock to melt. Large volumes of mafic magma produce new volcanoes. As the plate carrying a new volcano moves away from a hotspot, a new basaltic volcano emerges and a chain of volcanoes forms, such as the Hawaiian islands. Kilauea on the island of Hawaii is the youngest and most active of six active volcanoes in the chain. According to the US Geological Survey, eruptive activity began in 1983 and continues today, with a major eruption in 2018.

Thermal plumes and hotspot volcanoes

Learn more about thermal plumes and hotspot volcanoes with this video.

The chemistry of the erupted lava in Hawaii has changed little over time. The lava has remained very low in silica. This low silica magma erupts effusively, forming pillow lavas in the ocean and smooth lava flows on land.

Shutterstock.com/Deni_Sugandi

FIGURE 5.18 Pyroclasts exploding from Anak Krakatau in Indonesia

Explosive eruptions

Explosive eruptions occur when magma with a high silica content nears the surface. Silicate minerals form chains that trap gases and prevent gradual outgassing when lower pressure allows the gases to come out of solution. As magma rises in the conduit, the temperature decreases and the increasingly viscous magma forms a plug in the dome of the crater rather than flowing directly out. As pressure builds, the gases expand and eventually exceed the strength of the overlying plug, causing an explosive eruption (Figure 5.18). Bubbles of these gases escape, explosively fragmenting magma as pyroclasts. The greater the volume and pressure of gas, the higher the

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explosivity, particularly if the bubbles are formed lower in the conduit. The force of a large explosive eruption can be equivalent to 10 000 times the force of the Nagasaki atomic bomb.

Stratovolcanoes are often the result of explosive volcanism. They are tall, conically shaped volcanoes with steep profiles. A stratovolcano is made up of many layers of lava, pumice, tephra and ash and is flanked with cinder cones. The chemistry of the magma and exposure to lower temperatures leads to magma of significantly higher viscosity than that of effusive eruptions.

The violence of the eruption and the volume of material produced has been categorised as the volcanic explosivity index (VEI) (Table 5.2).

TABLE 5.2 The relationship between the volcanic explosivity index (VEI) and the characteristics of the eruption

VEI	VOLUME OF ERUPTED MATERIAL	PLUME HEIGHT	FREQUENCY OF ERUPTION	EXAMPLES
0	<10 000 m^3	<100 m	Persistent	Kilauea, Hawaii
1	>10 000 m^3	100–1000 m	Daily	Nyiragongo, Democratic Republic of the Congo (2002)
2	>1 000 000 m^3	1–5 km	Weekly	Ruapehu, New Zealand (1971); Mount Sinabung, Indonesia (2010)
3	>10 000,000 m^3	3–15 km	Few months	Soufriere Hills, Montserrat (1995); Nevado del Ruiz, Colombia (1985)
4	>0.1 km^3	10–25 km	≥1 year	Mount Pelee, West Indies (1902); Eyjafjallajökull, Iceland (2010)
5	>1 km^3	20–35 km	≥10 years	Mount Vesuvius, Italy (79); Mount St Helens, USA (1980)
6	>10 km^3	>30 km	≥100 years	Krakatoa, Indonesia (1883); Mount Pinatubo, Philippines (1991)
7	>100 km^3	>40 km	≥1000 years	Tambora, Indonesia (1815)
8	>1000 km^3	>50 km	≥10 000 years	Yellowstone, USA (Pleistocene)

Source: NASA

INVESTIGATION 5.4

Volcanic outgassing and explosivity

Critical and creative thinking

Asia and Australia's engagement with Asia

Volcanoes that have an open vent and constantly outgas generally have effusive eruptions, like those at Kilauea. Those with gas-rich magma and blocked vents are more likely to explode, like the volcanoes in Indonesia, Japan and the Philippines.

AIM

To observe the effect of outgassing speed on a simulated eruption

MATERIALS

- 2 unopened bottles of carbonated water
- Marking pen
- Graduated cylinder

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
The bottles may explosively release carbonated water.	Wear safety glasses. Angle bottles away from other people when opening.
Slippery floors could lead to falls.	Open the bottles outdoors, preferably in a garden, to avoid slippery laboratory floors.

RISK ASSESSMENT

What other risks can you identify in this investigation? How will you manage them?

»

METHOD

1. Copy the table in the Results section.
2. Vigorously shake the bottles of carbonated water. Note whether this changes the appearance of the water.
3. Use the marking pen to mark a line at the top level of the water in both bottles.
4. Angling the bottle away from your body and from other people, *slowly* open the cap over the course of 30 seconds if possible.
5. Record your observations of the eruption and draw a line at the top of the new water level. Label this bottle 'Slow'.
6. Angling the second bottle away from your body and from other people, *quickly* open and remove the cap.
7. Record your observations of the eruption and draw a line at the top of the new water level. Label this bottle 'Fast'.
8. Measure the amount of water lost from each bottle by filling to the top line, using a measuring cylinder. Record the volume in your results table.
9. Compare results with classmates. You may wish to calculate the average volume for fast and slow outgassing.

RESULTS

Copy and complete this table.

OUTGASSING SPEED	DESCRIPTION OF ERUPTION	VOLUME OF WATER (mL)
Slow		
Fast		

DISCUSSION

1. Compare the results of fast and slow outgassing on the characteristics of your eruption.
2. Volcanic eruptions with a high VEI are more violent and release more material. Which type of outgassing leads to a higher VEI?
3. Evaluate the validity and reliability of this experiment. How could you improve upon these?

CONCLUSION

Write a conclusion about the speed of outgassing and eruption characteristics.

Convergent (oceanic–oceanic) plate volcanic eruptions

As the subducting oceanic plate descends into the mantle, water and dissolved sedimentary material rises into the mantle. Water breaks the silicate mineral chains and causes partial melting of the mantle material, often referred to as flux melting. The partially molten mantle material is more viscous than the magma found at spreading ridges and is enriched with gas volatiles (mainly water and CO_2). The magma has to travel a much greater distance to the surface than magma at divergent boundaries. It has to move through the over-riding oceanic plate and loses heat energy as the magma rises.

When this intermediate silicate, volatile-rich magma reaches the surface, the lava produced has a high viscosity and often builds up into lava domes or spines in the mouth of the volcano. Collapse of these domes and spines leads to ash flows while explosions of gas through the domes causes ash eruptions. If sufficient magma and pressure build up, a violent pyroclastic eruption may occur. These eruptions are common in the volcanic island arcs that make up Indonesia, Japan and other locations around the Ring of Fire.

Convergent (oceanic–continental) plate volcanic eruptions

Oceanic plates subducting beneath continental plates undergo the same release of water to trigger partial melting of the mantle. Thus, the starting chemistry of the magma is very similar to that found

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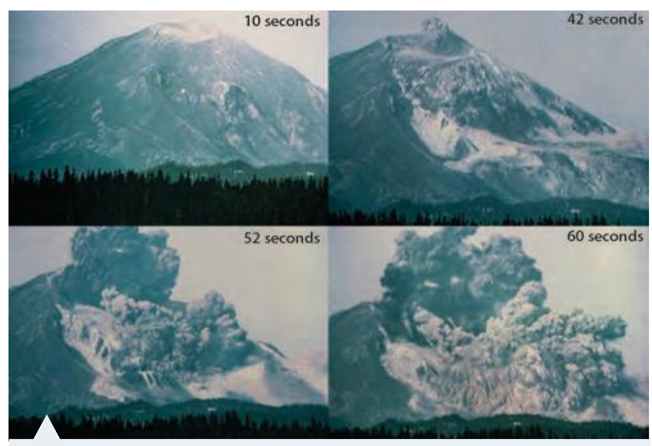
at oceanic–oceanic convergent boundaries. However, the overriding continental plate is much thicker than any oceanic plate, so magma has to travel a much greater distance up through the crust. Contact with continental rocks in the plate as the magma rises leads to a further increase in the silica content due to both crystal fractionation and assimilation, resulting in felsic lavas. Both the increase in silica content and the potential loss in heat produce extremely viscous lavas. The volcanos of the Andes often produce ash flows and explosive ash eruptions. On the rare occasions when they do erupt, lava may be rhyolitic and ash falls are extensive. When the Cerro Blanco Volcanic Complex in Argentina erupted 4200 years ago, it pushed gas and ash an estimated 32 km into the air, scattered ash over an area of 500 000 km^2 and filled valleys up to 35 km away with pyroclastic flows.

Getty Images/NASA

FIGURE 5.19 An erupting explosive volcano as seen from the International Space Station

Alamy Stock Photo/SuperStock/RGB Ventures

FIGURE 5.20 Successive ash fall layers near an explosive volcano



USGS/Gary Rosenquist

FIGURE 5.21 Time-lapse photographs of the eruption of Mount St Helens, USA, in 1980

Volcanic hazards

Ash falls and flows

When an explosive eruption occurs, the force of hot expanding gases can produce a roiling mushroom cloud of gas and ash, rising up to 50 km in extreme cases. Larger particles (0.1–10 metres in diameter) fall within 2 km of the vent, but prevailing winds can redistribute the ash particles (1–5 mm) over vast areas (Figure 5.19). Sharp and abrasive fine particles can enter the lungs and irritate the eyes of humans and animals. Ash fall may smother plant life, contaminate water, reduce visibility and accumulate on buildings, causing them to collapse. Sewer systems may become blocked and infrastructure such as machinery and communication equipment can be damaged.

Ash fall deposits often show a pattern of repeating eruptions over long periods and can build up to be very thick. Analysis of the decay of radioactive components in each erupted ash layer allows geologists to accurately date the eruptions, and the thickness of the ash layers gives some idea of the amount of material erupted (Figure 5.20).

Ash flows can have two causes – the collapse of an ascending eruption cloud or the collapse of a lava dome near the top of a volcano. In both cases, the movement of the mix of ash particles and gases behaves as a frictionless fluid and flows downhill at speeds often exceeding 160 km h^{-1} (Figure 5.21). Chemical reactions within the ash cloud can release significant amounts of heat and this helps the ash flow move downhill, even across water. The French term for these ash flows is *nuees ardentes* or 'glowing avalanches'.

The eruption of Vesuvius in 79 CE started as a series of smaller eruptions producing a wide ash fall, culminating in a massive blast that produced a large ash cloud, which collapsed down the flanks of the mountain. It was this final eruption that buried Pompeii but the ash flow also spread across the Bay of Naples, destroying a rescue fleet of ships crossing the bay to pick up survivors.

Alamy Stock Photo/Robert Wyatt

FIGURE 5.22 A lava tube at Undara, north Queensland. Note the visitors at the bottom left for scale.

The best documented ash flow was the eruption of Mount St Helens, USA, in 1980. As the main eruption started, one flank of the volcano collapsed, releasing pressure on the magma chamber beneath the volcano. The resultant eruption was directed sideways rather than vertically and devastated a large area to the north of the volcano (Figure 5.21).

Lava flows

Lava flows are the least dangerous of all volcanic hazards. In most cases, an adult human can walk faster than a lava flow. However, they can be harmful, as has been shown by the ongoing eruption of Kilauea in Hawaii.

Lava flows are generally confined to low points in the landscape because the movement of the flow is determined by the fluidity of the lava (due to temperature and chemistry), the slope of the land and the rate at which the lava loses heat. As the lava flow starts to cool and solidify on the surface, a crust forms that is an excellent heat insulator. This allows the lava beneath the crust to keep flowing while losing little heat. This combination of fluid lava and an insulating crust can allow the lava flow to travel long distances. Flows of basaltic chemistry flows easily because of their low viscosity, allowing flows to reach as far as 50 km from the eruption. The best example of this is the Undara lava tubes in north Queensland that extend for tens of kilometres (Figure 5.22). Flows rich in andesite are thicker and more viscous and can travel up to 5 km.

Lava flows can have a devastating effect on local communities as the flows advance across the landscape. Since the present eruptions at Kileaua started in 1984, whole suburbs have been consumed by the eruptions. However, on a global scale, lava flows have little effect.

Pyroclastic flows

Pyroclastic flows occur during a volcanic eruptions where explosive columns of volcanic debris, ash and hot gases (H_2O, SO_2 and CO_2) create flows of extremely high temperatures travelling at speeds as high as 200 m s^{-1}. Pyroclastic flows may also be created by collapse of a lava dome. Inside a pyroclastic flow is a ground layer of fragmented lava and rocks flowing downhill with a thick cloud of ash moving very fast above.

Pyroclastic flows destroy all that is in their path because of the high temperatures of volcanic material and hot gases (200–700°C). They are the deadliest of volcanic events and carry debris of destroyed vegetation and buildings in their wake.

Lahars

A **lahar** is a mixture of volcanic material and water that forms a mudflow. Lahars can occur when lava is in contact with water sources such as crater lakes, rivers, heavy rainfall or even a dam collapse. This may occur long after an eruption when the material around a crater lake or volcanic dam gives way. Considered the most dangerous, if not deadliest, of volcanic hazards, lahars can travel long distances at relatively high speeds (40 m s^{-1}) down a slope. They can be triggered by rainfall or seismic events. The composition of the volcanic material carried by a lahar can vary from very fine-grained sand to large boulders. In 1985, the town of Armero in Columbia was destroyed and more than 23000 people were killed by a lahar. The volcanic eruption that led to the lahar was small but the ash immediately settled on a snowfield near the summit of the Nevado del Ruiz volcano. The resulting mixture moved downslope at speeds exceeding 100 km h^{-1} and hit the town of Armero with little warning. Figure 5.23 shows a lahar flow in Ecuador.

Many volcanic deposits are acidic in nature and this can adversely affect soils and river systems for many years. The acidity is caused by **aerosols** (small solid particles or liquid droplets suspended in air) in the ash cloud that often contain chemicals such as hydrochloric and sulfuric acid. These

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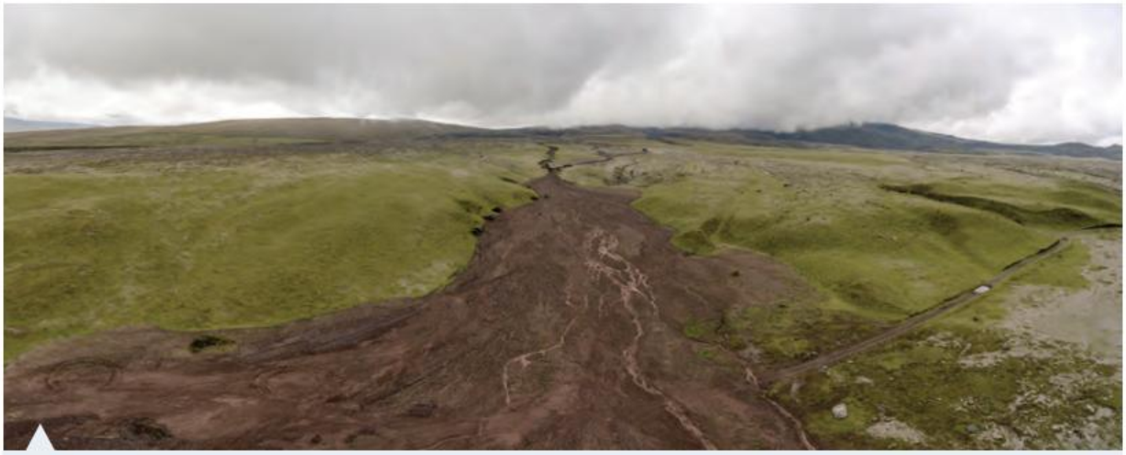
acids coat the ash particles while inside the eruption cloud and are incorporated in the ash deposits that result. Violent mixing of the ash particles with water as the mixture moves downhill renders the lahar strongly acidic.



Shutterstock.com/Dr Morley Read

FIGURE 5.23 A lahar flow on the slope of Tungurahua volcano in Ecuador

INVESTIGATION 5.5

Lahar composition

Critical and creative thinking

Numeracy

AIM

To investigate the effect of different lahar compositions upon flow

MATERIALS

- 2 L gravel
- 3 L sand
- 2 L garden soil
- 600 mL dry potters clay
- 5 × 500 mL plastic beakers
- 100 mL graduated cylinder
- Stick for stirring
- Watering can
- Hand trowel
- Bucket
- 1 metre gutter or board
- Stopwatch
- Water

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Soil may contain harmful microbes.	Wash your hands thoroughly after completing the experiment.

RISK ASSESSMENT

What other risks can you identify in this investigation? How will you manage them?

»

METHOD

1 Copy the table in the Results section.
2 Combine the gravel, sand, soil and clay in the bucket, mixing well with the hand trowel.
3 Use the trowel to place about 400 mL of the dry mixture in the bucket into each plastic beaker.
4 Press down the dry material and add or remove material until each beaker contains exactly 400 mL.
5 Add different amounts of water to each beaker to create different percentages of sediment in the lahar:
   a 80 mL water = 20%
   b 120 mL water = 30%
   c 160 mL water = 40%
   d 200 mL water = 50%
   e 240 mL water = 60%
6 Mix the sediment and water with a stick to thoroughly combine them.
7 Tilt each beaker and slowly rotate it to observe the consistency of the mixture.
8 Place one end of the gutter or board in a large pan or outdoor garden bed; prop the other end up at least 50 cm.
9 Calculate the slope of your lahar pathway.
10 Pour the 20% mixture onto the top of the board. Start the stopwatch as the mixture touches the board and stop timing when the front of the flow reaches the bottom.
11 Record the flow time and your qualitative observations in your results table.
12 Wash off the lahar by using the watering can.
13 Repeat steps 10–12 with each of the mixtures.
14 Construct a graph of percentage water versus flow time.

RESULTS

Copy and complete this table.

SLOPE OF BOARD =		
PERCENTAGE WATER	FLOW TIME (s)	QUALITATIVE OBSERVATIONS
20		
30		
40		
50		
60		

DISCUSSION

1 From your results, state the general relationship between the water content of a lahar and its flow speed.
2 What qualitative trends did you notice?
3 Washing the board with the watering can mimics a heavy rain after a lahar event. Describe the effect on lahar material that remains on the slope.
4 Analyse the validity and reliability of this experiment. How could you improve it?
5 Predict how your results would change if you altered the angle of the board.
6 Relate your results to lahar risk and formation on a named volcano.

CONCLUSION

Compose a suitable conclusion about lahar composition and speed.

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» EXTENSION

1. Explore the effect of increasing slope on flow rate. Is the relationship linear?
2. Alter the relative composition of the dry mixture and explore the effect this has on flow.
3. Create a simulated volcano outdoors with a pile of soil. Add appropriate contours for valleys. Observe the pathways of flow.
   a. Line one valley with newspaper to represent an engineered lahar channel.
   b. Place paper houses at different locations on the volcano to determine the areas of greatest danger.

Poisonous gas emissions

There is a varied mix of gases in any volcanic eruption. Water vapour and carbon dioxide make up a large component of the gases. However, there can be a wide range of other gases. Sulfur dioxide can combine with water in the eruption cloud or the atmosphere and chemically react with oxygen in the atmosphere to form sulfuric acid. Hydrogen sulfide, colloquially known as rotten egg gas, is a common component of volcanic gases. If you can smell it, it is at toxic levels to humans. Continued exposure in the short term can kill. Hydrogen chloride and hydrogen bromide emitted from volcanoes both form hydrochloric and hydrobromic acids in varying amounts depending on the volcano. However, hazardous concentrations of these gases only occur within a 1–2 km radius from the volcano and so they pose little threat to human life. Gases do not have to come from an eruption at the surface but can leak into water systems from magma deep underground.

INVESTIGATION 5.6

Lake Nyos disaster

Critical and creative thinking

Information and communication technology capability

Access the Internet and research what occurred in Lake Nyos in Cameroon in 1986. Outline how the disaster occurred, including the trigger for the gas release.

1. Explain why people and animals who were sleeping on or close to the ground were killed.
2. Why were plants unaffected by the gas cloud?
3. What is the likelihood of this type of disaster occurring again at Lake Nyos?
4. What steps have been put in place to reduce the chance of this type of disaster occurring again?

KEY CONCEPTS

- Divergent plate boundaries are characterised by effusive eruptions with mafic magma.
- Convergent plate boundaries where the oceanic lithosphere is being subducted are characterised by explosive volcanic eruptions due to silicate magma containing high gas levels.
- Ash falls may be spread by prevailing winds and affect large areas.
- Lava flows are locally destructive but rarely pose a danger to human lives.
- Lahars are the most dangerous volcanic hazard and may occur long after an eruption.
- Volcanic gases may be toxic and acidic, depending upon their composition.

CHECK YOUR UNDERSTANDING 5.3

1 Describe the difference between an effusive eruption and an explosive eruption.
2 What is the volcanic explosivity index and what can it be used for?
3 What is the usual depth range of earthquakes at divergent plate boundaries?
4 What is the usual depth range of earthquakes at convergent plate boundaries?
5 Outline the difference between ash fall and ash flow.
6 What features can combine to allow a fluid lava flow to travel many kilometres from where it was erupted?
7 Describe how a lahar can form.
8 List the gases that are commonly found in the eruption cloud of a volcano.

5.4 When a geological hazard becomes a disaster

You will learn more about preventing disasters in Chapter 7.

A 'hazard' can be defined as a risk, a chance or a probability of something happening. When it pertains to geological hazards globally, both seismic and volcanic activity pose potential risks of disaster.

For a hazard to become a disaster, the geological event, such as an earthquake or volcano, must affect humans and exceed the ability of society to cope with this hazard. The Kamchatka region of eastern Siberia has the highest concentration of volcanoes on Earth yet there are few disasters when they erupt because the human population in the region is low and spread out. The most important factors are population density and the built environment of a disaster zone. Effective governments implement risk management frameworks to help people identify geological hazards. Decision-makers can ensure that management plans (e.g. strict building codes for design and materials) are adhered to and put in place, thus minimising damage and saving lives when a hazard occurs.

In Australia, there are no active volcanoes on the mainland. Figure 5.24 shows the volcano crater lake at Tower Hill Reserve in Victoria – it is the site of a volcanic eruption more than 30 000 years ago.

However, earthquakes are common. It is estimated that there are more than 100 earthquakes each year with a magnitude above 3, which is the lower limit that humans can sense. However, there are many more below that magnitude across large areas of the country. Australia does experience larger earthquakes (Table 5.3).

Shutterstock.com/Stephane Debove

FIGURE 5.24 This lake at Tower Hill Reserve in Victoria is the site of a volcanic eruption more than 30 000 years ago

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TABLE 5.3 Earthquakes with a magnitude above 6.0 since 1940

MAGNITUDE	LOCATION	YEAR
6.6	Broome, WA	2019
6.6	Tennant Creek, NT	1988
6.5	Meckering, WA	1968
6.4	Simpson Desert, NT	1941
6.3	Tennant Creek, NT	1988
6.3	Meeberrie, WA	1941
6.2	Collier Bay, WA	1997
6.2	Tennant Creek, NT	1988
6.1	Cadoux, WA	1979
6.1	Petermann Ranges, NT	2016
6.0	West of Lake Mackay, WA	1970

The 1989 Newcastle earthquake had a magnitude of 5.6 and it is recorded as having the highest death toll (13) of any Australian earthquake. This earthquake falls into the category of a disaster because there were deaths and extensive damage to buildings and infrastructure over a wide area around Newcastle. It is often the damage to human structures and infrastructure that leads to an earthquake being classified as a disaster.

Earthquakes are not the only geological hazards to be monitored in this country. The north and east coasts of Australia sit near plate boundaries at Indonesia and New Zealand, respectively. Any major movement of the ocean floor, as happened in 2004, could lead to a tsunami risk for the north coast. A major volcanic eruption on the west coast of New Zealand could lead to a tsunami on the east coast of Australia. With most of Australia's population living near the coast, a large tsunami is likely to cause a disaster.

KEY CONCEPTS

- A geological hazard needs to cause significant damage to buildings and infrastructure before it is classified as a disaster.
- Effective government response may keep hazards from becoming disasters.

CHECK YOUR UNDERSTANDING 5.4

1 Outline factors that would make a geological hazard a disaster.
2 The Newcastle earthquake in 1989 caused the only recorded fatalities due to an earthquake in Australia. In 1968, an earthquake of similar magnitude severely damaged the town of Robertson in the southern highlands. Explain why one of these earthquakes is classified as a disaster and the other is not.
3 List the geological hazards that need to be monitored in Australia.

5 CHAPTER SUMMARY

- Earthquakes and volcanic activity occur mainly at plate boundaries.
- Relative plate movement stores energy that is released as earthquakes.
- Volcanoes may occur at rifting zones, subduction zones or hotspots.
- All types of plate boundary may have shallow-focus earthquakes.
- Subduction zone earthquakes may occur as deep as 670 km.
- Earthquake foci are mainly on the overriding plate at a subduction zone.
- Most earthquakes occur at convergent boundaries, especially around the Pacific Ocean.
- The main causes of damage during earthquakes are ground motion, landslide and ground liquefaction.
- Ground liquefaction only occurs in waterlogged soils.
- Tsunamis can be caused by ocean floor earthquakes, asteroid strikes, volcanic island eruptions or underwater sediments slides.
- Divergent plate boundaries are characterised by effusive eruptions with mafic magma.
- Convergent plate boundaries where oceanic lithosphere is being subducted are characterised by explosive volcanic eruptions due to silicate magma containing high gas levels.
- Ash falls may be spread by prevailing winds and affect large areas.
- Lava flows are locally destructive but rarely pose a danger to human lives.
- Lahars are the most dangerous volcanic hazard and may occur long after an eruption.
- Volcanic gases may be toxic and acidic, depending upon their composition.
- A geological hazard needs to cause significant damage to buildings and infrastructure before it is classified as a disaster.
- Effective government response may keep hazards from becoming disasters.

5 CHAPTER REVIEW QUESTIONS

Review quiz

1. Why are earthquakes at divergent plate boundaries generally very shallow and have a small magnitude?
2. Explain how the varying depth of earthquakes at ocean–ocean and ocean–continent convergent zones relates to the Benioff–Wadati zone.
3. Describe the relationship between the type of eruption, effusive or explosive, and the location of a volcano at different types of plate boundary.
4. Explain how the viscosity of the magma at spreading zones leads to the features observed in volcanic eruptions at this type of plate boundary.
5. Contrast the chemistry and temperature of magmas generated at spreading plate boundaries and subduction plate boundaries.
6. How does magma chemistry and temperature alter the type of eruption, effusive or explosive, of a volcano?
7. Ground liquefaction is a problem in any region where there is a risk of earthquakes occurring. Water-logged ground is the most susceptible. Choose a major Australian coastal city such as Brisbane, Sydney, Melbourne or Perth and assess the likelihood of ground liquefaction causing building damage. Outline what conditions need to be satisfied for the liquefaction to occur.
8. Explain why Darwin would be more likely to suffer tsunami damage than Melbourne.
9. Generally, weather systems in Australia move from west to east across the southern half of the country. If an explosive volcano was to erupt near the Western Australian–South Australian border, predict the extent of ash fall damage that might occur in Adelaide.
10. The current eruption phase of Kilauea in Hawaii began in 1984. Apart from the major increase in the release of lava in 2018, this eruption phase has continued at a fairly slow pace. Analyse the factors that lead to slow effusive eruption at Kilauea.
11. Ruapehu in New Zealand is an active explosive volcano. It has a history of small ash eruptions every few years. The mountain is also a popular ski resort. Describe the conditions required for the generation of a lahar on the slopes of the mountain.
12. Mount Agung in Bali erupted during 2018, leading to the cancellation of flights to and from the island for 3 days.

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In 2010, an Icelandic volcano erupted and effectively halted most air travel in western and northern Europe for nearly a week. Aside from halting air traffic, describe the other possible consequences of volcanic ash.

13 If the Yellowstone super-volcano had a major eruption in the near future, analyse the effects of the eruption on agriculture, transport and human health. Note that the last time Yellowstone erupted, more than 75% of the continental USA was affected by ash fall.

14 Go to the Geoscience Australia website and find the current Australian earthquake hazard map.

a Identify which three Australian capital cities have the highest earthquake risk.

b Evaluate the potential for a capital city earthquake to become a disaster in Australia.

6 The impact of natural disasters

OUTCOMES

In this chapter you will learn about:

- comparing the eruptions that occur at explosive and effusive volcanoes and the effects that they may have on both the biosphere and the atmosphere ICT L N
- the effects of a major eruption on the atmosphere with respect to changing the climate of Earth in terms of heating or cooling CCT ICT
- the effects of the 1991 eruption at Mount Pinatubo in the Philippines on both the biosphere and the atmosphere AAEA IU ICT L
- the causes and the physical impact of hailstorms, east coast lows, droughts, floods and bushfires on a local ecosystem CCT ICT IU L N
- how human activities can contribute to the frequency and magnitude of droughts, floods, bushfires and landslides. AAEA ICT IU

iStock.com/John Carnemolla

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In July 2019, a huge ash cloud spewed out of Tangkuban Perahu on the island of Java in Indonesia. Ash from the blast extended more than 1–2 km and diverted aircraft from the area. Kilauea, on the island of Hawaii, is the world's most active volcanic mass. It has been releasing lava and gases since its most recent eruption began in 1984. Lava from the volcano is slowly creeping into neighbourhoods in the surrounding area. In March 2019, hailstones the size of golf balls lashed suburban Sydney, causing flight cancellations at Sydney airport and a swathe of damage estimated to cost around $633 million across the western to northern suburbs (Figure 6.1). Natural disasters and extreme weather events occur every day somewhere in the world. A **natural disaster** is an extreme event that is caused by environmental factors (such as weather, earthquakes and volcanoes) and leads to large loss of life and extensive property damage. In this chapter, you will investigate these phenomena and how they influence the biosphere and atmosphere, and how human activity is contributing to their frequency and magnitude.


AAP Photo/Mick Tsikas

FIGURE 6.1 Hailstone damage to a car after the 2019 hailstorm in Sydney

6.1 Volcanic eruptions

A volcanic eruption occurs when lava in the magma chamber of a volcano, along with gases such as sulfur dioxide, are discharged through a volcanic vent. There are usually about 20 volcanic eruptions occurring somewhere in the world at any one time. There are two types of volcanic eruption: explosive and effusive (Chapter 5). The style of eruption depends on several factors in relation to the magma: chemistry and content, viscosity, temperature, volume, how much water and gas it contains, and how the volcano is constructed (Figure 6.2).

Global volcanism program
Learn about current volcanic eruptions. Click on the name of a volcano to get the latest information.

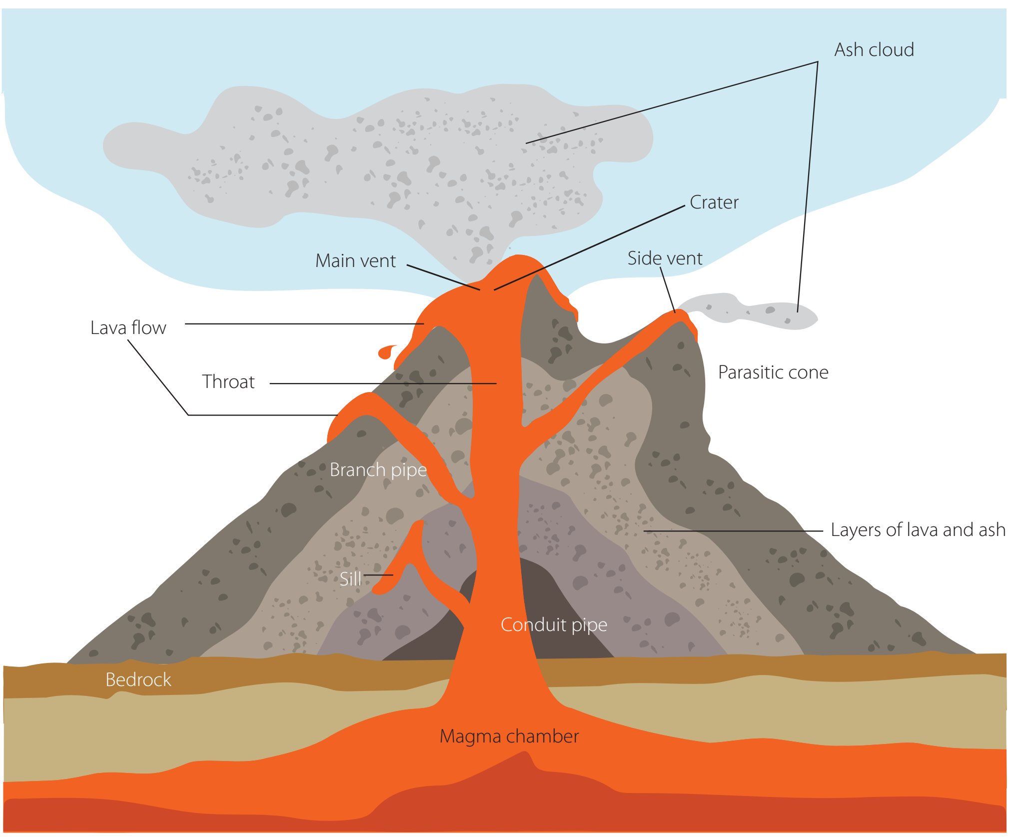

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FIGURE 6.2 Anatomy of a volcano

Explosive volcanic eruptions

Explosive volcanic eruptions discharge rock materials from the vent. They are classified according to their volcanic explosivity index (VEI). The VEI measures the volume of the erupted **pyroclastic** material called **tephra** (Table 6.1). Pyroclastic material includes ash, tephra, pyroclastic flows and other types of ejected material. New magma injected into the magma chamber can lead to marked differences in the style of the eruption over time.

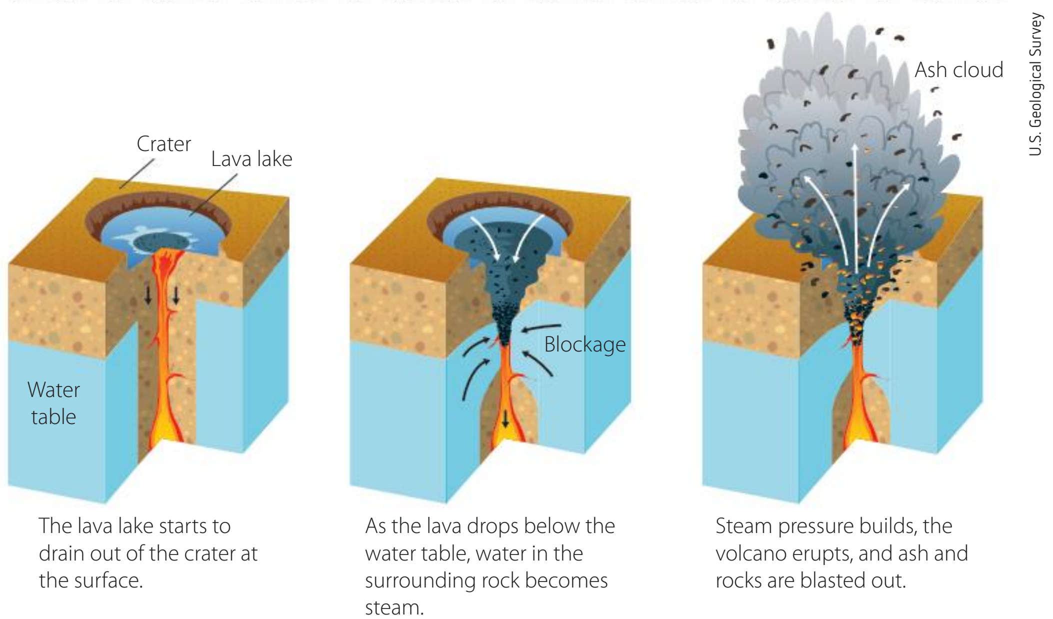
TABLE 6.1 The relationship between volcanic explosivity index (VEI) and the plume height of the eruption

VEI	VOLUME OF ERUPTED MATERIAL	PLUME HEIGHT
0	<10 000 m^3	<100 m
1	>10 000 m^3	100–1000 m
2	>1 000 000 m^3	1–5 km
3	>10 000 000 m^3	3–15 km
4	>0.1 km^3	10–25 km
5	>1 km^3	20–35 km
6	>10 km^3	>30 km
7	>100 km^3	>40 km
8	>1000 km^3	>50 km

Source: NASA

The shield volcano Kilauea, on Hawaii, has been oozing lava since 1983, but it erupted explosively in May 2018. Kilauea's summit had drained into the ground and interacted with the water table, causing a steam-powered explosion (Figure 6.3). When magma heats the surface or ground water, the resulting explosion is known as a **phreatic** eruption. The explosion sent large boulders, some weighing close to 500 kilograms, and an ash plume over 9000 metres into the atmosphere. The ash plume travelled up to 50 km north east from the volcano and caused ash to rain onto nearby communities. The ash posed the greatest threat to living things, making it difficult to breathe and covering plant life, blocking access to sunlight and their ability to photosynthesise. As the ash mixed with rain it created a thick dark paste that covered everything and fouled water supplies. The volcano's **caldera**, the depression in the centre of the volcano, dropped more than 1 metre, causing earthquakes in nearby areas.

FIGURE 6.3 How a steam-powered explosive eruption can occur



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Impact on biosphere

Volcanic eruptions have effects on the **biosphere**. For eruptions involving magma flows, there are usually warning signs, which provide time to evacuate of humans and livestock. However, phreatic eruptions can occur without warning (Figure 6.4). More than 30 hikers were killed by falling rocks and ash in 2014 when Mount Ontake in Japan erupted.

Mount Lamington in Papua New Guinea violently erupted in January 1951. The northern side of the mountain was blown away and pyroclastic flows gushed forth, setting fire to everything in their path. Damage extended over a radius of 12 km. Most of the 3000 human deaths were caused by the pyroclastic flows, and dust and ash eruptions. More than 5000 people lost their homes.

Alamy Stock Photo / Lucy Brown (loca4motion)

FIGURE 6.4 Pyroclastic flow of hot gas and debris erupting from a volcano

Gases escaping from pyroclastic flows, lahars, lava flows and burning vegetation can contain water vapour, sulfur dioxide, carbon dioxide, carbon monoxide, hydrogen sulfide, hydrogen fluoride and hydrochloric acid, among others. As ash falls to the ground, it can acidify streams and water supplies. In 1912, when Mount Katmai in Alaska erupted, clothes on clotheslines up to 2000 km away were affected by acid rain. Carbon dioxide and carbon monoxide can accumulate in low-lying areas and asphyxiate livestock and other animals.

Ash from the Cordón Caulle volcano in Chile in 2011 killed livestock, and others succumbed to ash-related blindness, tooth abrasion and digestive problems. In 2008, the Kasatochi Island volcano stopped birds from reproducing because their nesting grounds were covered in metres of ash. In 1980, the eruption of the stratovolcano Mount St Helens, USA, killed 57 people and most of the surrounding wildlife, although some species did eventually repopulate the area. Six hundred square kilometres of forest was destroyed.

Volcanic ash can ground airline flights. This happened in 2010 when Eyjafjallajökull in Iceland erupted. Ash can damage aircraft engines, and Instrument Flight Rules (regulations that govern civil and commercial aircraft operations) dictated an extended airline shutdown. This has economic effects.

The breakdown of volcanic material often produces soils that are rich in nutrients such as phosphates, nitrates, potassium and calcium. Farmers at the foot of Mount Nyiragongo in eastern Congo are slowly returning their flattened fields to productive farms after the eruption in 2002. Some farmers are finding that the amount of harvested material has doubled since the eruption. Researchers at the Goma Volcano Observatory say that '… the chemical make-up of volcanic soil makes for lucrative farming conditions'. This is the reason that communities live and flourish in areas around and on the sides of active volcanoes, despite the obvious risks.

Inside Nyiragongo

Look inside Nyiragongo and explore the structure of this volcano.

Impact on atmosphere

Any eruption of VEI ≥ 4 can penetrate through the atmosphere's lower layer, the **troposphere**, while eruptions with VEI = 8 can not only pass through the troposphere but all of the way through the **stratosphere**. The stratosphere extends from approximately 12 km above Earth's surface to a maximum height of 50 km. Within this layer is a region of the atmosphere known as the **ozone layer**, which extends from approximately 15 to 35 km above Earth's surface. The ozone layer contains a large amount of ozone (O_3) and can be adversely affected by explosive volcanic eruptions because the gases in the explosive **plume** may contain chemicals that can break down ozone, such as compounds of chlorine and fluorine, which are common in volcanic eruptions. The ozone layer absorbs ultraviolet radiation from the Sun, thereby protecting living things from its harmful effects.

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U.S. Geological Survey

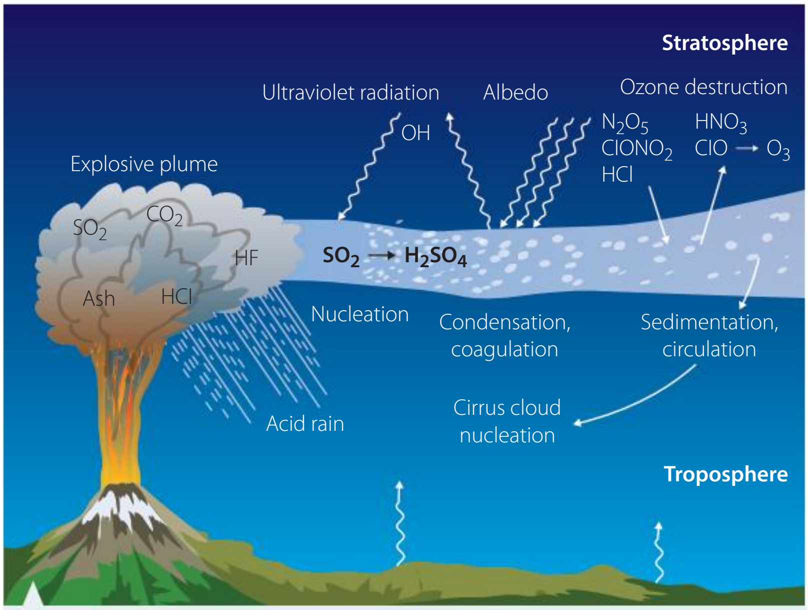

FIGURE 6.5 Volcanic gases react with the atmosphere in a number of ways.

The solid particles, or ash, in the eruption cloud are spread according to particle size and the prevailing winds. Typically, wind speeds in the stratosphere are much higher than those in the troposphere, often exceeding 400 $km\,h^{-1}$. Fine ash particles in the stratosphere can spread long distances from the erupting volcano and can produce red sunrise and sunset effects over large regions. Ash particles can also act as **nucleation points** where water vapour condenses to form droplets in clouds in the troposphere (Figure 6.5). This leads to higher rainfall after an eruption of this kind. Ash particles also reflect incoming solar radiation, leading to some local and possibly global cooling (page 139).

The most common gases that are released in an eruption are H_2O, CO_2, H_2S (hydrogen sulfide), HCl (hydrogen chloride), HF (hydrogen fluoride), SO_2 (sulfur dioxide) and CO (carbon monoxide). Any large explosive eruption column can easily ascend to the level of the ozone layer and be dispersed by winds at that altitude. HCl and HF can both actively destroy ozone, and eruption columns that contain high proportions of these gases affect the ozone levels in the region surrounding the eruption plume.

All of the gases mentioned so far, except CO, can produce acids when mixed with atmospheric water to form acid rain. Therefore, rain clouds near volcanic eruptions are often highly acidic. Within an eruption plume, SO_2 can produce the biggest change in the atmosphere. This gas can mix with water to form sulfurous acid and this then reacts with oxygen in the atmosphere to produce sulfuric acid droplets (H_2SO_4) according to the equations:

$$SO_2(g) + H_2O(l) \rightarrow H_2SO_3(l)$$

$$2H_2SO_3(l) + O_2(g) \rightarrow 2H_2SO_4(l)$$

In the stratosphere, ambient temperatures are well below 0°C and so the sulfuric acid droplets freeze and are known as **sulfate aerosols**. These aerosols can be dispersed globally by the winds in the stratosphere, where they form a highly reflective cloud that can lead to global cooling.

Eruptions occur in specific places on Earth, but their effects can be wildly distributed. Eruptions in the tropics can affect both hemispheres, whereas eruptions at mid or high latitudes only have an impact in the hemisphere in which the eruption occurred.

Effusive volcanic eruptions

Effusive volcanic eruptions occur when basalt magmas melt at 1200°C and reach the surface. Gases escape as the magma erupts and forms a lava flow down the sides of the volcano. Puʻu ʻŌʻō cone at Kilauea in Hawaii is the largest known effusive eruption (Figures 6.6 and 6.7). It lasted 35 years and ended with an explosive eruption in 2018. As the lava cools from an effusive eruption, it forms basalt such as the Columbia Plateau of eastern Washington state, USA.

Effusive volcanic eruptions are classified according to three indicators, which are the:

- area covered by the lava
- erupted volume
- duration of the eruption.

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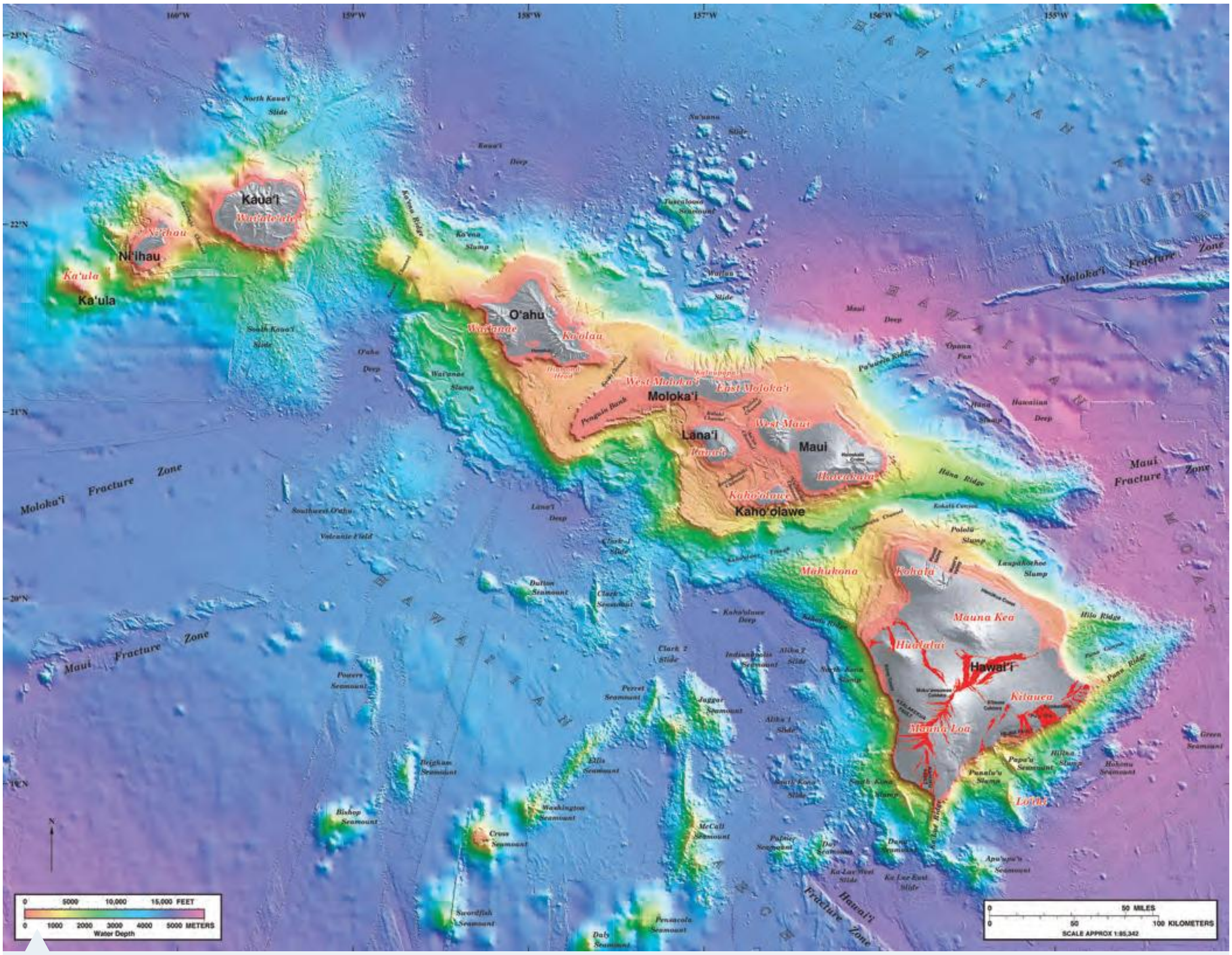

FIGURE 6.6 Hawaiian Islands

Alamy Stock Photo/JMST/Univ Hawaii/USGS/Phil Degginger/Color-Pic

It is not always easy to determine when an effusive eruption stops because the lava flow may pause for long periods.

FIGURE 6.7 Lava flow from Kilauea volcano in Hawaii

Alamy Stock Photo/Doug Perrine

Impact on biosphere

The best recorded effusive eruption and its effects on the biosphere is the 1783 Laki eruption in Iceland. The Laki fissures are part of the Grimsvötn volcanic system of southern Iceland and they produced more than 14 km^3 of basalt over an 8-month eruption. This is roughly 30 times the volume of erupted basalt that has come from Kilauea since the current eruptive phase began in 1983. The gases released produced acid rain, and the high fluorine content of the gases killed much of the island's livestock. An estimated 20% of the human population on the island died of starvation in the following year. In both Europe and North America, the following summer was unusually cool, and for a few years after that there were reduced plant growth and shorter growing seasons.

Impact on atmosphere

You learnt about the end-Permian mass extinction in Chapter 4.

Most effusive eruptions have a magma source in the mantle that is largely **anhydrous**. Levels of CO_2 in the mantle away from subduction zones can vary widely. There is a lot of debate among geological researchers as to what the source material of large-scale effusive eruptions might be. Regardless of the source material, CO_2 is a common component in erupted lava. While effusive eruptions rarely produce enough force to penetrate high into the atmosphere, the gases that are released can affect the global atmosphere by altering the gas mix.

One feature of the end-Permian mass extinction is marked global temperature variations with global cooling followed by a large temperature rise. The cooling has often been linked to the assembly of the supercontinent Pangaea but may have been intensified by a large release of SO_2 during the Siberian eruptions. It has been estimated that some explosive eruptions were possibly due to the lava encountering water. It has been estimated that the gases released by the Siberian trap effusive eruptions amounted to around 85 trillion tonnes of CO_2, 4.4 trillion tonnes of CO, 7 trillion tonnes of H_2S and 68 trillion tonnes of SO_2. The erupting lava also passed through extensive coal layers and limestone beds, setting the coal alight and causing the limestone to release large volumes of CO_2 into the atmosphere. All of this led to an intense greenhouse effect that rapidly heated the planet.

INVESTIGATION 6.1

Information and communication technology capability

Literacy

Numeracy

Comparing the impact of explosive and effusive volcanic eruptions

AIM

To use data from secondary sources to compare explosive and effusive volcanic eruptions and their impact on the biosphere and atmosphere

METHOD

Go to the weblink *Global Volcanism Program*. Click on Reports and go to Current Eruptions. Choose two volcanoes from the list of currently erupting volcanoes, making sure you have chosen one explosive volcano and one effusive volcano. (You may need to undertake some further research to confirm this.) Choose your volcanoes carefully, making sure they have enough eruptive, deformation and emission history for you to work with. You may need to go to other websites to locate these data if you cannot find it here. Hint: make sure you look at the Latest Activity Report and Weekly Report tabs.

Global Volcanism Program
Learn about currently erupting volcanoes.

RESULTS

For each of your chosen volcanoes, locate the following information:

- Name of the volcano
- Country of the volcano
- Primary volcano type
- Whether it is effusive or eruptive
- When the last known eruption was
- Description of the volcano, including elevation, rock types, tectonic setting and geological summary
- The impact the volcano had on the biosphere
- The impact the volcano had on the atmosphere. Check the SO_2 levels for the dates of the volcano by going to the weblink *Latest SO_2 eruption alerts*.

Latest SO_2 eruption alerts
Learn about how global SO_2 levels are monitored.

ANALYSIS OF RESULTS

1 Compare the impacts on the biosphere and atmosphere of your two chosen volcanoes.
2 Which had the greatest impact? Provide evidence for your answer.

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KEY CONCEPTS

- A volcanic eruption occurs when lava in the magma chamber of the volcano, along with gases such as sulfur dioxide, is discharged through the volcanic vent.
- There are two types of volcanic eruption: explosive and effusive.
- Volcanoes are classified according to their volcanic explosivity index (VEI).
- Magma flows, gases, falling rocks and ash, lahars and pyroclastic flows have an impact on the biosphere.
- Gases and ash entering the troposphere and atmosphere have an impact on the atmosphere.
- Sulfur dioxide reacts with water in the atmosphere to form sulfuric acid droplets, which freeze. These are known as sulfate aerosols.

CHECK YOUR UNDERSTANDING 6.1

1 Define 'natural disaster' and give an example.
2 Describe a volcanic eruption.
3 List the gases that are discharged during a volcanic eruption.
4 Describe how sulfate aerosols are formed.
5 Differentiate between the two types of volcanic eruptions.
6 What scale is used to classify explosive volcanic eruptions? How does this scale work?
7 Compare an explosive volcano of VEI 4 with one of VEI 8 in terms of its effect on the atmosphere.
8 Create a table to compare and contrast the effects that an explosive and an effusive volcanic eruption have on the biosphere.

6.2 Impact of volcanic activity on climate

In 1784, when US scientist Benjamin Franklin was stationed in Paris as a diplomatic representative, he unwittingly made an observation that connected volcanoes and global cooling. He noted that it was an abnormally cold year. In 1783, the Laki fissure system in Iceland erupted, spewing 14 km^3 of basaltic lava and an ash cloud that reached into the stratosphere. This cloud dimmed the Sun across Europe, leading to a period of global cooling.

Global cooling

Explosive volcanic eruptions eject large amounts of water vapour, ash and sulfur dioxide into the lower stratosphere. If the SO_2 mixes with water vapour, it forms a solution of sulfuric acid, which contributes to the acid rain around most volcanic eruption locations. An eruption with a VEI ≥ 5 and a high proportion of SO_2 in the eruption cloud has a completely different effect on the climate. The sulfuric acid droplets freeze in the upper troposphere or lower stratosphere and produce a sulfate aerosol that is highly reflective of incoming solar radiation (Figure 6.8, page 140).

It was first thought that ash fell from the sky soon after the eruption, but it is now known that ash can remain for a longer period of time. The ash particles are more prevalent in the lower layer of the volcanic cloud, whereas the sulfate aerosols remain at higher altitudes. Both types of particles play a role in reflecting solar radiation (**albedo**) long after the volcanic eruption has finished.

In the upper troposphere and lower stratosphere, water droplets freeze and form thin cirrus clouds that are highly reflective of incoming solar radiation.

Any change in the amount of solar radiation that reaches Earth's surface, either by being reflected into space or reflected back towards the surface, is called **radiative forcing**. The amount of radiative forcing can change global climate in both the medium and long term. Radiative forcing is the difference between the

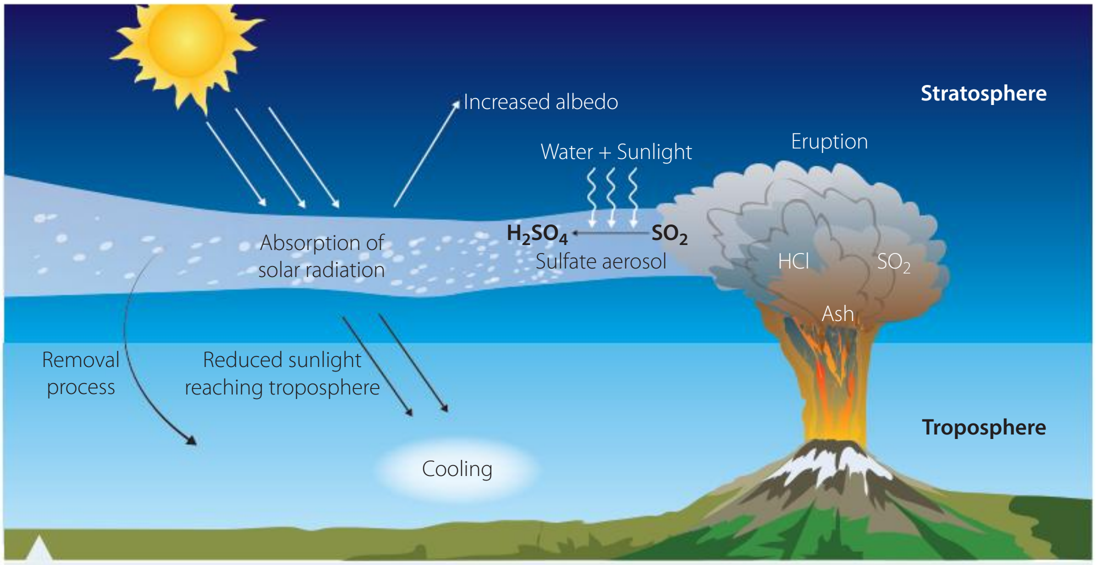

FIGURE 6.8 Sulfate aerosols in the stratosphere can increase radiative forcing, leading to global cooling.

amount of energy from the Sun radiating to Earth minus the amount radiated back into space. If the amount is positive, then some energy is absorbed by Earth. If the amount is negative, then Earth is cooling.

In 1815, the Mount Tambora eruption in Indonesia produced a marked global cooling that led to the years of 1815 and 1816 being known as 'the year without a summer' in North America. Hemispheric cooling of about 0.6°C occurred for about one decade.

Global warming

A volcanic eruption releases potent **greenhouse gases** such as water vapour, carbon dioxide (CO_2) and carbon monoxide (CO). Over time, CO oxidises in the atmosphere to become CO_2. Greenhouse gases absorb incoming **infrared radiation**, which we feel as heat, from the Sun. They trap this heat in the atmosphere. When a greenhouse gas molecule absorbs infrared radiation, atoms in the molecules vibrate more strongly. When a molecule collides with another molecule in the atmosphere, it transfers energy to the second molecule, thereby raising the temperature of the gas. The vibrating greenhouse gases also reradiate the infrared radiation. This radiation may be intercepted by other greenhouse gases, escape towards space or be radiated back towards Earth's surface. The net effect of the interaction between greenhouse gases and infrared radiation is a 5–6% transfer of incoming solar energy to the lower atmosphere.

Water vapour absorbs incoming solar radiation. Its presence in the lower atmosphere can lead to warming of the lower and middle layers of the troposphere.

The volume of CO_2 and how well it gets distributed into the atmosphere determine what heating effect the gas will have. Volcanoes are a major emitter of CO_2 and can change the climate in a significant way. If the gas can be injected into the stratosphere, it is more likely to be distributed around the globe than if it is injected into the middle to lower troposphere, where it mixes with rain to form carbonic acid (H_2CO_3) and is removed from the atmosphere when it falls in rain.

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INVESTIGATION 6.2

Analysing the effects of a major volcanic eruption on the atmosphere

Critical and creative thinking

Information and communication technology capability

Sustained periods of global cooling are often recorded in tree ring records. The width of a tree ring and its colour can tell a story of Earth's past climatic conditions in that region (Figure 6.9).

FIGURE 6.9 Trees grow faster in warmer years and slower in colder years. Each tree ring represents one year of growth.

METHOD

1 Synthesise and analyse the data in Figure 6.10 and Table 6.2 to provide an evidence-based argument of no more than 300 words that major volcanic events have a significant effect on climate.

2 To ensure that you have the data that cover all the volcanoes listed in Table 6.2, you need to search the Internet for climate data beyond 1980. Record the URL(s) of the site(s) and the date(s) and time(s) accessed. How can you ensure that these data are reliable?

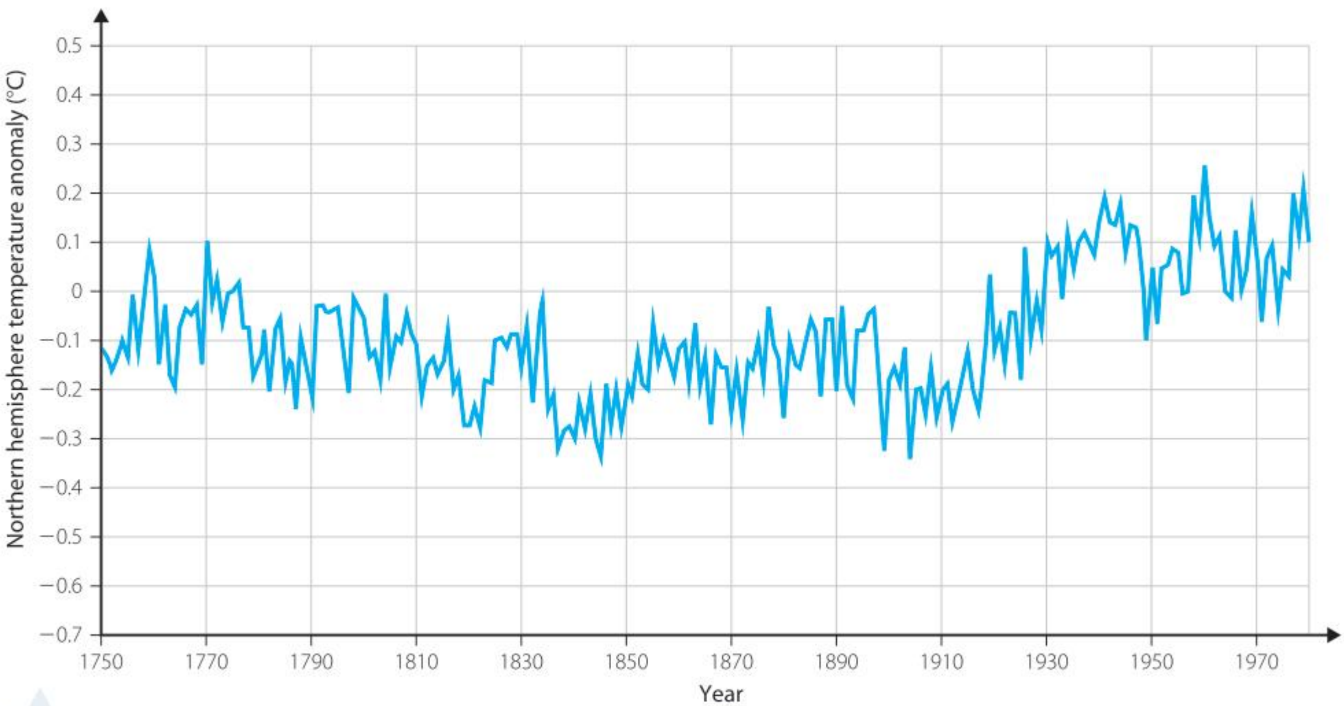

FIGURE 6.10 Northern hemisphere surface air temperatures constructed from tree-ring data

TABLE 6.2 Selected large volcanic eruptions and their climate effects since 1783

VOLCANIC ERUPTION	HIGH SO_2	VEI	DUST VEIL INDEX	GLOBAL HEATING OR COOLING (°C)
Laki, Iceland, 1783	Yes	4	2300	–4.8
Tambora, Indonesia, 1815	Yes	7	3000	–0.6
Cosiguina, Nicaragua, 1835	Yes	5	4000	–0.75
Askja, Iceland, 1875	No	5	1000	No change
Krakatau, Indonesia, 1883	Yes	6	1000	–0.3
Tarawera, New Zealand, 1886	No	5	800	No change
Santa Maria, Guatemala, 1902	No	6	600	No change
Ksudach, Russia, 1907	No	5	500	No change
Katmai, Alaska, 1912	No	6	500	No change
Mount Agung, Indonesia,1963	Yes	4	800	–0.3
Mount St Helens, USA, 1980	Yes	5	500	No change
El Chichon, Mexico, 1982	Yes	5	800	–0.2
Mount Pinatubo, Philippines,1991	Yes	6	1000	–0.5

Source: Alan Robock, Rutgers University, New Jersey, USA

KEY CONCEPTS

- Volcanic ash remains in the lower stratosphere for a significant length of time and reflects solar radiation. Sulfate aerosols remain in the upper stratosphere and reflect solar radiation. This leads to global cooling.
- Any change in the amount of solar radiation that reaches Earth's surface is called radiative forcing.
- Sustained periods of global cooling are often recorded in tree ring records.
- Volcanic eruptions release potent greenhouse gases, such as CO_2 and water vapour, which absorb infrared radiation and lead to global warming.

CHECK YOUR UNDERSTANDING 6.2

1 Complete the following table.

PARTICLE EJECTED FROM A VOLCANO	HOW PARTICLE CONTRIBUTES TO GLOBAL COOLING OR WARMING
SO_2	
H_2O	
Ash	

2 Explain what is meant by radiative forcing, albedo and greenhouse gas.

3 List the greenhouse gases that are ejected during a volcanic eruption.

4 Explain how greenhouse gases contribute to global warming.

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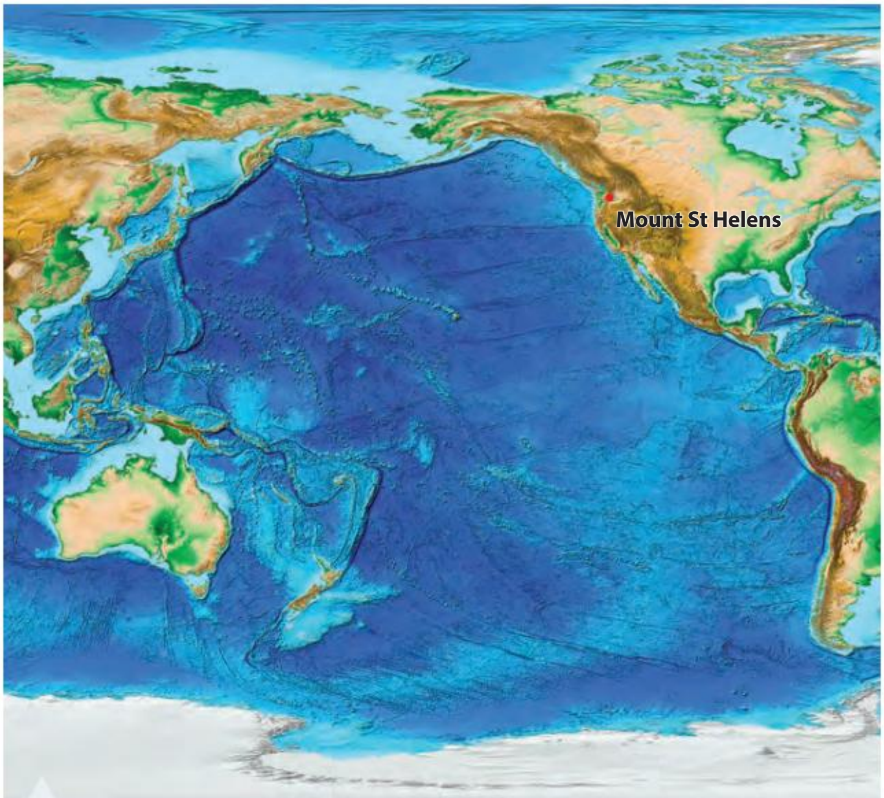
6.3 Case study: Mount St Helens

Mount St Helens is a 2550 metre stratovolcano in the USA. It is part of the volcanic Ring of Fire that encircles the Pacific Ocean (Figure 6.11). Mount St Helens lies near the edge of the Juan De Fuca plate, which is subducting under the North American plate.

A series of small earthquakes and steam-venting events occurred on Mount St Helens from mid-March 1980. On 27 March, steam explosions created a 75-metre-wide crater. Ash and smoke began to escape from the mountain's peak. By 18 May, thousands of small earthquakes had weakened the north face, causing fractures and a huge bulge that grew 2 metres per day. Indications were that the magma and gases deep within Earth were moving upwards. At 8.32 a.m. Pacific Daylight Saving Time on 18 May a magnitude 5.1 earthquake broke off the bulge and collapsed the north flank. A huge explosion of VEI 5 erupted out the north side of the mountain blowing the top 400 metres off the mountain (Figure 6.12).



Alamy Stock Photo/Science Photo Library

FIGURE 6.11 Location of Mount St Helens with reference to the Pacific Ring of Fire

Effect on the biosphere

The major eruption tore thousands of trees from 600 km^2 of forest. It caused a gigantic debris avalanche that covered more than 80 km^2 and deposited more than 2.3×10^9 m^3 of trees, ash

Alamy Stock Photo/Everett Collection Inc

FIGURE 6.12 Mount St Helens **a** before and **b** after the 1980 eruption

Alamy Stock Photo/Granger Historical Picture Archive

FIGURE 6.13 The log mat formed on Spirit Lake after Mount St Helens erupted

NASA

FIGURE 6.14 This photo was taken in 2008 and shows that the impact on the biosphere from the Mount St Helens eruption is still obvious.

and volcanic debris into nearby Spirit Lake (Figure 6.13) and the Toutle River basin. Spirit Lake suffered the full force of the eruption and a wave of over 260 metres formed due to the influx of material. Fish and other aquatic organisms were washed up onto the shores. The water in Spirit Lake became highly toxic due to volcanic gases and devoid of oxygen, which killed any remaining living organisms in the lake.

Debris to a depth of approximately 45 metres covered streets and buildings in nearby Spirit Lake, and Skamania and Cowlitz counties. More than 7000 deer, elk and bears perished along with birds and small mammals. Lahars filled the Cowlitz River channel, which ran down the valley into the Columbia River, resulting in elevated sediment levels that have lasted decades and affected the migration of salmon and steelhead trout.

It is estimated that 12 million Chinook and Coho salmon fingerlings died as a direct result of the eruption, and another 40 000 died when they swam through hydroelectric turbine blades along the Lewis River. The river was deliberately being kept at a low level to accommodate the incoming mudflows. Fifty-seven people were killed, mainly from asphyxiation due to ash.

Figure 6.14 starkly shows the long-term devastation of the biosphere that a volcano can cause. Even after three decades, south of the mountain is flourishing green forest, but north, in the blast zone, the forest remains sparse, particularly at the higher levels.

However, not all the effects of the volcano were negative. Many agricultural crops had increased yields due to the thin layer of rich volcanic ash enriching the soil. With greater than usual rainfall in 1980, a thin crust of ash mixed with water to form an impervious layer that reduced evaporation from the soil.

Effect on the atmosphere

Within 15 minutes of the eruption, the eruptive column of ash, gases and water vapour had risen 24 km into the stratosphere and began to expand into a characteristic mushroom-shaped cloud. Fine ash from the volcano reached the north-east of the state within 90 minutes. It blocked all sunlight from reaching the ground, activating the darkness-sensitive streetlights in Yakima and Spokane for the rest of the day. The eruption continued to eject ash into the atmosphere for another 9 hours, feeding the moving ash cloud.

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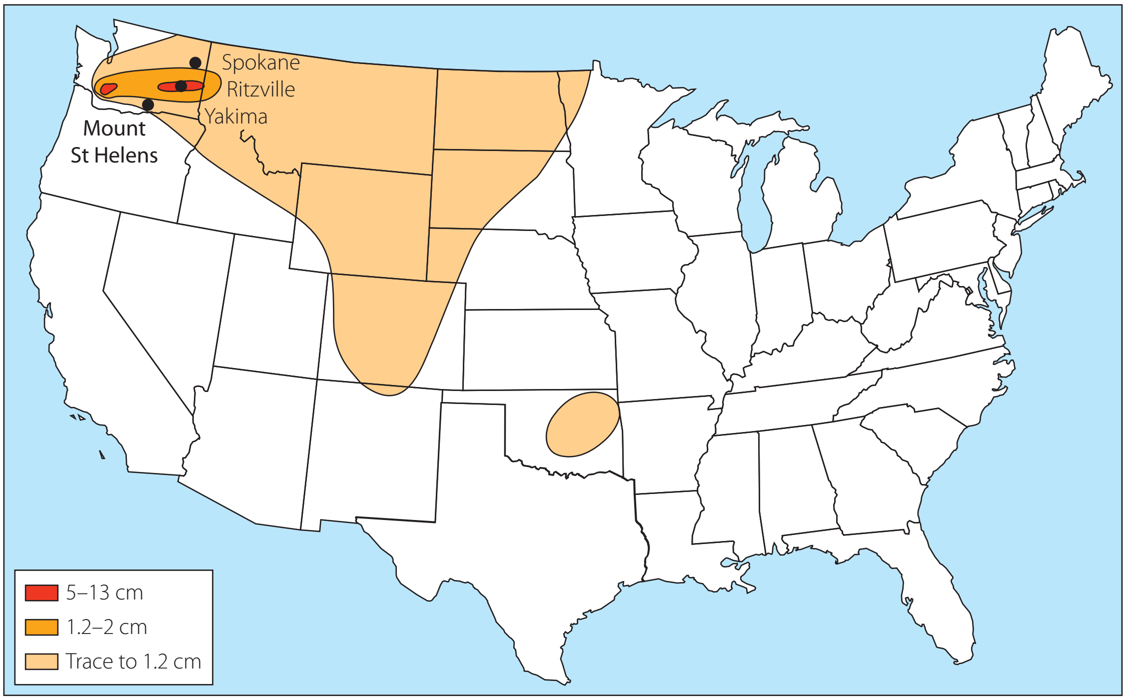

Map of ash fallout from Mount St Helens eruption. Courtesy of the U.S. Geological Survey

FIGURE 6.15 This map shows the spread of the ash cloud 2 days after eruption of Mount St Helens.

Within two days, the ash cloud had spread to the centre of the USA and within 15 days it had encircled Earth (Figure 6.15). Over time, some of the ash settled on the surface of Earth, but much remained suspended in the stratosphere for many years. Because the eruptive column contained very little sulfur dioxide, very little sulfate aerosol formed.

Assessing the impact

The Mount St Helens eruption was the most destructive volcano in the history of the USA.

Impact on the human environment

Within hours of the eruption, 57 people had died and many more were injured. There was extensive damage to forests, waterways, towns, buildings, bridges and other civil works. More than 200 houses, 450 km of roadways and 24 km of railway were damaged or destroyed. More than 9 500 000 m^3 of commercial timber was destroyed, although 25% of this was recovered quickly from Spirit Lake and surrounding forest areas. The fine ash from the volcano clogged pumps, filters and other mechanical equipment. It took several weeks to remove 190 000 m^3 of ash from roadways, buildings and airport runways and cost more than US $2.2 million. The final cost of the damage caused by the volcano was about US $1.1 billion.

Unemployment rose 10-fold in the weeks following the eruption due to the destruction of the forestry, tourism and farming industries. Some residents reported suffering mental health issues because of the emotional stress of dealing with the level of destruction.

Impact on weather

There was slight cooling of approximately 0.8°C in eastern Washington state during the day of the eruption due to increased albedo produced by the ash in the troposphere and stratosphere. Although sunlight could not penetrate the thick ash cloud, infrared radiation could not get out, so overall, there was little effect on the temperature.

INVESTIGATION 6.3

Asia and Australia's engagement with Asia

Information and communication technology capability

Intercultural understanding

Literacy

Case study: Mount Pinatubo

Your task is to investigate the eruption of Mount Pinatubo in 1991. Use the following headings to structure your investigation.

- Geography of Mount Pinatubo
- Timeline of the events leading up to the eruption
- The eruption
- Effects of the eruption on the biosphere
- Effects of the eruption on the atmosphere
- Assessing the impact of the eruption
- References

Present your findings in a format agreed on with your teacher; for example, written, oral, digital or a combination of these.

KEY CONCEPTS

- Mount St Helens is a stratovolcano in USA. It is part of the Pacific Ring of Fire.
- Mount St Helens erupted on 18 May 1980, destroying 600 km^2 of forest and many waterways and killing many land animals
- Fifty-seven people were killed due to ash asphyxiation
- The eruptive column of ash, gases and water vapour rose 24 km into the stratosphere
- The ash cloud encircled Earth within 15 days
- The economic cost of the eruption was calculated at US $1.1 billion.

CHECK YOUR UNDERSTANDING 6.3

1. Which tectonic plates are interacting in the region where Mount St Helens is located?
2. Had there been any activity at Mount St Helens before the major eruption?
3. What were the major effects of having research scientists in the region of the volcano before the eruption?
4. The major eruption caused changes to the biosphere and the atmosphere. Construct a table to show what these effects were.
5. Assess the impact of the Mount St Helens eruption on the:
   - a economy
   - b biosphere
   - c atmosphere.

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6.4 Climate phenomena

Dorothea Mackellar was an Australian poet and writer. Her thoughts on the variability of the Australian climate have become part of Australian folklore. She is best known for her poem *My Country*, particularly the beginning of the second stanza:

I love a sunburnt country
A land of sweeping plains
Of ragged mountain ranges
Of droughts and flooding rains.

By arrangement with the Licensor, the Dorothea Mackellar Estate,
c/- Curtis Brown (Aust) Pty Ltd

Drought

Australia is the second driest continent on Earth, surpassed only by Antarctica. So, it is not surprising that there are repeated and long periods of **drought**. According to the Bureau of Meteorology, drought is when rainfall over a 3-month period is in the lowest **decile** of what has been recorded for that region in the past. In other words, it is when the normal precipitation for a particular time of year does not occur. As a result, some regions can become drought declared while adjacent regions still have sufficient rainfall.

Causes of drought

Droughts in Australia occur because of its geography. Australia sits below a subtropical high-pressure belt. This causes dry and sinking air resulting in clear skies and little rain. In order for it to rain, the air needs to lift.

Another driver of drought is the El Niño Southern Oscillation (ENSO). During El Niño warming years, Australia has less rainfall and becomes a lot drier. El Niño occurs when the water in the central and eastern tropical Pacific Ocean beco-mes substantially warmer than usual. This warm water moves eastwards, dropping rain over the central and eastern Pacific Ocean. Usually, this warm water is in the western Pacific Ocean and Australia experiences rain. An El Niño event is officially declared if the temperature of the eastern tropical Pacific Ocean rises 0.5°C above the long-term average.

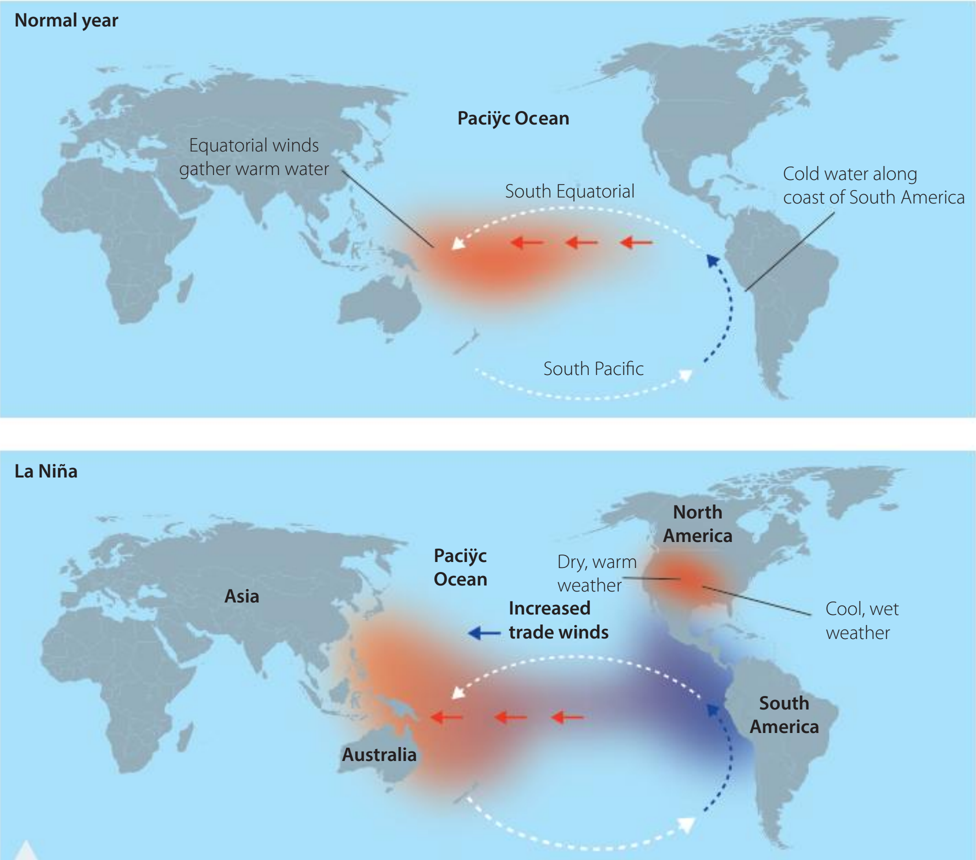

FIGURE 6.16 The movement of water in the Pacific Ocean that leads to a normal year and an El Niño year

Physical impact on a local ecosystem

It is important that scarce supplies of freshwater are carefully managed so that it is available for all living things. In times of drought, the lack of fresh water affects the whole ecosystem, including freshwater communities. When it does not rain for an extended time, run-off from the soil fails to recharge ponds, lakes and streams. Freshwater organisms are well adapted to short periods of drought but are less well adapted to **supra-seasonal drought**, when it fails to rain for extended periods such as years. In this case, freshwater bodies may be reduced to a series of small pools. If the drought continues, these small pools may dry up. Groundwater volumes may also decrease due to lack of recharge but little research has been done into this and it is poorly understood.

You learnt about water management in Chapter 11 of *Earth and Environmental Science in Focus Year 11*.

When freshwater bodies dry up, the living organisms that depend on them are affected. Macroscopic fish, yabbies, snails and plants, and microscopic *Daphnia*, *Cyclopoids* and *Cladocera* (water flea), are stranded with little water and usually high temperatures increase evaporation and salinity. If the conditions become stagnant, fish and other animals may die due to a lack of oxygen and the subsequent increase in nutrients in the water could lead to algal blooms, particularly the toxic blue-green and golden algae. Some species of algae can be toxic to humans and animals, affecting access to clean water for local animals such as kangaroos, possums, wombats, bilbies and birds (Figure 6.17). This forces them closer to populated areas where they risk being hit by cars.

Impact of humans

Australia is the flattest, driest inhabited continent. The flora and fauna of Australia are specifically adapted in their physiology and behaviour to deal with drought. Over millennia, Aboriginal and Torres Strait Islander peoples learnt how to live with the changeable Australian climate. The ability to find food and water in what, to European eyes, was a forbidding and inhospitable landscape was necessary to their survival.

Damming inland river systems has changed the flood regime of the inland. Groundwater systems were regularly recharged by floodwaters but this has largely been halted by damming river systems to control water flow and prevent flooding. The removal of large numbers of trees has increased run-off from cleared areas, leading to less infiltration of the soil by rain. The dams hold back large amounts of water that are seldom very deep, which means that there is a large amount of surface evaporation from the dammed waters. Allowing water to be moved across large distances in shallow irrigation channels also causes the loss of water by evaporation. An example of the loss of water to other purposes is the ongoing argument between the state governments of New South Wales, Queensland, Victoria and South Australia about the allocation of water rights on the Murray–Darling River system.


Auscape/Michael Maconachie

FIGURE 6.17 This freshwater system is affected by a toxic algal bloom.

Agricultural practices that lead to soil compaction, such as overstocking and excessive use of heavy farm vehicles, also contribute to reduced rain infiltration and increased run-off from farm areas. Water that does not get into the soil is often lost to evaporation in slow-moving river systems and large dam impoundments.

Flooding rains

Floods are part of the natural water cycle. Floods recharge freshwater systems such as rivers and lakes, infiltrate the soil and recharge groundwater.

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Causes of flooding

Floods are caused by prolonged heavy rain when the capacity of the water-holding body is overwhelmed.

Rainfall in Australia is controlled mostly by the El Niño Southern Oscillation and to a lesser extent the Indian Ocean Dipole. El Niño conditions lead to low rainfall and dry conditions in Australia (page 147). At the same time, there is higher rainfall in South America. The opposite effect of the cooling phase occurs during La Niña years. During La Niña years, the winds over the Pacific Ocean are much stronger and push the warm ocean water west towards Indonesia (Figure 6.18). This causes cold water to rise to the surface near South America, making the ocean slightly colder and drier. As the warm water moves west, so do the clouds, and Indonesia and Australia receive more rain than usual. Large storm systems form around moist air masses and move across the country and cause floods over large areas of inland Australia. Cyclones can bring large amounts of moisture from the ocean and cause coastal flooding. This leads to a balance in the **global water budget** – the total amount of water involved in the water cycle on an annual basis.

WS El Nino and La Nina

The **Indian Ocean Dipole** is the temperature difference between two areas of the Indian Ocean. The effects of the dipole on rainfall in Australia depends on whether it is a positive or negative value.

A positive event leads to higher water temperatures in the western part of the ocean, which leads to a reduction in cloud formation over the north of Australia and less than average rainfall across the country, with a weak wet season in the north. A negative event leads to higher water temperatures in the eastern part of the ocean, which leads to an increase in cloud formation over the north of Australia and higher than average rainfall across the country, with a strong wet season in the north.

Over the last 20–30 years, there has been a marked increase in the number of negative events, leading to increased rainfall on average across tropical Australia.

Physical impact on a local ecosystem

Floods can have both positive and negative effects. This is seen in this following example of water from the same flooding rains. In January 2011, devastating floods occurred in north-eastern Australia. Much of this water flowed into the ocean at the ports of Bundaberg, Gladstone and Brisbane. Such a huge volume of fresh water, containing sediments, nutrients and pesticides, poses a large threat to marine environments. Flood plumes such as this have a significant impact on seagrass

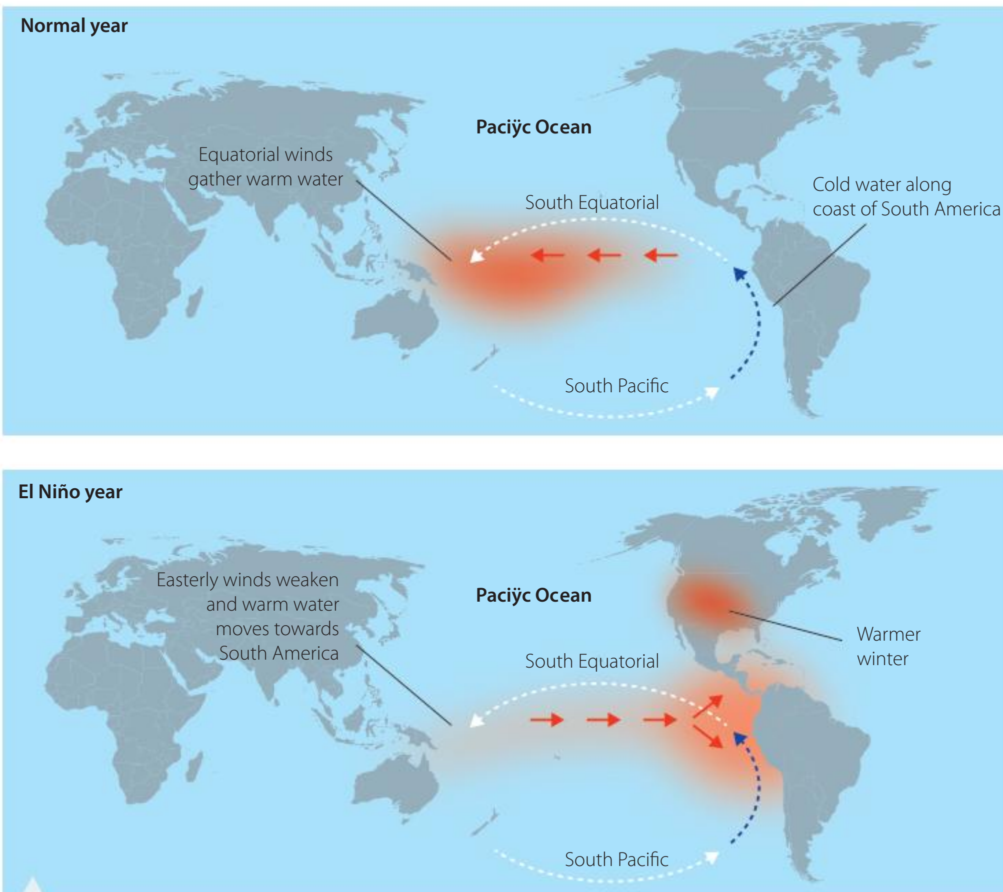

FIGURE 6.18 The movement of water in the Pacific Ocean that leads to a La Niña weather event

Getty Images/Sami Sarkis

FIGURE 6.19 Dugong feeding on a seagrass bed covered in silt

Getty Images/Auscape

FIGURE 6.20 After the Queensland flood, water made its way to Kati Thanda–Lake Eyre.

beds, covering them with silt and reducing their ability to photosynthesise.

High concentrations of nutrients can cause algal blooms, which cover large areas of the surface of the ocean, reducing the amount of light and oxygen reaching marine plants. Animals such as dugongs and sea turtles that rely on these seagrass beds may be unable to find an alternative food source (Figure 6.19). This can lead to malnutrition, disease and death, and removal of a significant number of organisms from the area.

Kati Thanda–Lake Eyre in South Australia has one of the world's largest basins, covering 1.2 million square kilometres, almost one-sixth of Australia. It is 12–17 metres below sea level and is the end point for many inward-draining rivers. Kati Thanda–Lake Eyre is a salt lake; its edges are crusted with white crystals. It has an annual rainfall of just 120 mm and much of the time it is empty or has low water levels. In 2010, flood water from Queensland made its way to Kati Thanda–Lake Eyre, and the region received heavy rainfall, approximately 450 mm. This combined influx of water into the lake resulted in an increase in populations of the birds and mammals living there (Figure 6.20). Pelicans and Eyrean grasswren flocked to the lake to feed on the plentiful water life. Populations of small mammals increased dramatically, resulting in an abundance of predators such as letter-winged kites (*Elanus scriptus*). The flooding filled rabbit burrows, forcing rabbits to the surface, which provided plenty of food for eagles and dingoes. Coolabahs (*Eucalyptus coolabah*), native Australian eucalypts made famous by poet Banjo Paterson, finally germinated. Coolabahs are very resistant to drought and their seeds only germinate after flooding. This ensures that seedlings are only produced when there is enough water for them to become established.

Impact of humans

Rainfall across much of southern Australia has been gradually decreasing and large-scale flooding has been less of a major concern for several years. Any floodwaters that are generated can largely be controlled by the dams along many of the river systems. However, this does not mean that flooding is a thing of the past. Northern New South Wales towns can be affected by tropical cyclones moving south from Queensland, while the Illawarra and Hunter regions can experience flooding due to east coast lows (page 153).

Conversely, localised flooding is increasing in many regions. Localised flooding is a result of the combination of paved areas, ground compaction that reduces the ability of rain to enter the soil profile and the occurrence of local heavy rain. In 2015, flash flooding in Dungog, New South Wales, was a result of more than 300 mm of rain falling in a confined area in a 24-hour period.

Increased urbanisation can also increase the risk of flash flooding during abnormal weather events. Paved surfaces do not allow rain to infiltrate the soil and any rain that falls is redirected into stormwater channels and pipes. When the amount of water exceeds the capacity of the stormwater pipes to remove it, localised flooding occurs. The risk of local flash flooding increases with the amount of paved surfaces and abnormal rainfall events in a small area. When Hurricane Harvey hit Houston, Texas, USA, in 2011, the increased urbanisation was estimated to have increased the flooding risk by 2000%

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(Figure 6.21). This large increase was due to tall buildings pushing the air upwards and causing more rain to fall, as well as the large amount of paved surfaces decreasing the land available for the water to soak into.

As humans increase the amount of heat-trapping gases in the atmosphere, leading to hotter oceans and climate, the drought and flood effects of El Niño and La Niña are becoming magnified. Researchers at the University of Iowa estimated that global warming increased the rainfall from Hurricane Harvey between 15 and 40%.


iStock.com/Eric Overton

FIGURE 6.21 Flooding from Hurricane Harvey in 2011 was made worse by urbanisation

Hailstorms

Hail is precipitation that falls in the form of ice.

Causes of hailstorms

Hail is formed when sharply rising air currents in a large cloud carry rain into regions that are cold enough for it to freeze (Figure 6.22). Repeated movements within the cloud coat the initial ice balls with successive ice layers. Eventually, the hailstones become too heavy and fall out of the cloud.

The most common type of clouds that can produce hail are **cumulus** or **cumulonimbus** clouds. They are characterised by having a wide base, a narrower central section and a broad top. They are often called anvil-shaped because they resemble a blacksmith's anvil in cross-section. These clouds have a limited extent and are usually caused by a combination of high humidity and high temperatures. As such, they are more common during the summer than during the cooler parts of the year.

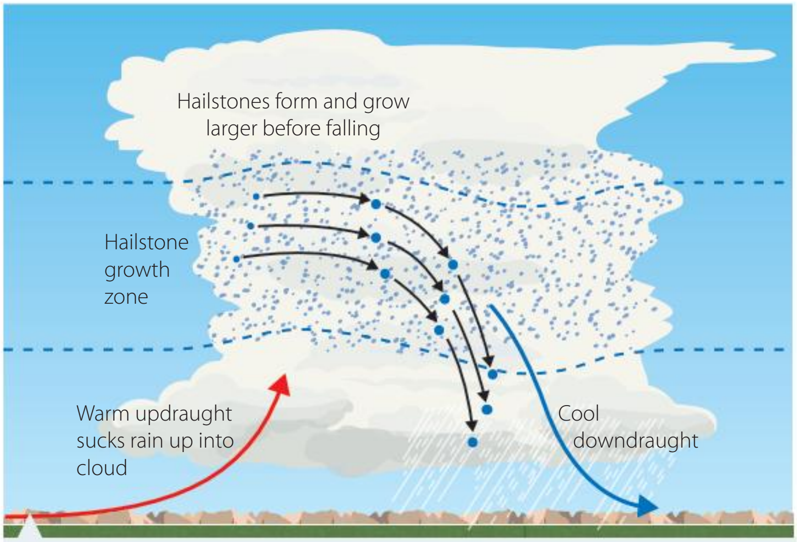
Hailstorms are often accompanied by very heavy local rain that follows the path of the cloud as it moves over the surface of Earth. In extreme cases, the rainfall can cause local flooding, and in desert regions, flash flooding often follows these storms (Figure 6.23).

The largest hailstones are formed in **supercells**; these have strong updraughts that take the forming hailstones to the ice region of the cloud where they become very large before they fall. The conditions needed for a supercell to form are warm and moist, which promote strong updraughts.

Physical impacts on a local ecosystem

Large hailstones can strip vegetation from trees and extensively damage livestock and property due to the impact force of the hailstones. Crops are particularly vulnerable to hail, with the greatest cost to farmers if the hail event occurs close to harvest. In March 2018, the hailstorm that hit the Orange region of New South Wales caused $4 million worth of damage to cherry, flower, apple and stone fruit crops.

In March 2019, large hailstones more than 7 cm in diameter hit the fruit-growing area of Northern Rivers district in New South Wales. In just 10 minutes, about 4 million avocados that were ready for harvest were destroyed. The hail snapped branches off trees and scarred tree tissue, creating an entry point for disease-causing organisms. Hail also damaged other fruit crops (Figure 6.24).



NOAA/SciJinks

FIGURE 6.22 How hailstones form. Warm updraughts suck rain drops up into the cloud. The hail grows in circulating currents and eventually becomes too large for the cloud to hold. It falls, causing a strong downdraught.

Alamy Stock Photo/Room the Agency

FIGURE 6.23 Intense storm cells often lead to hail and local heavy rain.

FIGURE 6.24 Hail damage to apple orchards

Shutterstock.com/Lorenza62

INVESTIGATION 6.4

Information and communication technology capability

Literacy

Sydney hailstorm December 2018

In December 2018, a hailstorm hit Sydney, causing enormous damage. Use more than three references, including the Internet, to answer these questions.

1 What was the extent of the hailstorm across New South Wales?
2 What was the path of the storm as it moved across the state?
3 What were the weather conditions that led to the hailstorm?
4 Describe the hail that fell in some regions.
5 What other weather events accompanied the hailstorm?
6 What impacts did the hailstorm and associated weather events have on the areas affected? List the references that you used to find the answers.

Sydney hailstorm 2018
Read about the devastating effects of the hailstorm.

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KEY CONCEPTS

- Drought is when the normal precipitation for a particular time of year fails to occur.
- Drought occurs due to Australia's geographical location and El Niño.
- Drought conditions affect surface and groundwater reserves.
- Drought conditions affect all living organisms that depend on the supply of fresh water.
- Humans affect the frequency and magnitude of droughts through damming river systems, removing trees, agricultural practices and climate change.
- Floods are periods of prolonged heavy rain that overwhelm the capacity of the water-holding body.
- Floods are controlled by La Niña and the Indian Ocean Dipole.
- Humans affect the frequency and magnitude of floods through increasing urbanisation reducing soil infiltration and climate change.
- Hail is precipitation that falls in the form of ice.
- The largest hailstones are formed in supercells.
- Large hailstones strip leaves from trees and kill livestock.

CHECK YOUR UNDERSTANDING 6.4A

1. Define 'drought', 'flood', 'ENSO', 'supra-seasonal drought', 'Indian Ocean Dipole' and 'supercells'.
2. List the causes of drought.
3. List the impacts of drought.
4. How have humans increased the frequency and magnitude of droughts?
5. Evaluate how drought conditions affect the biotic and abiotic environments.
6. Distinguish between El Niño and La Niña. Describe why one causes drought and the other causes floods.
7. Evaluate the impact of floods on the biotic environment.
8. How have humans increased the frequency and magnitude of floods?
9. Describe how hailstorms form.
10. Evaluate the impact of a large hailstorm on an agricultural area.

East coast lows

An **east coast low** is an intense low-pressure system off the coast of New South Wales, southern Queensland or northern Victoria. They most commonly affect the New South Wales coast between Coffs Harbour and the Victorian border.

Causes of east coast lows

East coast lows are not new weather phenomena. Historical work on shipping reports and ship losses suggests that many of the losses of ships on the east coast were caused by these storms. The wreck of the *Dunbar* in 1857 caused the greatest loss of life from a single shipwreck in Australian history. It is now recognised as probably having been caused by an east coast low. In 2007, the coal ship *Pasha Bulker* was caught in a storm caused by an east coast low and ran aground on Nobbys Beach in Newcastle (Figure 6.25).

Alamy Stock Photo/Lincoln Fowler

FIGURE 6.25 The coal ship *Pasha Bulker* washed ashore on Nobbys Beach, Newcastle

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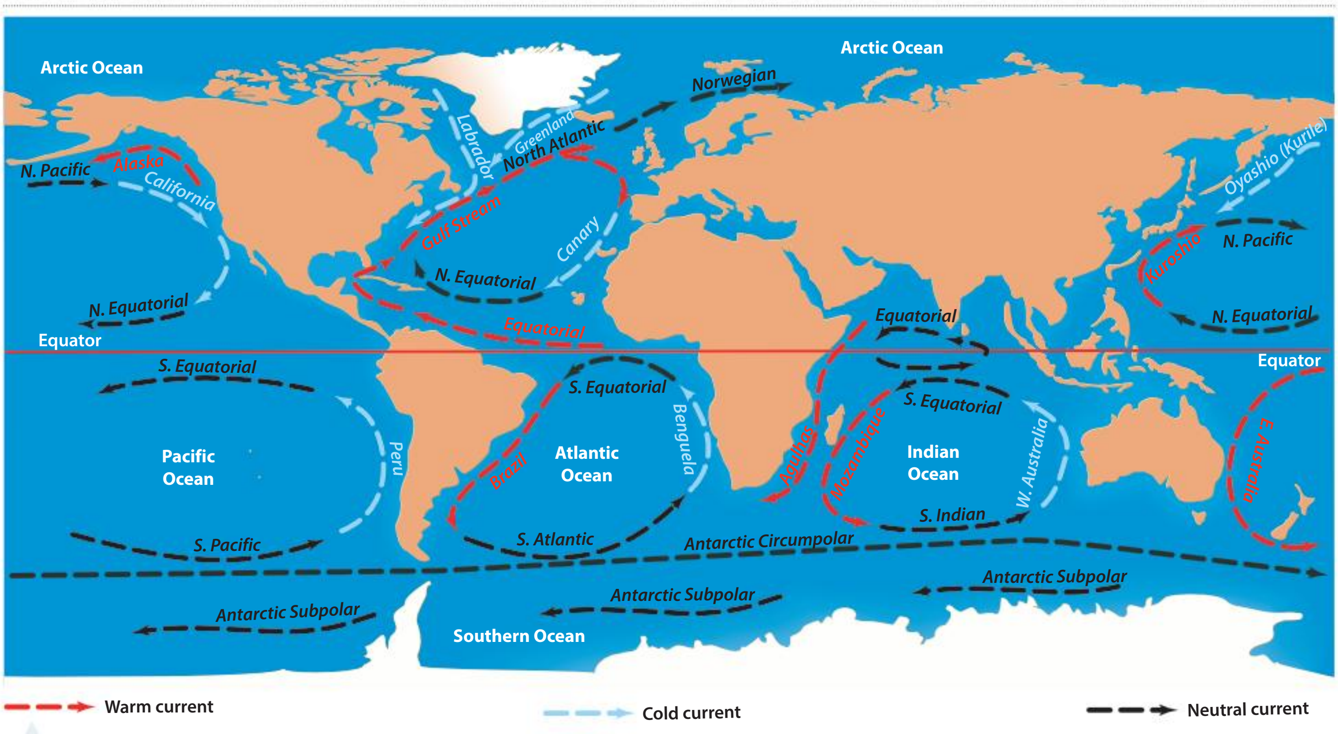

FIGURE 6.26 A world map showing the main ocean currents, including the East Australian Current

WS Synoptic chart

East coast lows typically occur during the cooler months of the year and are most frequent from May to September. To have an east coast low develop, a series of atmospheric events have to occur. The East Australian Current is a southward movement of warm water from Queensland parallel to the east coast of Australia. At different times of the year, eddies spin off from the main part of the current and these can be relatively stable for up to a week before they dissipate (Figure 6.26).

The ideal conditions for the development of an east coast low are a deepening low-pressure system that moves off the coast and sits over one of the warm water eddies that has broken off the East Australian Current. To the east of the Tasman Sea, a strong high-pressure system needs to be in place over New Zealand with a strong high-pressure system approaching from the west across Australia. As the low-pressure system sits over the eddy of warm water, it gains heat and intensifies. The approaching system from the west and the blocking high-pressure system near New Zealand help to raise the windspeed around the low-pressure system.

When this set of circumstances occur, a steady flow of moist air moves towards the coast. High wind speeds lead to extreme sea conditions with accompanying coastal erosion, as seen in Sydney in 1974 and 2016. Strong winds from the south or south-east direct large areas of rainfall along the coast and adjacent ranges. Localised and regional flooding often occur in the Illawarra, Sydney and Hunter regions of New South Wales. In the worst cases, an east coast low operates for about 5 days. There can be several successive low-pressure systems leading to east coast lows in some years.

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INVESTIGATION 6.5

Investigating the frequency of east coast lows

Critical and creative thinking

Numeracy

Go to the Bureau of Meteorology weblink to research east coast lows.

1 Construct a table to show the number of east coast lows each year over the last 20 years.
2 Plot the year (x-axis) against the number of storms in each year (y-axis).
3 Describe the trend shown in your graph.
4 Compare the weather maps shown for each of the low-pressure systems mentioned. Do they conform to the general pattern of an east coast low?
5 Analyse your data to answer whether there has been an increase in the number of east coast lows per year over the last 20 years. Provide evidence from the data for your answer.

Bureau of Meteorology
Learn about recent east coast lows – how they form and why they are dangerous.

Physical impact on a local ecosystem

Although it is well known how tropical cyclones affect the north of Australia during the summer months, it has only become apparent to most people just how damaging an east coast low can be in recent years. The Sygna storm of 1974 and the 2016 storm that destroyed parts of the Northern Beaches of Sydney are two recent examples of damage caused by east coast lows (Figure 6.27).

In June 2016, an east coast low produced heavy rain, strong winds and powerful surf. It moved down the central Queensland coast, dumping heavy rain as it went. More than 170 mm fell on the Sunshine Coast. Brisbane and the Gold Coast were both inundated with water before the east coast low entered New South Wales. The Richmond River in Lismore peaked at 9.1 metres (it is usually under 4 metres) and Lavenders Bridge in Bellingen collapsed, cutting the town in two.

Getty Images/Daniel Munoz

FIGURE 6.27 This damage to the beachfront at Collaroy Beach in Sydney in 2016 was caused by an east coast low.

On Sydney's Northern Beaches, waves up to 8 metres eroded the coastline and travelled 50 metres inland with subsequent loss of sand. The built environment along Collaroy and Narrabeen beaches were greatly affected due to development along the coast (Figure 6.27).

Bushfires

Bushfires are a natural consequence of living in Australia. Before European settlement, Aboriginal and Torres Strait Islander peoples had a well-established method of using fire to control the growth of

Newspix/Alex Coppel

FIGURE 6.28 The Black Saturday bushfires in Victoria occurred in early February 2009.

vegetation and help with hunting. This method is often referred to as 'fire-stick farming' and it produces a mosaic of freshly burned and unburned landscapes that reduces the risk of catastrophic bushfires.

Over the last 100 years, many people have moved from city areas into or close to forested areas. These people are at risk if there is a bushfire.

Causes of bushfires

The prevalence of bushfires is governed by high fuel loads accompanied by a period of below average rainfall, high wind speeds and low humidity (Figure 6.28). Bushfires can start by human action or by natural causes. Regardless of the cause, a bushfire needs three things to start: oxygen, heat and fuel.

Bushfires are more likely to occur in years when these is a strong El Niño in operation. If this follows years with mild to strong La Niña patterns, then there can be a large increase in the fuel load available.

INVESTIGATION 6.6

Information and communication technology capability

Critical and creative thinking

ENSO
Look up the El Niño or La Niña years.

Bureau of Meteorology
Find out the weather in particular years.

Bushfires and ENSO

Choose one bushfire event from Table 6.3. Use references to find out the major areas affected by that bushfire and record in the last column of the table.

Locate and use data from ENSO and the Bureau of Meteorology weblinks to determine if there is a correlation between bushfire events and the overall weather patterns at the time.

TABLE 6.3 Major Australian bushfires

DATES	BUSHFIRE NAME	AREAS AFFECTED
1 February to 10 March 1926	Black Saturday	
13–20 January 1939	Ash Wednesday	
7 February 1967	Black Friday	
16–18 February 1983	Black Tuesday	
7–8 February 2009	Gippsland bushfires and Black Sunday	
June 2019 to January 2020	2019–20 bushfire season	

1 Was the year of your chosen fire an El Niño or La Niña year?
2 What were the rainfall patterns leading up to your chosen bushfire?
3 Using the data as evidence, is there a correlation between ENSO events and your chosen bushfire? Explain.
4 Share your findings with your class and use all the evidence to draw a conclusion.
5 Comment on the accuracy of the data that you have used.
6 Explain why you combined all the class data before you drew a conclusion.

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Physical impact on a local ecosystem

Bushfires can have major effects on ecosystems, including burning forests that could take hundreds of years to recover. The loss of plants and plant roots from the ecosystem can make the soil unstable and erode into creeks and rivers during subsequent wind or rainstorms. Loss of plant life can also open areas up to invasion by introduced species that compete with native species for space, water and light. Animals can be killed or injured by bushfire, reducing numbers of already vulnerable native species.

Many Australian plants are adapted to survive bushfires and fire is essential to their life cycle. *Banksia* species produce hard woody cones. They are sealed closed by a waxy resin that requires fire to melt it. After the resin melts, the seeds escape the cones and germinate in the post-fire fertilised soil (Figure 6.29). *Eucalpytus* trees can be extensively burned during bushfires but new shoots will sprout from **lignotubers** that develop at ground level, or epicormic buds on the branches.


iStock.com/KarenHBlack

FIGURE 6.29 Banksia with open seed pods after a fire. They have adapted to survive bushfires.

Human impact

Bushfire seasons are starting earlier in the season because of the hotter conditions and low rainfall due to El Niño conditions. In July 2018, New South Wales experienced 525 bushfires, twice the number of 2017. In June 2019, several uncontrolled burns spread to burn over 18.6 million hectares of land. Many were still burning into 2020. If rainfall remains low, then the outlook is for above normal fire potential across large parts of Queensland, Victoria and New South Wales. This was shown to be the case during the bushfire season across 2019 and early 2020.

The most common causes of bushfires are lightning strikes, arcing of overhead power cables, arson or negligence; for example, not extinguishing a campfire properly or throwing away a lit cigarette or match. Bushfires can also be caused by sparks from machinery such as grinders, or controlled burns that have got out of control. Controlled burns usually take place during the cooler months in an effort to reduce the amount of fuel on the forest floor.

Landslides

Landslides, or mass wastings, are part of a group of mechanisms that move material down a slope under the force of gravity. Landslides can refer to falls, topples, slides, spreads or flows of bedrock, debris or earth (Figure 6.30). They occur when gravitational force exceeds the strength of the materials that make up the slope. If the structure of a slope comprises excess water pressure or movement (such as in an earthquake), then it is more likely to slide. The deadliest landslide event occurred in Ningxia, China, in 1920. A magnitude 8.5 earthquake shook the ground and caused more than 650 landslides. More than 100 000 people were killed and the extent of the damage covered 20 000 km^2.


Alamy Stock Photo/Glenn Aguilar

FIGURE 6.30 A landslide near Fox Glacier, New Zealand iStock.com/Ross Tomei

FIGURE 6.31 To avoid landslides, part of the Grand Pacific Drive was built alongside the old road cut into the cliff at Coalcliff, south of Sydney.

Human impact

Any change in the mechanical strength of the rocks or soil making up a slope or a change in the slope, particularly by undercutting, can cause a landslide. The construction of a road into the side of a hill is one of the most common causes of landslides in hilly terrain. A good example of the problems associated with maintaining roads in hilly terrain was the construction of the main road along the edge of the ocean at Coalcliff in southern New South Wales. Due to the weak nature of some of the rock layers in the hill, landslides were common, particularly during or after wet weather. The addition of water to soil makes it heavier and more likely to slide. The solution was to abandon the original road and build a new elevated road alongside the cliff (Figure 6.31).

In hilly countries, changing the load on rocks and soils can also lead to landslides, due to the destabilisation of slopes from building on them.

In many less-developed countries, removal of vegetation is a major cause of landslides because water moving down the slope erodes and destabilises the slope. More frequent bushfire events remove the stabilising effects of plant roots on soil. Heavy rain can saturate the soil, making it heavier and more prone to sliding.

KEY CONCEPTS

- An east coast low is an intense low-pressure system off the east coast of Australia.
- East coast lows typically occur during the cooler months of the year and are most frequent from May to September.
- A series of atmospheric events has to be in operation to form an east coast low.
- East coast lows produce strong winds, intense rainfall and huge waves.
- Bushfires need oxygen, heat and fuel to start.
- Bushfires can kill plant life and kill and injure animal life.
- Some native plants are adapted to surviving bushfires.
- Landslide is the movement of soil, rocks and trees down a slope under the force of gravity.
- Land clearance, bushfires and road building can increase the frequency of landslides.

CHECK YOUR UNDERSTANDING 6.4B

1. What particular weather and ocean conditions are necessary for an east coast low to develop?
2. List the effects of an east coast low on coastal areas.
3. List the features that lead to a high possibility of a bushfire.
4. How can bushfires have negative and positive effects on a natural forest community?
5. Are human activities increasing the frequency and magnitude of bushfires?
6. How has human activity increased the frequency of landslides?

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6 CHAPTER SUMMARY

- A volcanic eruption occurs when lava in the magma chamber of the volcano, along with gases such as sulfur dioxide, is discharged through the volcanic vent.
- There are two types of volcanic eruption: explosive and effusive.
- Volcanoes are classified according to their volcanic explosivity index (VEI).
- Magma flows, gases, falling rocks and ash, lahars and pyroclastic flows have an impact on the biosphere.
- Gases and ash entering the troposphere and atmosphere have an impact on the atmosphere.
- Sulfur dioxide reacts with water in the atmosphere to form sulfuric acid droplets, which freeze. These are known as sulfate aerosols.
- Volcanic ash remains in the lower stratosphere for a significant length of time and reflects solar radiation. Sulfate aerosols remain in the upper stratosphere and reflect solar radiation. This leads to global cooling.
- Any change in the amount of solar radiation that reaches Earth's surface is called radiative forcing.
- Sustained periods of global cooling are often recorded in tree ring records.
- Volcanic eruptions release potent greenhouse gases such as CO_2 and water vapour, which absorb infrared radiation and lead to global warming.
- Mount St Helens is a stratovolcano in USA. It is part of the Pacific Ring of Fire.
- Mount St Helens erupted on 18 May 1980, destroying 600 km^2 of forest and many waterways and killing many land animals
- Fifty-seven people were killed due to ash asphyxiation
- The eruptive column of ash, gases and water vapour rose 24 km into the stratosphere
- The ash cloud encircled Earth within 15 days
- The economic cost of the eruption was calculated at US $1.1 billion.
- Drought is when the normal precipitation for a particular time of yeat fails to occur.
- Drought occurs due to Australia's geographical location and El Niño.
- Drought conditions affect surface and groundwater reserves.
- Drought conditions affect all living organisms that depend on the supply of fresh water.
- Humans affect the frequency and magnitude of droughts through damming river systems, removing trees, agricultural practices and climate change.
- Floods are periods of prolonged heavy rain that overwhelm the capacity of the water-holding body.
- Floods are controlled by La Niña and the Indian Ocean Dipole.
- Humans affect the frequency and magnitude of floods through increasing urbanisation reducing soil infiltration and climate change.
- Hail is precipitation that falls in the form of ice.
- The largest hailstones are formed in supercells.
- Large hailstones strip leaves from trees and kill livestock.
- An east coast low is an intense low-pressure system off the east coast of Australia.
- East coast lows typically occur during the cooler months of the year and are most frequent from May to September.
- A series of atmospheric events has to be in operation to form an east coast low.
- East coast lows produce strong winds, intense rainfall and huge waves.
- Bushfires need oxygen, heat and fuel to start.
- Bushfires can kill plant life and kill and injure animal life.
- Some native plants are adapted to surviving bushfires.
- Landslide is the movement of soil, rocks and trees down a slope under the force of gravity.
- Land clearance, bushfires and road building can increase the frequency of landslides.

CHAPTER REVIEW QUESTIONS

Review quiz

1 Explain why different systems are used to classify explosive and effusive volcanos.

2 List the effects on the biosphere of a major explosive volcanic eruption and a major effusive volcanic eruption. What are the differences between the two lists?

3 Compare the effects on the atmosphere of a major explosive volcanic eruption and a major effusive volcanic eruption.

4 Evaluate the effects on the atmosphere if an eruption of VEI 6 produced large volumes of sulfate aerosols.

5 A major eruption of a volcano in Iceland has the potential to produce serious changes in temperature in the northern hemisphere but only limited changes in the southern hemisphere. Explain why this is the case.

6 The island of Java has a very high population density while the Okhotsk Peninsula in Russia has a very low population density. Both geographic locations have a similar density of active, explosive volcanos. Outline how a major eruption would have different impacts on the biosphere in both locations.

7 Explain why the location, chemistry of the eruption cloud and style of eruption all combined to produce global temperature change after the eruption at Mount Pinatubo in 1991.

8 Mount St Helens in 1980 and El Chicon in 1982 had similar VEIs and sulfur dioxide levels produced in the eruption. Explain why the 1980 eruption produced a much smaller global temperature change than the 1982 eruption.

9 The 1991 eruption of Mount Pinatubo was the second largest of the 20th century. Very few human deaths occurred as a direct result of the eruption. Explain why this was the case.

10 There are four subduction volcanos on the island of Luzon. Mount Pinatubo is the only volcano in the north-west of the island of Luzon that has erupted in the last 500 years but when geological mapping was done around the volcano, there was extensive evidence of lahars from older eruptions. Imagine that you are a senior geologist attached to the Philippine government. What programs would you put in place if a series of earthquakes was detected near each of the other three volcanos on Luzon?

11 Gases released from volcanos have the potential to produce both heating and cooling of the atmosphere. Explain how this can occur.

12 Flash floods are becoming more common as the intensity of thunderstorms increases with climate change. Much of the water involved in flash flooding comes from urban roof drainage. What practices could a local council put in place to reduce the amount of stormwater run-off from suburban houses?

13 In 2012, the New South Wales government implemented a new bushfire management plan for the state. The plan limits the building materials that can be used in the construction of new buildings within 1 km from bushland. Research the requirements for windows, doors and decks under the new bushfire management plan and evaluate whether there is an advantage in making the changes retrospective.

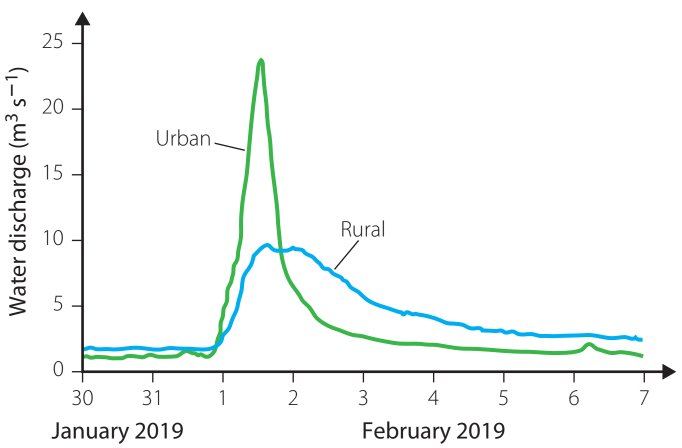
14 Discuss and evaluate whether water in large shallow dam impoundments should be kept or released as a series of timed environmental flows to duplicate the historical flood pulses that would have moved down inland river systems.

15 Level 1 water restrictions have been put in place in a number of locations as dam levels have dropped. Some country regions are on Level 4 restrictions. What can you do at your home to reduce the water usage in your house and around your property?

16 Many areas of national parks in New South Wales have not had a substantial bushfire through them in many years. What effect would this be having on native plant life?

17 Figure 6.32 shows the discharge of water through two flood areas in 2019. The green line represents a flood in an urban area, the blue line represents a flood in a rural area. Explain the differences in the two graphs.

FIGURE 6.32 Discharge of water through two flood areas in 2019



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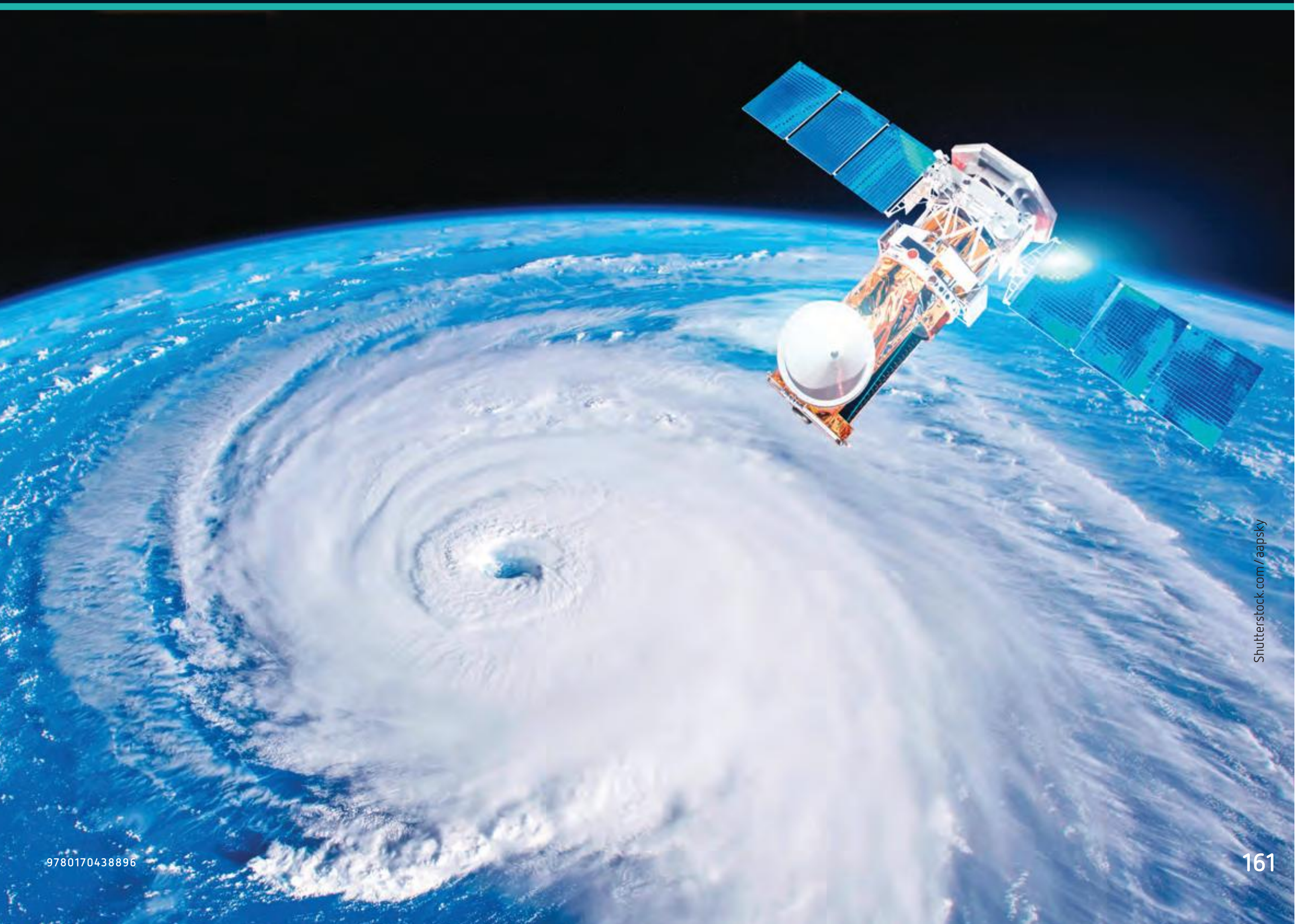
7 Preventing natural disasters

OUTCOMES

In this chapter you will learn about:

- the effectiveness of technologies used to predict natural disasters CCT ICT IU L
- technologies used to minimise the effect of volcanic and earthquake hazards CCT ICT L N PSC
- the accuracy of technologies used in meteorology to predict natural weather events. AAEA CCT ICT L



Shutterstock.com/aapsky

Volcanic eruptions, earthquakes, drought, fire, cyclones and east coast lows – all may cause widespread or local devastation (Figure 7.1). Disasters due to weather accounted for three-quarters of the world's disaster-related damage from 2008 to 2017, but earthquakes were the biggest killers. Australia was among the top 10 countries for disaster costs. We are becoming increasingly dependent on technology to predict hazardous events and mitigate their effects. Improving technology is vital to saving human lives and avoiding financial ruin.

Getty Images/Ian Hitchcock

Getty Images/Heath Holden

FIGURE 7.1 In February 2019, **a** floods ravaged Townsville in Queensland and **b** a series of uncontrolled fires burned the Tasmanian Wilderness World Heritage Area.

7.1 Technologies used to predict natural disasters

Our ability to predict natural disasters depends on the type of disaster and available technologies. Volcanic eruptions can be predicted weeks in advance. East coast lows may develop in 12–24 hours. Earthquakes can only be tracked as they occur, and the best warning scientists can provide is only a matter of minutes. Scientists can use computer modelling to quickly interpret large amounts of data from sensors and determine the level of risk. Communication technologies deliver warnings to emergency services and the public to allow orderly evacuation and deployment of resources.

Technologies used to predict volcanic eruptions

Predicting a volcanic eruption has one simple advantage over predicting earthquakes and weather events – the volcano has a known location. It is very helpful to know the location of a natural disaster. Monitors can be placed on the ground around the volcano and satellites can be programmed to collect data on that location.

As technology has advanced, so has our ability to predict and monitor volcanoes. Warning of the 1980 eruption of Mount St Helens in Washington, USA, first came from a manual seismometer that recorded tracings on film. It took 20 minutes to process the film, which seismologists then viewed with a magnifying glass. Their measurements were fed into a punch-card computer that took half an hour to calculate the epicentre of the observed earthquakes. A radio-equipped seismic station was installed days before the initial eruptions, but analysis software had not yet been written. Despite this very basic technology, geologists anticipated the eruption and evacuated the area. However, they did not anticipate the lateral blast from the north flank that flattened trees 30 km away and caused 57 deaths.

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Mount St Helens is now surrounded by radio-linked real-time seismic stations, global positioning system (GPS) receivers, tiltmeters and gas detection devices. Volcanic eruptions around Earth have been predicted, monitored and used to refine forecasting technologies.

Deformation and ground movement

Changes in the shape of a volcano can indicate rising magma and an imminent eruption. Tiltmeters, strain meters, GPS and radar are used to detect three-dimensional variations caused by the movement of subsurface magma. For example, as fresh magma enters the magma chamber beneath the volcano, it may bulge outwards, as did the north flank of Mount St Helens before the large landslide and eruption in May 1980 (Figure 7.2).

Tracking ground movement was the first method used to monitor volcanoes and is still important today. When magma accumulates in a volcano, the tilt of the slope increases; if magma drains out of a subsurface reservoir, the tilt decreases. Electronic tiltmeters have a small container filled with conducting fluid and a bubble that measures minute changes in slope (Figure 7.3). This advanced version of a carpenter's level measures tilt in microradians (0.00006°). These very sensitive instruments are placed in boreholes at least 1 metre below the surface to insulate them from changes in temperature and pressure that could affect the readings.

Strain meters detect tiny changes in the shape of Earth's crust. They are so sensitive that they can detect changes caused by passing weather fronts. This sensitivity means that strain meters must be buried tens of metres below the surface and cemented into place to connect them to the surrounding rock. As earthquakes or moving magma change the shape of the volcano, the strain meter measures the minute changes in shape.

GPS consists of a group of satellites that orbit Earth twice a day and transmit information to ground-based receivers. GPS can be used to monitor a volcano by placing receivers around a volcano in a network (Figure 7.4). In some locations, this installation is permanent (e.g. Kilauea, Hawaii); in other locations, a network may be temporarily installed to monitor a volcano of concern. Networks of GPS receivers track three-dimensional movements of less than 1 mm a year.

Alamy Stock Photo/CPC Collection

FIGURE 7.2 The large bulge on the north flank of Mount St Helens expanded horizontally by 2 metres per day before the eruption on 18 May 1980.

Alamy Stock Photo/CNP Collection

FIGURE 7.3 Scientists prepare to install a tiltmeter to monitor Mount Pinatubo, Philippines, in 1991.

Alamy Stock Photo/Hemis

FIGURE 7.4 Scientists from the Montserrat Volcano Observatory, on the Caribbean island of Montserrat, place a temporary GPS monitor on Soufriere Hills volcano.

InSAR (interferometric synthetic aperture radar) is a three-dimensional mapping technique that uses radar images collected by satellites. Radar images of the same area at different times are compared and a map of ground deformation is created by computers (Figure 7.5, page 164). InSAR is useful because it measures an entire area and can be used in areas that are difficult to access for ground-based volcano monitoring. Images have centimetre-scale accuracy over very large areas.

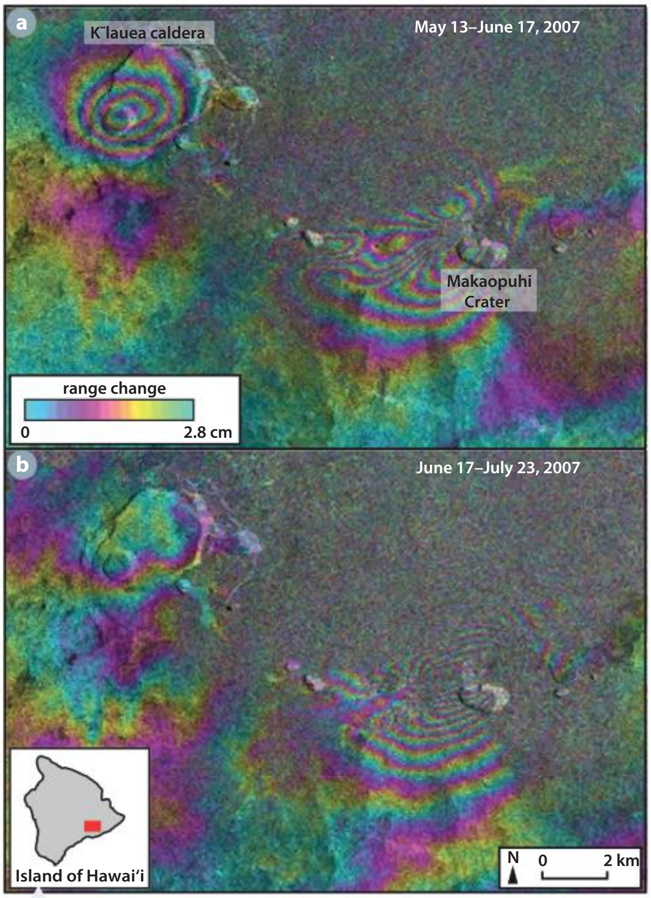

FIGURE 7.5 InSAR images of **a** the start and **b** the end of the eruption at Kilauea, Hawaii, 17–19 July 2007

An emerging technology in volcanic monitoring is LiDAR (light detection and ranging). LiDAR is similar to radar but uses ultraviolet, visible, or infrared light rather than radiowaves. In LiDAR, light is emitted by a laser on an aeroplane and reflected back to a telescope on the same aeroplane. LiDAR can reveal the shape of a mountain under vegetation. LiDAR is currently being used to monitor and forecast the distribution of volcanic ash from Mount Agung in Bali (Figure 7.6). Differential absorption LiDAR can also measure flux of volcanic CO_2 emissions.

Seismic data

Any movement of magma beneath a volcano produces distinctive earthquakes that reflect the type of movement, as shown in Table 7.1. Seismic data are a key technology used in volcanic monitoring. Most earthquakes are too small to feel and are quite shallow. They may occur in swarms with hundreds of events. Most swarms do not lead to eruptions, but eruptions are generally preceded by swarms. Geologists measure the depth and type of signals in a swarm to help determine the likelihood of an eruption.

Effective seismic monitoring requires at least 10 stations around a potentially hazardous volcano. Seismographs are buried 1–2 metres below the surface, and their electronics, batteries and solar panels are installed above ground. Signals are sent to a nearby observatory where computer models analyse the data in real time. It is important to know the baseline seismicity of an area so that significant changes can be noted. Seismic data, in conjunction with deformation measurements, can be used to track the movement of magma below the surface and predict eruptions. In the future, techniques such as seismic tomography will produce images of rock and magma below the surface, much like a computed tomography (CT) scan does for our bodies.

FIGURE 7.6 A ground-based LiDAR system used to monitor ash from Mt Agung on Bali

Gas monitoring

Volcanic gases indicate what is happening inside a volcano and can pose serious health risks. The most abundant volcanic gases are water vapour, CO_2 and sulfur dioxide (SO_2). Other notable gases include hydrogen sulfide, hydrogen, carbon monoxide, hydrogen chloride, hydrogen fluoride and helium. Gases can be collected and measured by a mass spectrometer in a

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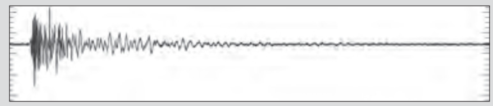
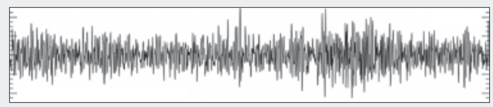
TABLE 7.1 Typical seismic signals associated with volcanic activity

NAME	DESCRIPTION	SEISMIC TRACE
Volcano–tectonic (VT)	Rapid magma intrusion causes abrupt fracture of surrounding rock. Trace is similar to tectonic earthquakes.	
Long-period (LP)	Magma and gases flow through conduits, causing surrounding rock to vibrate. Earthquakes have a lower frequency of oscillation. Glacier movement may also cause this type of seismicity.	
Hybrid	Pressurisation under a volcanic dome at shallow level causes seismicity with features of both VT and LP earthquakes.	
Tremor	The continuous high-amplitude signal of a tremor can be caused by extended magmatic flow, continuous VT or LT events, or explosions with continued ash and gas venting.	

lab, but this method may be dangerous and the gas analysis can take weeks. Instead, ground, air or satellite instruments are used to detect CO_2 and SO_2 (Figure 7.7).

Alamy Stock Photo/AB Forces News Collection

FIGURE 7.7 Ground-based monitoring of SO_2 at Leilani Estates during the eruption of Kilauea, Hawaii, in May 2018

An airborne correlation spectrometer (COSPEC) is an established method for measuring SO_2 concentrations. COSPEC measures the amount of ultraviolet light absorbed by SO_2 in a volcanic plume, using scattered sunlight as the light source. COSPEC is calibrated by comparing measurements to known SO_2 standards mounted in the instrument. A COSPEC is typically mounted in an aircraft with the telescope out the window, and several traverses are flown underneath the volcanic plume to determine the average SO_2 concentration. COSPEC is being replaced by DOAS (differential optical absorption spectroscopy) instruments that make similar measurements and can also be mounted on satellites. Both types of spectrometer are also used for ground-based monitoring.

LI-COR is a small infrared spectrometer that is used to measure CO_2 in volcanic plumes. Unlike the SO_2 detectors, Li-COR must be flown through the volcanic plume to directly sample the air.

CO_2 comes out of solution at greater depths than other gases, so rising CO_2 levels can indicate new magma entering the system. SO_2 is released by magma near the surface and is a reliable indicator of eruption danger. However, SO_2 is highly soluble, so if the volcano has crater lakes or glaciers, it may be impossible to determine how much SO_2 is being released.

Although highly specialised gas monitors are the most accurate monitoring methods, in Costa Rica scientists have developed a method to predict eruptions of the Turrialba volcano using images from normal digital cameras. They found that distinctive pulses of steam occur a few hours before eruptions that hurl pyroclasts into the air.

INVESTIGATION 7.1

Information and communication technology capability

Asia and Australia's engagement with Asia

Monitoring Indonesian volcanoes

There are approximately 1500 potentially active volcanoes, not counting those on mid-ocean ridges. Indonesia has the greatest number and density of active volcanoes in the world, mostly along the Sunda Volcanic Arc. The Volcanological Survey of Indonesia operates a network of 64 volcano observatories that monitor 59 volcanoes.

AIM

To determine which technologies are being used to monitor an active Indonesian volcano

METHOD

Volcano Discovery

1. Search recent news articles or reports on the website Volcano Discovery to choose an Indonesian volcano that is actively erupting or predicted to erupt soon.
2. Search for articles from news services and geological sites about the current or predicted eruption.
3. Record the monitoring technology used and information gained from the technology.

RESULTS

Present a summary of the current eruption as a table or infographic.

DISCUSSION

1. Which type of data is being used most extensively?
2. How do the data relate to the movement of magma and eruption hazards?
3. Are only Indonesian scientists involved in the monitoring, or are other countries and organisations contributing to the monitoring effort?
4. What prediction do volcanologists make about this volcano based upon current data?

CONCLUSION

Summarise the usefulness of technologies to monitor your chosen volcano.

Early warning systems

WS Monitoring volcanic activity

Data from deformation, seismic and gas monitoring are used to predict the likelihood of volcanic eruptions but communicating these to people in affected areas is best done with an early warning system. When Mount Pinatubo became increasingly active in 1991, volcanologists issued warnings that led to large-scale evacuations from a broad area around the volcano. These warnings saved thousands of lives and hundreds of millions of dollars in property losses.

Although multiple organisations warned the Colombian government of an imminent eruption of the Nevado del Ruiz volcano in 1983, no early warning was given. The resulting lahars killed more than 23 000 people in the towns of Armero and Chinchiná. Had the warnings of volcanologists been heeded, the loss of life could have been drastically reduced.

Until recently, early warning systems have relied on scientists warning the public about increasing danger levels. In 2010, geophysicists from the University of Florence, Italy, created the world's first automated early warning system, which alerted authorities near Mount Etna an hour before an eruption. This warning system was based upon infrasound that is produced when gas rising in the volcano's crater moves back and forth. The early trial proved so successful that in 2015 the system was programmed to send automatic email and text message alerts to authorities.

In 2019, the US Senate passed legislation creating the National Volcano Early Warning System (Figure 7.8) to ensure that the nation's 161 active volcanoes are monitored in a standardised way and that those without adequate monitoring will have appropriate instrumentation installed. Early warning gives people time to

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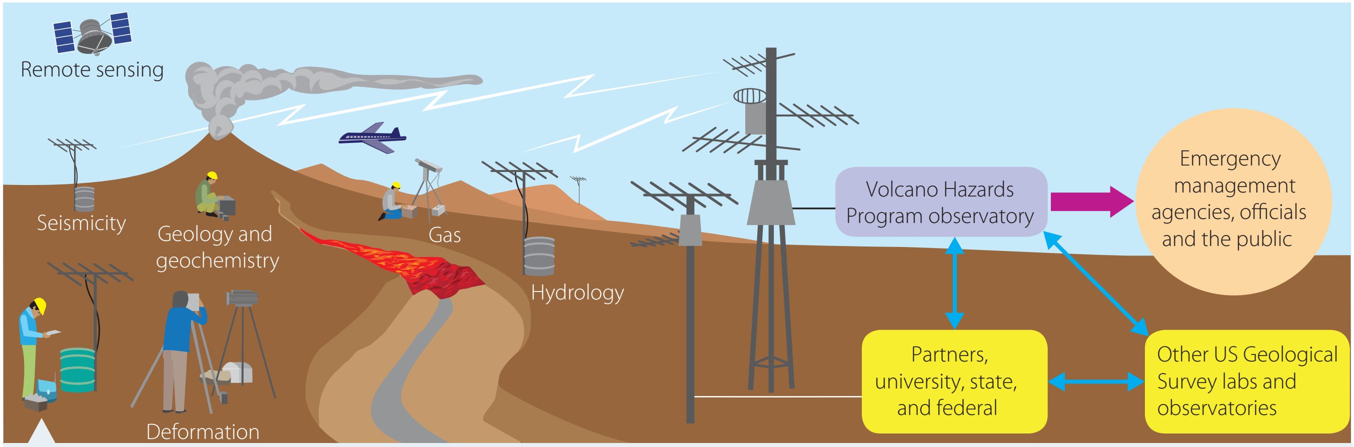

U.S. Geological Survey

FIGURE 7.8 Data from volcanic monitoring are coordinated by an observatory and used for early warning in the US National Volcano Early Warning System.

evacuate and governments time to coordinate emergency responses.

The volcano Sakurajima on the southern Japanese island of Kyushu is the most active and closely monitored of Japan's volcanoes (Figure 7.9). Sakurjima is only 8 km from the city of Kagoshima (population approximately 700 000) and just 50 km from a nuclear power plant. The volcano is in a state of near constant activity, with minor eruptions every 4–24 hours and larger strombolian-style eruptions every few months.

The Kagoshima Meteorological Office and the University of Kyoto have installed 18 seismometers and 24 GPS stations around the volcano. This system led to evacuations in August 2019 when the alert level was raised to level 4 of 5. Ash forecasts are included with weather reports in Kagoshima and the Volcanic Ash Advisory Centre in Tokyo issues alerts for all of Japan's active volcanoes.

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FIGURE 7.9 Sakurajima in Japan erupts nearly daily, just across the bay from Kagoshima.

Historical data

While Japan has extensive historical data about volcanos and their eruptions, other regions have few written records. In Australia, the Gugu Badhun people have passed down stories of an explosion that created a massive crater, filling the air with dust and lava flow around the Kinrara volcano in northern Queensland approximately 7000 years ago. Stories of a shrieking bullin and Craitbul's family cooking food buried in hot earth document the most recent volcanic activity more than 4000 years ago in the Newer Volcanics Province at Mount Gambier in South Australia (Figure 7.10).

Shutterstock.com/ian woolcock

FIGURE 7.10 Blue Lake at Mount Gambier, South Australia, is a volcanic crater lake.

INVESTIGATION 7.2

Information and communication technology capability

Aboriginal and Torres Strait Islander peoples

Intercultural understanding

Literacy

Interpreting Aboriginal and Torres Strait Islander oral traditions

Aboriginal art depicts megafauna that became extinct up to 40 000 years ago. Oral histories accurately recount sea level changes that occurred more than 7000 years ago. Volcanic eruptions between 7000 and 4000 years ago are described in stories handed down for hundreds of generations.

AIM

To illustrate an oral history of an Australian volcanic eruption

METHOD

1. Search the Internet to find traditional accounts of Australian volcanic eruptions. Helpful search phrases include 'when the bullin shrieked' and 'Gugu Badhun Kinrara volcano'.
2. Record the traditional story and the volcanic events described in the story.
3. Create a series of illustrations telling the story and showing the features of the volcanic eruption.

DISCUSSION

1. Based on the traditional story you read, describe the volcanic eruption and associated hazards.
2. Discuss the benefit of preserving stories of a volcanic eruption for future generations.

CONCLUSION

Summarise the accuracy of an Aboriginal oral history of volcanic eruption.

Volcanic eruptions can be accurately dated using igneous deposits from eruptions. Multiple eruptions in a single location can indicate the relative frequency of eruptions over time. Mapping the extent of the eruptions indicates how violent the eruptions were. When a volcano's history is known, the long-term eruptive risk can be confidently predicted.

Technologies used to predict earthquakes

In late 2008 and early 2009, the city of L'Aquila, north-east of Rome, experienced a seismic storm. Some tremors were powerful enough to prompt school evacuations. An amateur seismologist forecast an imminent earthquake based on steep rises in his radon detectors. Amid growing public unrest, Italian government seismologists held a special meeting in L'Aquila. They pointed out that:

- the area had a high risk of earthquakes
- seismic swarms only rarely precede major earthquakes
- radon spikes have no forecasting value.

On 6 April 2009, a week after the meeting, a magnitude 6.3 earthquake shook the region around L'Aquila, resulting in 308 deaths (Figure 7.11).

Six of the scientists and one government official who participated in the L'Aquila meeting were charged with manslaughter. After a year-long trial, all were found guilty and sentenced to 6 years' imprisonment. Their appeal took 2 years, after which the six scientists were finally acquitted.

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FIGURE 7.11 The aftermath of the 2009 L'Aquila earthquake in Italy

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The L'Aquila case highlights the unpredictability of earthquakes and the public's poor understanding of predicting risk versus predicting events. An earthquake prediction must give the date and time, location and magnitude of an event. An accurate prediction of this nature has never been made.

Earthquakes are a sudden release of stress in Earth's crust. The crust is complex and highly variable, making its response to changing stress very difficult to predict. Laboratory simulations cannot accurately reflect real-world complexity. Many seismologists maintain that there is little chance of ever developing an accurate way to predict exactly where and when an earthquake might occur. However, the probability of a significant earthquake can be predicted based upon data from current technologies and historical records.

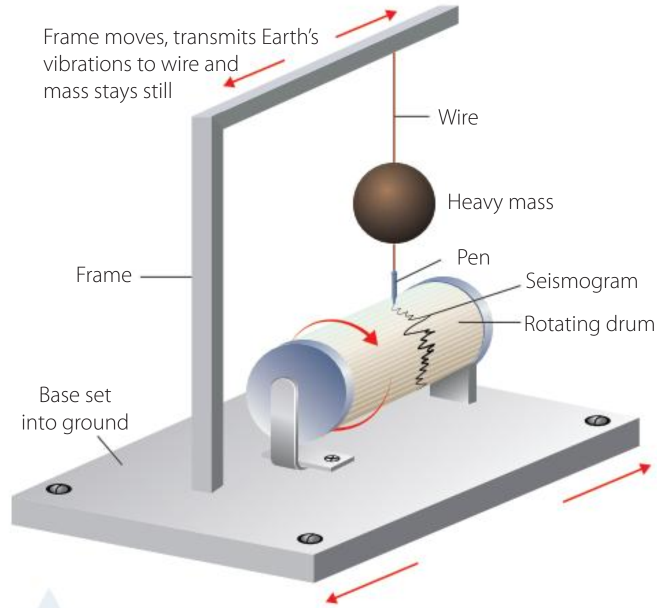

FIGURE 7.12 The heavy mass in a seismograph stays still, while Earth moves around it. Older seismograms are recorded by a pen attached to the mass.

Ground movement

Many of the technologies used to monitor deformation and ground movement in volcanic activity are also used along active faults with high earthquake risks. The main technology used in earthquake monitoring is the **seismograph**. Seismographs are instruments that record ground movement. The internal portion of a seismograph is the **seismometer**. The original seismometers were a pendulum or mass mounted on a spring (Figure 7.12). These bulky devices have been replaced by electronic detectors that measure movement of a mass in a frame by the voltage generated. Electronic systems allow the measurement of movement in all directions. A **seismogram** is the graphical record of ground movement with time (in seconds) on the horizontal axis and ground displacement (usually in millimetres) on the vertical axis. Earthquake monitoring seismographs are sensitive enough to measure movements as small as 10^{-7} cm at very quiet sites. Thus, seismograms can record ground motions from trees blowing in the wind, highway traffic and ocean waves.

Seismologists use the technique of triangulation using the distance measurements from multiple seismographs to determine the epicentre of an earthquake. The depth of the focus is determined by measuring the time between P-waves and reflected P-waves. The time difference is then compared to published depth tables.

Seismographs can be used for short-term risk prediction because large earthquakes are generally followed by aftershocks. In hindsight, a strong aftershock may be considered the main earthquake and prior events are then considered foreshocks. For example, on 4 July 2019, a magnitude 6.4 earthquake occurred near Ridgecrest in eastern California. This was followed by thousands of aftershocks, including a magnitude 7.1 earthquake on 5 July. The large event on 4 July was subsequently considered a foreshock of the larger event on 5 July.

GPS accurately measures ground movement and tracks the ongoing deformation of the crust between earthquakes. GPS can also record displacement during earthquakes. Displacement is related to the magnitude of earthquakes. GPS data are used in a warning system known as G-FAST, soon to be operational around the Pacific Rim. Ground displacement data from real-time GPS allow scientists to quickly determine the magnitude of a large earthquake and provide immediate information to emergency and aid agencies.

Another application of real-time GPS is to measure the speed of the initial movement along a fault. Initial movement is higher when magnitude is higher. This pattern is apparent 10–15 seconds into the earthquake and allows warnings to be issued along fault lines to emergency services and those who might be affected by the earthquake or subsequent tsunami.

Strain meters

As in volcanic monitoring, strain meters are buried deep in boreholes near faults and are used to monitor crustal strain. Analysis of correlation coefficients of strain components may identify an imminent earthquake, but this correlation has only been noted after earthquakes. Increased strain readings may be used for generalised risk assessment but are not accurate enough for predicting a single event.

Animal behaviour

Throughout history, there have been many reports of unusual animal behaviour before an earthquake. The earliest reference to this is from Greece in 373 BCE, where small mammals and insects were seen to move out into the open before a damaging earthquake. Unfortunately, reports of animal behaviour do not tell us when this occurred other than before the event. As with other types of predictions, animal behaviour is only useful if it can predict exactly when and where a major earthquake will occur.

Many animals can detect the P-wave vibrations of an earthquake that humans cannot feel, but this is detection rather than prediction. German researchers studied 729 reports of abnormal animal behaviour, most of which related to three specific earthquakes: Darfield, New Zealand, 2010; L'Aquila, Italy, 2009; and Nagano-ken Seibu, Japan, 1984. Unusual behaviour occurred seconds to months before the earthquakes at distances ranging from kilometres to hundreds of kilometres from the epicentre. Many correlated with foreshocks, indicating that animals were detecting actual earthquakes that humans did not feel. No behaviours predicted earthquakes.

The Indian Ocean tsunami on Boxing Day in 2004 was followed by numerous reports of unusual elephant behaviour (Figure 7.13). Elephants are known to detect seismic waves at distances of more than 30 km. After the tsunami, it was claimed that elephants had a sixth sense that enabled them to avoid the damaging wave. However, data from two satellite-collared Asian elephants in Sri Lanka showed no change in behaviour that would indicate flight due to seismic vibrations or foreknowledge of the tsunami. Although from a very small sample, these data are the only systematically collected data on the movement of wild animals during the earthquake and tsunami.

In 2016, Martin Wikelski from the Max Planck Institute for Ornithology started a prospective scientific investigation of animal behaviour and earthquakes. Wikelski tagged Italian farm animals with small sensors that measure movement and location. Animals tagged included a rabbit, sheep, cows, turkeys, chickens and dogs. This study is part of the larger ICARUS (International Cooperation for Animal Research Using Space) initiative that has fitted more than 10 000 animals with radio transmitters to monitor migratory behaviour. The tracking system on the International Space Station went live in July 2019, but no distinctive behaviours predicting earthquakes had been detected by that time.

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FIGURE 7.13 Elephants were reported to run for high ground before the 2004 Indian Ocean tsunami, but studies of satellite-collared animals in Sri Lanka showed no difference in behaviour associated with the earthquake or tsunami.

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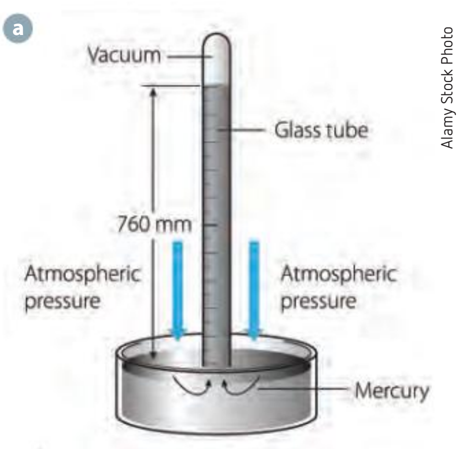
Technologies used to predict east coast lows

East coast lows are characterised by intense low-pressure systems that may be caused by a variety of weather phenomena at any time of year. Accurate technologies to monitor the movement of pressure systems and their interaction with warm waters off the east coast of Australia are vital to predicting these damaging events.

Pressure systems

Atmospheric pressure is the force per unit area exerted by the weight of the atmosphere. Pressure is measured by a barometer. The first barometers were open-ended metre-long columns filled with mercury sitting in a container of mercury (Figure 7.14a). Due to the large size and chemical hazard of mercury barometers, they were replaced by aneroid barometers. Aneroid barometers contain a flexible metal box from which air has been extracted. The box is compressed as air pressure increases and expands as pressure decreases. A pointer attached to the box moves as it expands and contracts, indicating changes in pressure (Figure 7.14b).

Aneroid barometers are commonly used in households but have been replaced by more accurate digital technologies for weather tracking. Digital barometers are based on a pressure transducer and are found in most smartphones to augment elevation data provided by GPS services. The SI unit of pressure is the pascal (Pa). This is equivalent to 1 newton of force over 1 square metre. In weather forecasting, the most commonly used unit is the millibar (mbar), which is equal to 100 Pa. The millibar and hectopascal (hPa) are the same quantity with different unit names. Normal atmospheric pressure at sea level is 1013.25 mbar (hPa) or 101 325 Pa.



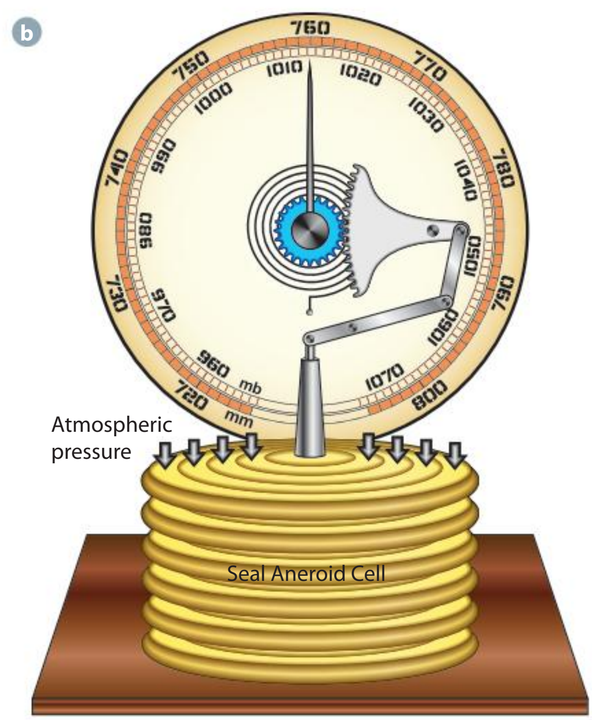


FIGURE 7.14 **a** The original mercury-filled glass barometer was replaced by **b** the safer aneroid barometer.

Barometric pressure varies at different locations. Barometric pressure in weather reports is presented as the **mean sea level pressure** (MSLP) map shown in Figure 7.15. An MSLP map is a summary of hundreds of weather observations taken at the surface by land-based weather stations, ships in the Australian Voluntary Observing Fleet and weather buoys drifting in the oceans; in the

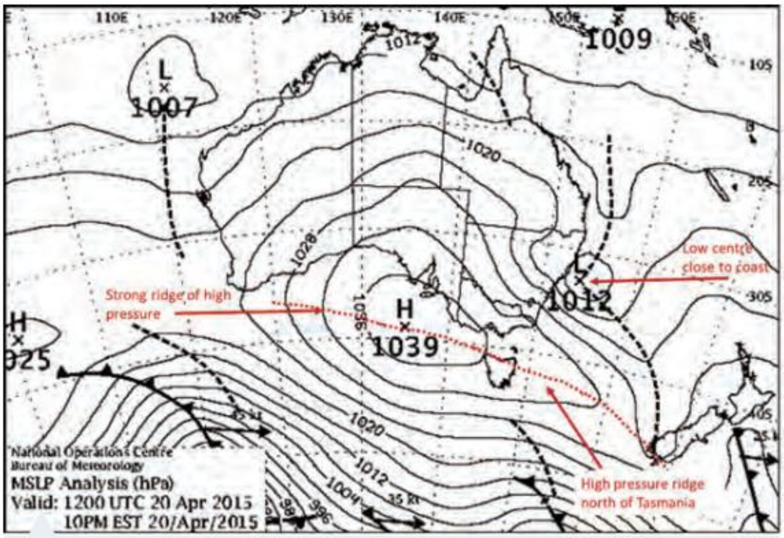


FIGURE 7.15 Mean sea-level pressure analysis showing an east coast low

atmosphere by weather balloons; and from weather satellites in geostationary orbits. MSLP maps are used to report the current weather and projections are used for short-term weather forecasting. In general, low-pressure systems are associated with clouds and rain, while high-pressure systems are associated with clear weather.

East coast lows occur when a wave of air 10–15 km above the ground moves towards the coast, causing a low-pressure system in the low levels to develop along its eastern side. This low-pressure system close to the surface interacts with warm water along the east coast, causing the low pressure to develop more rapidly. If a high-pressure ridge to the south blocks the low from moving away, it creates a strong pressure difference along the south side of the low, causing even stronger winds.

Meteorologists can see signs of a developing east coast low up to a week in advance. However, the severity of the system is not apparent until it has developed. East coast lows may develop over the course of 12–24 hours, prompting severe weather warnings.

FIGURE 7.16 A moored weather buoy

Temperature

A large temperature gradient between the air of a low-pressure system and warm sea surface temperatures is key in the development of an east coast low. Air and sea temperatures are monitored by the same weather stations that record barometric pressure. Automated weather stations and buoys (Figure 7.16) send information about wind speed, pressure, air and water temperature to the Bureau of Meteorology for analysis. Readings are updated every 30 minutes and are fed into sophisticated computer models to analyse the likelihood of dangerous conditions on land and at sea.

INVESTIGATION 7.3

Information and communication technology capability

Critical and creative thinking

Literacy

Numeracy

Forecast the local weather using MSLP maps

AIM

To create a weather forecast for the next four days

METHOD

1. Access the Bureau of Meteorology website.
2. Click on 'Weather maps'; select 'Australian Region' and then 'Forecast map for the next 4 days'. You will find weather map forecasts for 10 a.m. and 10 p.m. for each of the next four days.
3. Construct a table to record the following data for each of the eight weather maps for your region of the state: closest pressure isobar, maximum and minimum pressures shown on the map for the country, and the location of the nearest warm or cold front.

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» **RESULTS**

Write a weather report similar to those on the news. Predict the likelihood of rain based on the prevailing pressure systems. Illustrate your forecast with a print-out of the maps.

DISCUSSION

1 What is the trend in air pressure at your location over the next four days?
2 In which direction are current weather systems moving across Australia?
3 If the distance between Sydney and Perth in a straight line is 3300 km, calculate the speed of movement of the weather systems across Australia (over the four days) in km h^{-1}.
4 Based on the short-term maps, are there any patterns that might lead to an east coast low? Explain your answer.

CONCLUSION

Write a suitable conclusion about local weather conditions.

KEY CONCEPTS

- Volcanic eruptions can be predicted using tiltmeters, GPS, InSAR and LiDAR to measure ground swelling.
- Seismic data indicate the type of magma movement within a volcano.
- Gas emissions correlate with magma composition.
- Early warning systems use volcanic monitoring data to prompt evacuation before eruptions.
- The volcanic history of an area can provide an indication of long-term risk and eruption type.
- Earthquakes cannot be accurately predicted with current technologies.
- Seismographs, GPS and animal behaviour can indicate the start of an earthquake.
- East coast lows are tracked and predicted by measurement of barometric pressure and temperature with the aid of computer modelling.

CHECK YOUR UNDERSTANDING 7.1

1 Outline changes in volcano shape that may indicate an eruption is imminent.
2 Explain the advantage of InSAR monitoring for ground deformation.
3 Identify two reasons to carry out monitoring of volcanic gases.
4 What are the advantages of early warning for volcanic eruptions?
5 List the three criteria required for accurate earthquake prediction.
6 Which existing technologies can be used to detect earthquakes?
7 How are the data collected to create mean sea level pressure maps?
8 Why are both pressure and temperature measurements needed to predict formation of an east coast low?

7.2 Technologies used to minimise the effect of geological hazards

To minimise the effects of geological hazards on humans, we need to predict the overall risk at a location and, when possible, predict individual events. As you learnt in section 7.1, many technologies are available to predict volcanic eruptions and allow evacuation of vulnerable populations, but technology can only detect earthquakes as they occur. Earthquakes cause approximately 10 000 deaths annually. The United Nations says that alleviating poverty and developing effective government responses are the two highest priorities in reducing this grim statistic.

Australia is in the middle of a tectonic plate and geological disasters affect us much less than other countries, but we are not immune. Australia has small earthquakes every day and a magnitude

Jozua van Otterloo

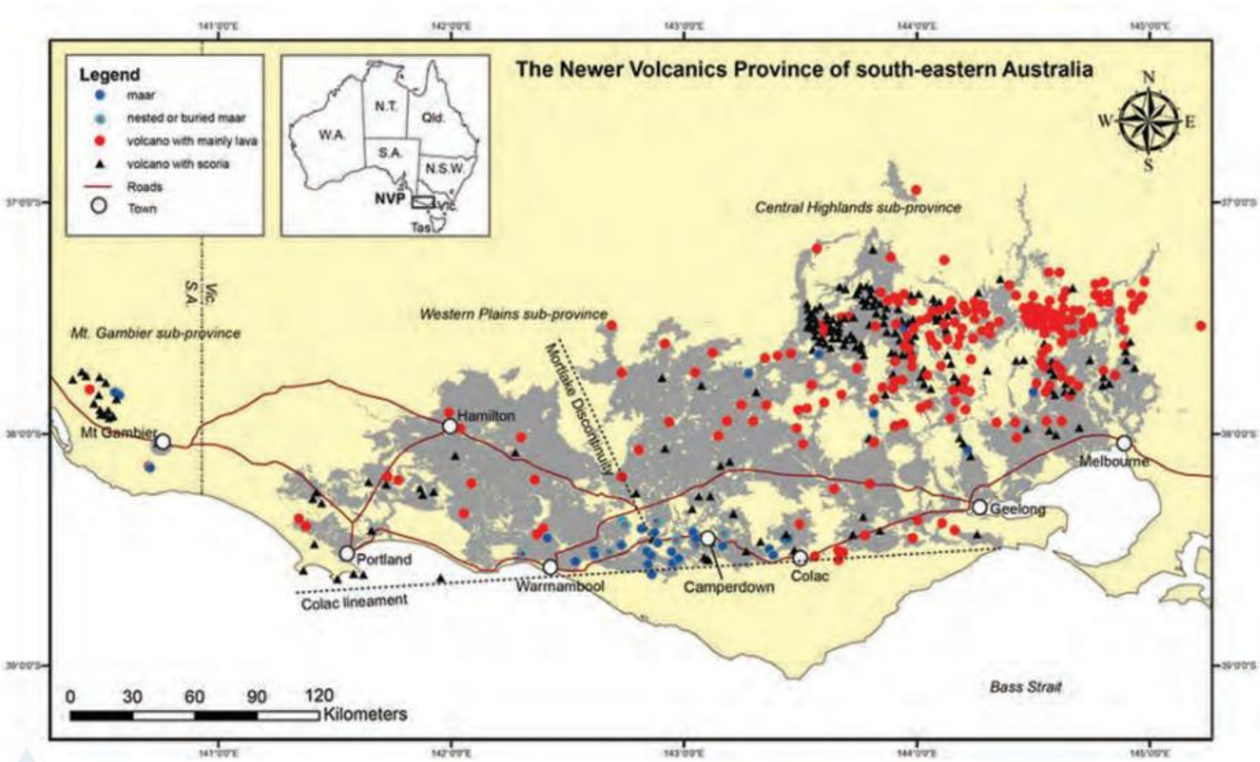


FIGURE 7.17 Many volcanologists consider the Newer Volcanics Province to still be active.

6 earthquake every 5 years or so. The Newer Volcanics Province stretches more than 400 km and contains more than 400 volcanoes (Figure 7.17). Most of these produced effusive eruptions and extensive lava flows, but some, including Mount Gambier, featured explosive eruptions and pyroclastic flows.

Building codes

A building code is a set of rules put in place by local, regional or national governments for the construction of new buildings. In 1997, Australia began calling these rules Australian Standards. Standards may be modified in response to events in Australia and elsewhere. After the 1989 Newcastle earthquake, building codes were amended to design for seismic load in Australia (Figure 7.18). This was fortunate for the people of Broome when a magnitude 6.5 earthquake shook the city in July 2019, releasing 100 times more energy than the magnitude 5.6 Newcastle event. Many older buildings in cities such as Sydney and Melbourne pose a great risk with their unreinforced masonry (brick and concrete) construction.

with permission from Newcastle Libraries

FIGURE 7.18 Damage from the 1989 Newcastle earthquake prompted revision of Australian building standards.

Earthquake-resistant buildings

Ground movement can be terrifying, but building collapse causes most deaths from earthquakes. Most buildings are designed to resist the downward vertical force of gravity, but not the lateral movement of earthquake waves. Fortunately, there are a variety of engineering solutions that can make a building earthquake resistant.

Base isolation involves constructing a building on flexible pads, bearings or springs so that the base moves during the earthquake and absorbs the shock wave, without moving the building above (Figure 7.19). This reduces horizontal movement so that there is less damage. Pads are typically made of lead for vertical strength, and wrapped in rubber and steel bands that allow horizontal flexibility. These are attached to the foundation with steel plates.

Force damping can be by fluid-filled pistons (similar to a shock absorber in a car) or by pendulums. Pistons convert movement into compression of oil and heat, while the pendulum ball moves in the opposite direction to the building sway, stabilising the structure. Both features must be tuned to counteract the building's natural sway frequency. The Taipei 101 skyscraper is located 200 metres from a major fault in a typhoon-prone city (Figure 7.20). It features a 660-tonne tuned damper pendulum connected to eight dampening pistons at the base.

Structural reinforcement in both horizontal and vertical structures is key. Vertical structures are often built using cross-bracing. In addition, stiff shear walls around lift shafts or stairwells help the structure resist rocking forces. If a more flexible design is needed, moment-resisting frames allow columns and beams to bend while keeping the joins between them rigid. Horizontal bracing uses diaphragms, which are the floors and roof of a building. These are placed on a reinforced frame that spreads horizontal forces to the vertical structures.

Flexible materials such as steel and wood allow a structure to bend and deform without breaking. These materials absorb the energy of an earthquake without breaking. This was evident in the 2011 Sendai earthquake in Japan when the swaying of buildings in Tokyo was captured on film. No buildings collapsed, thanks to Japan's stringent building codes.

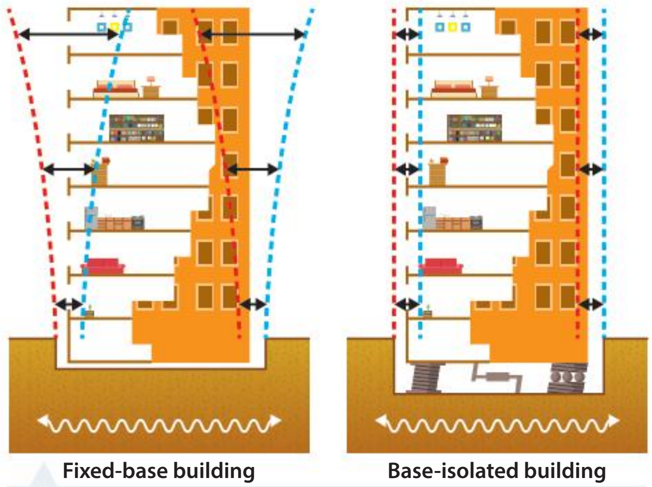


FIGURE 7.19 Pads, bearings or springs under a building absorb the horizontal movement during an earthquake in a base-isolated building.

FIGURE 7.20 The 660-tonne tuned damper in the Taipei 101 super skyscraper is augmented by two 6-tonne dampers in the spire and reduces building sway by 40% in an earthquake or typhoon.

INVESTIGATION 7.4

Open-ended investigation – build an earthquake resistant structure

Information and communication technology capability

Critical and creative thinking

Literacy

Engineers must carefully test building designs to determine their resistance to seismic forces. To test these designs, they place components of a building or scale models on a shake table and test them during simulated earthquakes.

AIM

To build a shake table that can be used to replicate earthquake ground movement and use it to test structures

»

Numeracy

Personal and social capability

MATERIALS

Create a detailed list of materials when you have decided upon the materials for your shake table and structures.

RISK ASSESSMENT

What are the risks associated with your design? Identify the risks and how you will manage these risks to stay safe.

METHOD

1. As a class, decide upon a shake table design and permissible building materials. Possible options include using jelly as a substrate, suspending a platform by elastic bands or placing a platform on a tray of ball bearings. In choosing your design, consider how closely the movement mimics real seismic waves.
2. Determine how you will measure the strength of shaking. You might use a seismograph app on a smartphone, a spring balance or an actuator with different settings.
3. Choose building materials that are easily available. Examples are toothpicks, marshmallows, straws, paperclips, pins, string and paper.
4. Give everyone a set length of time to use identified building strategies that will strengthen their structures. Decide whether you will build similar structures without special features to act as controls.
5. Decide upon a standardised testing method. How long will structures be shaken? How will you increase the force of shaking? Will you test to failure? How will you decide that a building has failed? What data will you record?

RESULTS

Record your results in a well-designed table that includes the structural features and amount of shaking that each structure could withstand.

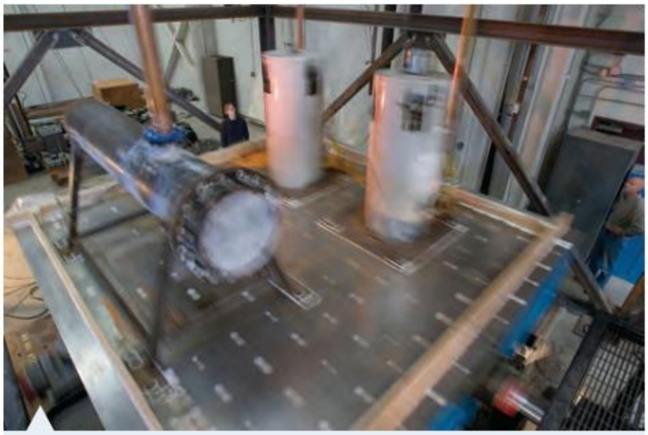
DISCUSSION

1. Explain your design choices for the shake table.
2. Describe the effect of different building techniques or combinations of techniques.
3. What features improved earthquake resistance in this investigation?
4. Evaluate the validity, reliability and accuracy of your experiment.
5. Assess the applicability of your results to real world buildings.

EXTENSION

Improve your experiment to yield more valid and reliable results.

Test structures with the same design features, but different heights or widths.



Alamy Stock Photo/Cavan

FIGURE 7.21 Shake table testing of water heaters and piping at the University of Nevada Reno, USA

Building for volcanic hazards

The most important decision when building in a volcanic region is where to place structures. Historical data can be used to assess areas of greatest risk and topography must also be considered. Structures should be located near evacuation routes and away from valleys that may funnel pyroclastic flow and lahars toward buildings. Key infrastructure should be as far from the volcano as possible.

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Buildings in a volcanic region should have steeply pitched smooth roofs that allow ash to slide off. Ash is at least three times as heavy as snow, so roofs require triple the support. During the 1991 eruption of Mount Pinatubo, steep roofs were more likely to fail due to wind, so adequate bracing is vital. Roofs with wide spans, such as warehouses, are more vulnerable to collapse than those on small homes. Solar panels, roof tanks and chimneys can cause ash to accumulate unevenly and increase the risk of roof collapse. Ash builds up in gutters and drains, so they should be avoided if possible.

Structures near a volcano must be built to withstand the seismic activity that is common around volcanoes. Buildings made from reinforced concrete can better withstand the wind, earthquakes, rock and ash fall associated with volcanic eruptions.

The ash and gases released from volcanoes are highly acidic and corrosive. These will not corrode through a metal roof during an eruption but can cause considerable damage if left in place for weeks afterwards. Outdoor electronics should be wrapped in plastic to avoid corrosion and windows should have shutters to tightly seal them and protect them from windblown debris during an eruption.

As you learnt in Chapter 5, lahars pose a serious risk to buildings downhill from the volcano and can occur at any time – not just during eruptions. Lahar flows follow valleys, so their pathways can be predicted and avoided or modified to channel the flow (Figures 7.22 and 7.23).

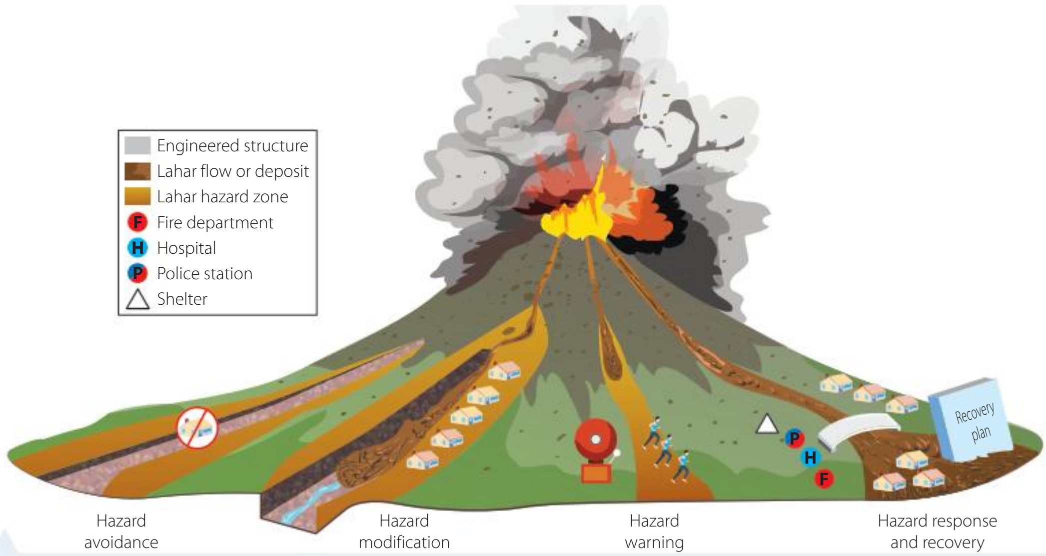

FIGURE 7.22 Strategies for reducing lahar risk include avoidance by zoning regulations, flow deflection, evacuation warnings and long-term recovery plans

FIGURE 7.23 Lahar diversion structures on **a** Sakurajima and **b** Usu volcanoes in Japan

Disaster warning systems

As described in section 7.1, early warning of volcanic eruptions is possible using a range of technologies. Advances in computer modelling allow government scientific agencies to monitor real-time events and warn populations of the risk of the need to evacuate. However, a warning by itself is useless without an educated population and planned emergency response.

Effective governments have agencies that prepare for all types of disasters by modelling risk and developing response plans. The Department of Home Affairs leads the Australian government's disaster and emergency management response. This includes evacuating Australian citizens from overseas in the event of natural disasters. Australia's tectonic stability means that geological disasters are much less likely than extreme weather events.

Coordinated government response to geological disasters involves providing staged warnings of danger so that people know when to evacuate. Emergency response teams are put on alert before an event and mobilised as needed. An example of this is the Japan Meteorological Agency's warning system. The Japan Meteorological Agency regularly updates volcanic warnings on a five-level scale, eruption notices, ash fall forecasts, tsunami warnings and earthquake information.

Japanese volcano warning system

A network of remote monitoring equipment around each active volcano sends real-time data to the constantly monitored volcanic observations centres in Sapporo, Sendai, Tokyo and Fukuoka. In addition, mobile teams perform measurements on the ground. If danger from a volcano is detected and assessed according to predetermined criteria, recreational activities are restricted and evacuations are triggered. Warning levels are shown in Figure 7.24.

Abbreviated term	Target area	Levels and keywords		Explanation		
				Expected volcanic activity	Action to be taken by inhabitants	Action to be taken by climbers
Warning	Residential areas	Level 5	Evacuate	Eruption that may cause serious damage in residential areas, or imminent eruption.	Evacuate from the danger zone. (Target areas and evacuation measures are determined in line with current volcanic activity.)	
		Level 4	Prepare to evacuate	Possibility or increasing possibility of eruption that may cause serious damage in residential areas.	Prepare to evacuate from alert areas. Let disabled persons evacuate. (Target areas and evacuation measures are determined in line with current volcanic activity.)	
Near-crater warning	Non-residential areas near the crater	Level 3	Do not approach the volcano	Eruption or possibility of eruption that may severely affect places near residential areas (threat to life is possible in these areas).	Stand by, paying attention to changes in volcanic activity. Let disabled persons prepare to evacuate in line with current volcanic activity.	Refrain from entering the danger zone. (Target areas are determined in line with current volcanic activity.)
	Around the crater	Level 2	Do not approach the crater	Eruption or possibility of eruption that may affect areas near the crater (threat to life is possible in these areas).	Stay as usual.	Refrain from approaching the crater. (Target areas around the crater are determined in line with current volcanic activity.)
Forcast	Inside the crater	Level 1	Normal	Calm: Volcanic ash emissions or other related phenomena may occur in the crater (threat to life is possible in these areas).		No restrictions. (In some cases, it may be necessary to refrain from approaching the crater.)

FIGURE 7.24 Japan Meteorological Agency's volcanic alert levels are easy for the public to understand.

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Earthquake warning systems

Seismograph data are used by the US Geological Survey ShakeAlert system and the Japan Meteorological Agency J-Alert Earthquake Early Warning System. P-waves are detected and used to estimate the magnitude of the earthquake. People need to know about earthquake and tsunami hazards as soon as these events begin because a warning may precede shaking by only seconds. The J-Alert system transmits emergency information via sirens, loudspeakers, phones, televisions and other electronic media. Alerts are triggered by the detection of tremors, and no human intervention is required. With no human oversight of warnings, the system can occasionally be tricked. In January 2018, two minor earthquakes struck at almost the same time in different locations, tricking the system into warning Tokyo commuters that a major earthquake was coming.

The ShakeAlert system in western USA became operational in late 2018, with the goal of warning the public of magnitude 5.0 or greater earthquakes through phone alerts in the initial stages. Los Angeles residents were angered when there was no warning of the 6.4 magnitude earthquake that originated approximately 200 km north-east of the city on 4 July 2019. Although Los Angeles experienced shaking, the ShakeAlert system had forecast only weak shaking and the warning threshold was set for higher levels of ground movement. Officials debate the setting at which to notify the public of shaking that is not predicted to cause damage.

Public education

Hazard warnings are only helpful if they trigger responses from utilities, emergency services and an educated public. A 2-day warning is needed for orderly evacuation, but is only possible for volcanic eruptions. Short-term earthquake warnings can still be very helpful. A warning of up to 30 seconds allows trains to slow, aeroplanes to stop taxiing, lifts to open and people to move away from dangerous machinery or take cover under a desk. Utilities can be automatically isolated to reduce the number of fires and emergency vehicles can be moved out of their garages. These events require an educated public to cooperate without panic.

Japan is a world leader in disaster management education. School students learn about the causes and effects of natural disasters in subjects such as social science and science. After school, students take part in disaster drills that incorporate lifesaving techniques and evacuation training. Students learn how to evaluate risk and respond accordingly. This knowledge saves lives. In the coastal city of Kamaishi, all 3000 school children evacuated to higher ground during the 2011 tsunami. The city suffered heavy damage and 1000 casualties, but the students took appropriate actions, make quick judgements and helped more vulnerable individuals.

Disaster education is not limited to schools in Japan. Since 1960, Japan has held Disaster Prevention Day on 1 September each year. This day commemorates the 1923 Great Kantō earthquake, which killed more than 100 000 people. On Disaster Prevention Day, drills are held around the country to improve coordination between government organisations, volunteer centres and the public (Figure 7.25).

Alamy Stock Photo / Newscom

FIGURE 7.25 Tokyo residents participate in a disaster drill for a possible massive earthquake on the eighth anniversary of the East Japan Great Earthquake.

KEY CONCEPTS

- Building codes prevent deaths caused by collapsing structures.
- Base isolation, movement dampers, structural reinforcement and flexible materials help buildings withstand the force of earthquakes.
- Building away from the path of lahars or redirecting their flow saves lives around volcanoes.
- Steep, well-braced roofs and reinforced concrete structures withstand heavy falls of ash and volcanic rock impacts.
- Early warning systems allow evacuation before volcanic eruptions occur.
- Earthquake warnings allow people to take cover or move away from danger.
- A coordinated government response and public education save lives and property in geological disasters.
- Japan's disaster education program includes school and public disaster drills.

CHECK YOUR UNDERSTANDING 7.2

1 How can building codes reduce building damage from volcanic eruptions?
2 Is it possible for building codes to reduce the possible damage from an earthquake?
3 Why are Australian cities particularly poorly prepared for an earthquake?
4 What are the advantages and disadvantages of installing early warning disaster systems.
5 How can education systems prepare the population of a city or region for both a volcanic eruption and an earthquake?

7.3 Accuracy of technologies used to predict natural weather events

On Christmas Day 1974, Cyclone Tracy hit Darwin with wind speeds of more than 100 km h^{-1}, killing 65 people and causing $800 million in damage. The first warning of this disaster came at lunchtime on Christmas Eve, leaving residents little time to prepare. Fortunately, the Bureau of Meteorology (BOM) has dramatically improved weather modelling and now warns of cyclones days in advance. The improvement in modelling over time is illustrated in Figure 7.26. Seven-day weather forecasts are now as accurate as three-day forecasts were in 2000.

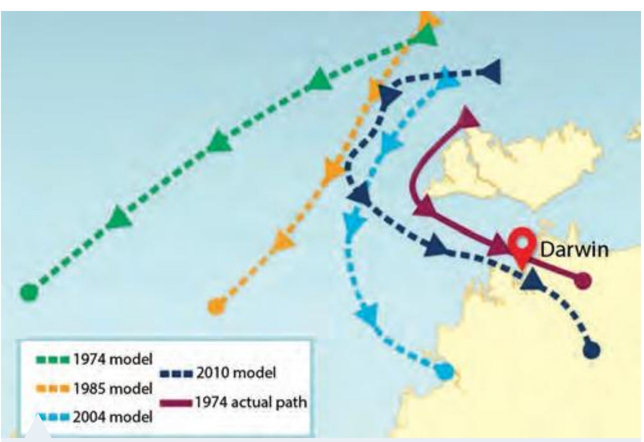


FIGURE 7.26 Improvements in computer models of cyclones are demonstrated with these predictions of Cyclone Tracy's path.

Meteorology is a global cooperation and Australia is one of the 192 members of the United Nation's World Meteorological Organisation that exchange observations and data. Accurate forecasting is vital to warn the public about storms and cyclones, to predict bushfire risk, for farmers to make decisions about planting and for the aviation industry to plan safe flight paths.

When making weather forecasts, the BOM collects data from many sources and analyses this with the

Australian Community Climate and Earth System Simulator (ACCESS) run on supercomputers managed by the National Computational Infrastructure. These forecasts are compared with different variations run in ACCESS and forecasts from Japan, the USA, the UK, France, Canada and a European collaboration. For longer forecasts of climate, simulations are run 165 times with slightly different starting conditions. When multiple repetitions and several different models predict the same outcome, forecasters can be more confident about that outcome. Seven-day summary forecasts are visible on the BOM's MetEye tool that allows visualisation of current conditions as well as the forecasts for temperature, rain, wind, waves, storms and UV Index.

MetEye
Use the MetEye information to summarise the weather forecast for the next three days in your area.

Technologies used in meteorology

As you learnt in section 7.1, temperature and air pressure are monitored by ground, sea and atmospheric instruments. Forecasting involves other technologies that feed into computer modelling, such as satellite imaging and Doppler radar. When the models do not agree, the experience of human meteorologists with local knowledge is vital to predict the likelihood of unique local conditions such as southerly busters or low-lying fog.

Satellite imagery

Most of Australia's space observations come from Japan's Himawari-8 and Himawari-9 satellites. These geostationary satellites scan Earth every 10 minutes. Sixteen channels record information about the atmosphere and take true colour photos. These allow the detection of tropical cyclones, developing thunderstorms, volcanic ash, fire and smoke, fog and clouds at resolutions of 0.5–2 km.

Satellite images
View the latest images from the Himawari satellites on the BOM website.

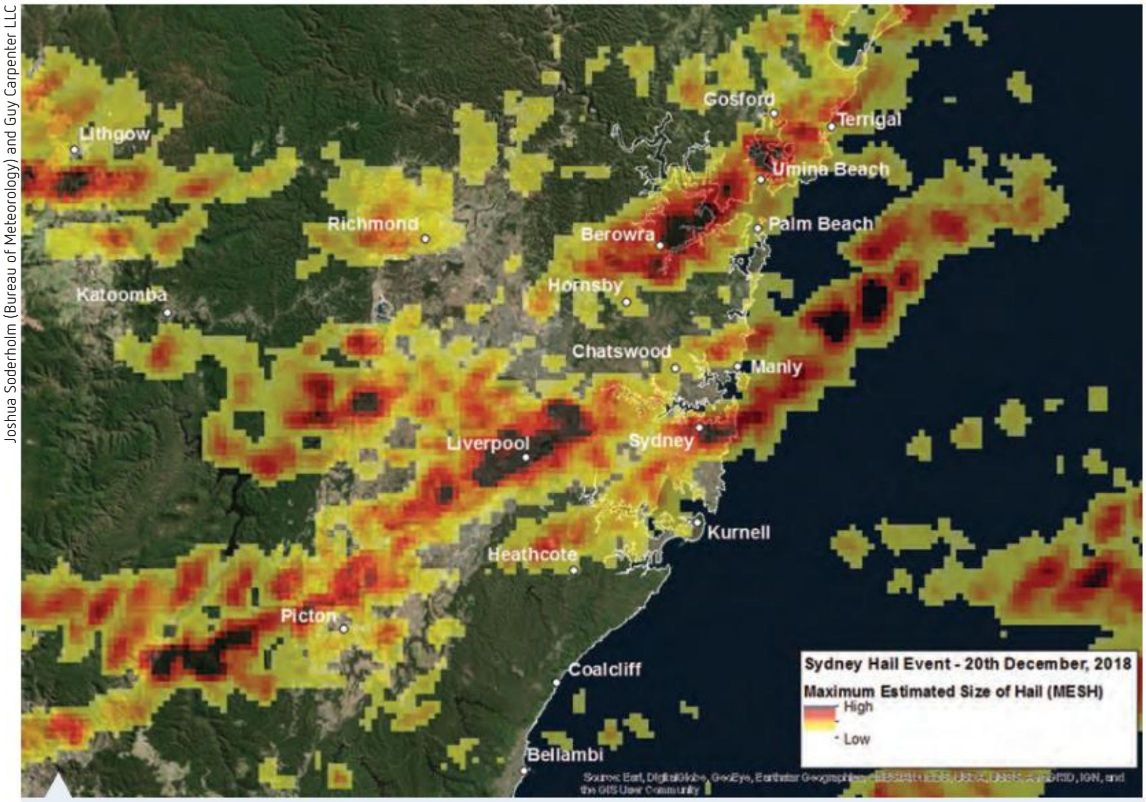
Radar

A national network of more than 60 Weather Watch radars sends out short pulses of electromagnetic waves and detects the reflected waves. This is similar to hearing an echo. The waves are reflected from precipitation and the distance can be calculated using the lag between emission and detection. Slight changes in frequency of the reflected wave allow calculation of whether the precipitation is moving towards or away from the source because of the Doppler effect.

WS **Satellite imagery**

The radar images are a map of reflected particles. These particles are usually water or hail. The strength of the returned pulse indicates the size of the particles and is used to create colour images of rainfall strength, as seen in Figure 7.27. Wind speed is assumed to be the same as precipitation speed, as the rain is blown by prevailing winds.

The optimal range for radar is 5–200 km. The curvature of Earth means that radar images beyond 200 km may reflect rain that only falls in the high atmosphere rather than at the ground. Inside the optimal range, rain detected on radar may evaporate before it reaches the ground. Weather radars may be fooled by swarms of insects, flocks of birds, sea waves, smoke and ash from large fires or aircraft. Comparison with satellite images and subsequent radar scans allows these false images to be eliminated. Reflections from local buildings and ground features create permanent echoes that are removed in image processing.



Joshua Soderholm (Bureau of Meteorology) and Guy Carpenter LLC

FIGURE 7.27 A radar image of a severe storm that hit Sydney on 20 December 2018, producing 8 cm diameter hailstones

Preventing damage from weather events

WS Weather monitoring

Long-term climate predictions allow investment in infrastructure that is designed for rising sea level, fresh water shortages, and increasing frequency and severity of storms. These most drastically affect the 85% of Australians living within 50 km of the coast and Australia's fisheries. Emergency services need to prepare for changes to fire-fighting as bushfire seasons become longer and fires more intense. Landscape design and plantings can be chosen for future climate conditions.

Seasonal forecasts help water authorities better manage water use, guide agricultural decisions about stocking numbers and crop choice, and help utilities prepare for extra demand during extreme heat. Decisions about when and how to undertake hazard reduction burns are guided by weather forecasts and current fuel loads. Water restrictions are enacted with respect to both storage levels and seasonal weather outlook.

Weekly weather forecasts are vital to avoid infrastructure damage and protect people from extreme weather events. The accuracy of forecasts is excellent for 48 hours, good for 5 days and reasonable for 7 days. The World Bank estimates that a 24-hour warning can prevent 5% of infrastructure damage, while a 7-day warning could prevent 15%. This translates into millions of dollars every year. Short-term forecasts enable communities and emergency services to prepare for events such as cyclones and to evacuate vulnerable areas. Shipping routes can be altered to avoid hazards or to take advantage of good conditions. Warnings of the sudden development of a dangerous storm provide people with time to move indoors and put vehicles under cover.

INVESTIGATION 7.5

Weather prediction accuracy

Information and communication technology capability

Critical and creative thinking

Literacy

Numeracy

AIM

To determine the accuracy of the 7-day weather outlook and record the actual temperatures and rainfall

METHOD

1. Access the BOM 7-day forecast for your city or area.
2. In a well-constructed table, record the predicted maximum and minimum temperatures for the coming week, along with any predictions of rainfall.
3. In an identical table, record the actual values for each day as they occur.
4. Calculate the percentage variation for each minimum and maximum temperature. Graph these values, using a key to distinguish the minimum and maximum percentage variations.

DISCUSSION

1. The BOM says that 2-day forecasts are very accurate, but longer forecasts are less so. Evaluate this statement with reference to your graph of percentage variation.
2. If you were packing clothes for a trip, would the 7-day outlook provide enough detail for you to decide whether you needed rain gear, a warm coat or short sleeves?
3. Was there any rain during the week? If so, how did this compare to the predicted rain?

EXTENSION

Investigate the meaning of the daily rainfall predictions. What does the percentage mean? What do the numbers mean?

KEY CONCEPTS

- Weather forecasting has become more accurate because of international cooperation, sophisticated computer modelling and a variety of data inputs.
- Satellite imaging allows tracking of cloud systems and large (0.5–2 km) scale systems.
- Radar provides detailed precipitation maps, allowing storm tracking and local warnings.
- Long-term climate predictions allow infrastructure planning.
- Seasonal forecasts are used to plan water allocation, agricultural activity and hazard reduction.
- Weekly forecasts guide storm preparation and evacuations.

CHECK YOUR UNDERSTANDING 7.3

1. Which of the services provided by the BOM do you think would be the most useful to people living outside major cities?
2. What is the time interval of the Doppler sweeps used to maintain the rain radar maps?
3. Why would the BOM require a Cray supercomputer to maintain their prediction and monitoring systems?
4. What are the types of information that can be collected from the MetEye system?

7 CHAPTER SUMMARY

- Volcanic eruptions can be predicted using tiltmeters, GPS, InSAR and LiDAR to measure ground swelling.
- Seismic data indicate the type of magma movement within a volcano.
- Gas emissions correlate with magma composition.
- Early warning systems use volcanic monitoring data to prompt evacuation before eruptions.
- The volcanic history of an area can provide an indication of long-term risk and eruption type.
- Earthquakes cannot be accurately predicted with current technologies.
- Seismographs, GPS and animal behaviour can detect the start of an earthquake.
- East coast lows are tracked and predicted by measurement of barometric pressure and temperature with the aid of computer modelling.
- Building codes prevent deaths caused by collapsing structures.
- Base isolation, movement dampers, structural reinforcement and flexible materials help buildings withstand the force of earthquakes.
- Building away from the path of lahars or redirecting their flow saves lives around volcanoes.
- Steep, well-braced roofs and reinforced concrete structures withstand heavy falls of ash and volcanic rock impacts.
- Early warning systems allow evacuation before volcanic eruptions occur.
- Earthquake warnings allow people to take cover or move away from danger.
- A coordinated government response and public education save lives and property in geological disasters.
- Japan's disaster education program includes school and public disaster drills.
- Weather forecasting has become more accurate over time because of international cooperation, sophisticated computer modelling and a variety of data inputs.
- Satellite imaging allows tracking of cloud systems and large (0.5–2 km) scale systems.
- Radar provides detailed precipitation maps, allowing storm tracking and local warnings.
- Long-term climate predictions allow infrastructure planning.
- Seasonal forecasts are used to plan water allocation, agricultural activity and hazard reduction.
- Weekly forecasts guide storm preparation and evacuations.

7 CHAPTER REVIEW QUESTIONS

Review quiz

1 Construct a summary table of technologies used to predict volcanic eruptions. Include the name of the technology, what it measures and how measurements could indicate an eruption.

2 Explain why scientists use several different types of data to predict volcanic eruptions.

3 If you could only use one type of volcanic monitoring, which would it be? Justify your choice.

4 Evaluate the usefulness of volcanic early warning systems, using named examples.

5 How might information about the volcanic history of an area be useful to the people who live there now?

6 Distinguish between prediction and detection of earthquakes. What is required for each of these?

7 Outline the factors that affect the energy released in an earthquake.

8 A prospective study of animal behaviour to detect earthquakes involves animals in Italy. Would it be useful to repeat this study at a farm in western New South Wales? Justify your answer.

9 Evaluate the reliability and accuracy of mean sea level pressure maps used for weather tracking and forecasting.

10 Compare the amount of advance warning for different natural disasters and the responses that can be made within those time limits.

11 Describe the role of computer modelling in predicting natural disasters.

12 Explain the benefits of structural reinforcement of buildings in areas with geological hazards.

13 Is the choice of building location or structural design of buildings most important in tectonically active areas? Use examples to support your answer.

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14 The ShakeAlert warning system did not warn Los Angeles residents of shaking that was felt, but not considered dangerous in the computer modelling.

a Discuss factors forecasters must consider when setting the level at which the general public is warned of disaster.

b Should the warning level be different for emergency services and utilities?

15 Describe the benefits of early warning of disaster, using named examples.

16 Construct a table comparing satellite and radar data for weather forecasting. Incorporate at least three different features in your comparison.

17 The United Nations says that alleviating poverty and developing effective government response are the most important steps in mitigating natural disasters. Discuss the benefits of both.

18 You are monitoring a large Indonesian volcano. Gas level and seismic readings for the past week are shown in Figure 7.28. There are multiple seismograms with this pattern.

a Interpret each of these readings.

b Assess the risk of eruption based on these readings and assign a volcanic alert level from Figure 7.24.

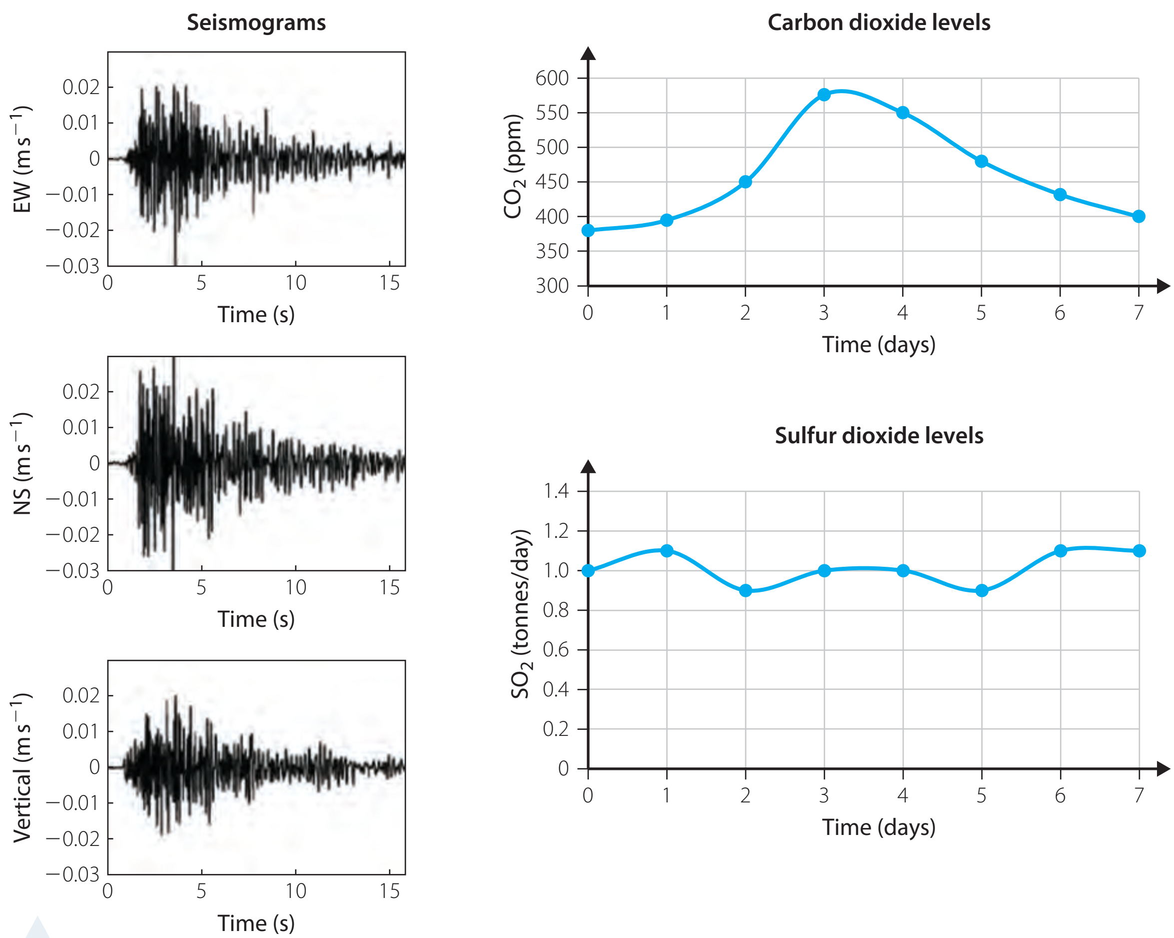

FIGURE 7.28 Gas level and seismic readings around a volcano

MODULE 6: HAZARDS

Answer the following questions.

1 What are the different technologies that can be used to monitor a volcano? How can these technologies be used to accurately predict an eruption?

2 Contrast the different technologies used to detect and predict earthquakes and their success in predicting an earthquake.

3 What are the features of a volcanic eruption that lead to the eruption having a cooling effect on the global climate? You will need to discuss the:

- size (VEI) and style of the eruption
- chemistry of the gas and particle cloud produced by the eruption
- geographic location of the volcano.

4 Hailstorms are very rare occurrences during the winter months in Australia. Outline the conditions required for the formation of a hailstorm and suggest reasons why they are restricted to the warmer months of the year.

5 Tropical cyclones can affect New South Wales in a number of ways. Contrast how rainfall in New South Wales can be affected by tropical cyclones that have their origins in the Indian or Pacific Ocean.

6 For an east coast low to develop, specific conditions are required. Outline the conditions necessary for a low-pressure system to be classified as an east coast low.

7 Flash flooding is common in cities and towns. Evaluate the likelihood of flash flooding in your area as a result of sudden extreme rainfall.

8 Drought in eastern Australia is strongly influenced by the ENSO. What is the combination of weather conditions and the amount of combustible fuel available that will likely lead to major bushfires? How did Aboriginal communities avoid major bushfires before European settlement?

9 Weather prediction over the last 50 years has improved a lot. Outline the technologies available to the Bureau of Meteorology that have enabled this improvement to occur.

10 Tsunamis pose a large risk to coastal communities. What physical features and human activities can contribute to the severity of a tsunami? Is there any way to reduce the risk to coastal communities?

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DEPTH STUDY SUGGESTIONS

- Investigate the similarities and differences between the eruptions of Mount St Helens in 1980 and Krakatoa in1883 and their effects on both local and global communities.
- Why are the three eruptions associated with major global cooling since 1800 all located within island arc systems in Asia? You will need to research the conditions that occur on the sea floor that can lead to the development of sulfur-rich sediments in and around subduction zones.
- Research an east coast low that has occurred in the last 50 years and describe the climate pattern that led to its development, the extent of the rainfall it caused and the cost to communities of the rainfall.
- Research the conditions that led to the Sydney thunderstorm of 1999. What was the cost to the regional economy due to hail damage?
- Research the occurrence of El Niño and La Niña cycles in the western Pacific over the last 120 years. What are the inferences that can be drawn from the frequency and severity of the ENSO cycles and their impact on eastern Australia?
- Investigate the risks from earthquakes and tsunamis for people living along the New South Wales coast. Suggest changes to building codes and local planning for buildings in a location of your choice.
- Research the weather conditions and human activities that contributed to the flash flooding in Dungog in 2015.
- Investigate procedures and changes to farming practices that could be put in place to reduce the severity of drought on a farm in a region of your choice.

» MODULE SEVEN

CLIMATE SCIENCE

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8 Climate variation and natural processes

OUTCOMES

In this chapter you will learn about:

- climate and the timescales over which it changes CCT L
- the natural greenhouse effect L N
- the use of models to study climate change CCT ICT N
- natural processes causing climate variation. CCT ICT N

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Getty Images/sjallenphotography

FIGURE 8.1 A shelf cloud ahead of a thunderstorm approaches a sunny Bondi Beach.

We do not expect the weather to be the same every day. It can change very quickly. Figure 8.1 shows a shelf cloud advancing ahead of a thunderstorm towards a sunny Bondi Beach. The storm was one of many that affected New South Wales in early November 2015. Many areas received good rainfalls early in the month, but towards the end of November, little rain fell in most parts of the state. Was this what people expected? Was it an unusual pattern for that time of year? To answer these questions, we need to look at long-term descriptions of weather – the climate.

In this chapter, you will learn about climate and processes that cause it to change over long periods. You will learn that climate-shaping processes are part of a very complex system. You will also learn about the role of models in helping scientists understand climate and what we know of the processes that have shaped Earth's climate over the last half a billion years.

8.1 Climate, weather and the timescales of change

There is an important difference between weather and climate. **Weather** refers to the day-to-day changes in the atmosphere – whether it is hot or raining, whether a breeze is blowing and if so, from where and how strongly? **Climate** is a description, a statistic, of the system that generates weather. Climate is the set of measured averages, variations and extremes of phenomena such as temperature, precipitation and wind conditions throughout the year. Climate is calculated over decades or centuries, and our climate records cover a relatively short length of time – less than 200 years. The first reliable thermometer was produced in 1640, but it was not until the mid-18th century that reliable worldwide temperature data became available.


Alamy Stock Photo/LizCoughlan

FIGURE 8.2 Drought-affected land in the upper Hunter Valley of New South Wales

The variations we see in a day do not necessarily match the average variations measured over a long time. At the time this book was written, Eyre in Western Australia held the record for the greatest daily temperature variation in Australia. On 5 March 2008, the temperature in Eyre ranged from −8.3°C to 47.8°C. However, according to records from 1899 to 2018, the average maximum and minimum temperatures for March in Eyre ranged from 14.2°C to 25.7°C. On average, the extreme values of climate cancel each other out, and it is the more common, less extreme measurements that contribute more to the overall climate over the years. Drought (Figure 8.2) may affect an area for a year or several years but, in the long term, the climate in that area may have sufficient rainfall for farming.

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The climate system is the sum of Earth's components – atmosphere, hydrosphere, lithosphere, cryosphere and biosphere – and their interactions. Later in this chapter, you will see how these components interact to cause climate change.

First, consider the factors that affect the climate where you are now. The climate of any location is influenced by a range of factors. Latitude, altitude, wind patterns, topographic relief and how close the area is to the ocean all influence climate characteristics such as rainfall, temperature and humidity. Latitude predicts temperature and humidity. Altitude affects temperature, pressure and the amount of rain that may occur. Figure 8.3 shows Laguna Colorada – a shallow salt lake in Bolivia. It is on the elevated Altiplano (high plains) more than 4 km above sea level. As a result of both its location and altitude, the area has an annual rainfall of only 48 mm.

Shutterstock.com/milosk50

FIGURE 8.3 Laguna Colorada in Bolivia. The white areas in the lake are salt deposits. The red-brown areas are due to microorganisms living in the shallow salty water.

Winds are a product of atmospheric circulation and depend on latitude and the movement of air masses. Moving air masses carry moisture and affect rainfall. Ocean currents carry heat or bring cool water to coastal areas and this moderates the temperature close to the coast. Large continental areas a long way from the coast are often dry because water vapour either does not reach the area from the coast or fails to precipitate due to pressure and temperature conditions.

Although the factors that determine climate in an area do not change much over hundreds of years, they do change over millions of years. Mountains are formed by plate tectonic processes and are levelled by weathering and erosion. Mountains affect how air masses and winds circulate. Mountains can also intercept moisture-bearing air, causing it to rain where the winds arrive and creating a dry area known as a rain shadow on the other side of the mountain.

Oceans open and close (see Figure 8.17 on page 206). There have also been times when Earth was colder or warmer than it is today. The temperature differences between the Equator and the poles can affect air flow, rainfall and the temperature of ocean currents along a coast. As Australia has moved north towards the Equator after separating from Antarctica 65 million years ago, the continent has gradually warmed.

Climate changes over a wide range of timescales. Climate may change in an area over thousands or millions of years, and there are many reasons for those changes. In the next section, you will look at an important phenomenon that affects global temperature – the natural greenhouse effect.

KEY CONCEPTS

- Climate is a long-term description of the weather system.
- Climate is described in terms of averages and variations of characteristics such as temperature, precipitation, winds and atmospheric pressure.
- The climate system consists of Earth's five parts and their interactions: atmosphere, hydrosphere, lithosphere, cryosphere and biosphere.
- An area's climate is affected by a range of factors, including latitude, altitude, wind patterns, topographic relief and proximity to the ocean.
- The natural climate changes over a wide range of timescales – from hundreds to millions of years.

CHECK YOUR UNDERSTANDING 8.1

1. Define 'climate'.
2. How is climate different from weather?
3. Describe two ways in which the atmosphere influences weather on land.
4. Outline three factors that affect climate and give an example of each factor.
5. Describe the factors that make Laguna Colorada an arid, cold environment (Figure 8.3, page 191).
6. Identify some of the processes that can alter climate in an area over a long time.

PhET greenhouse simulator

Use the interactive simulation app to explore the natural greenhouse effect and how greenhouse gas molecules interact with infrared radiation. How does the amount of greenhouse gas affect surface temperature?

Is global warming only heating the atmosphere?

Read the article and summarise where the extra heat energy due to the greenhouse effect is stored.

8.2 Natural greenhouse effect

Earth's atmosphere plays an important role in regulating its temperature. The Moon, which has no atmosphere, has an average surface temperature of −23°C. On the side of the Moon facing the Sun, the surface temperature reaches 127°C; on the dark side of the Moon, the temperature drops to an average of −173°C. Life cannot survive under these conditions. In comparison, Earth has an average global temperature of 15°C. Although local daily changes in temperature can be large, average global temperature variation is fairly small. The annual mean temperature at the Equator is only 4% above Earth's global average and at the poles it differs by 10% for the Arctic and 21% for Antarctica. Earth's atmosphere maintains this small, and relatively warm, temperature range. The process that warms the atmosphere is called the **natural greenhouse effect**.

The natural greenhouse effect is caused by the interaction of the heat radiated from Earth's surface with the atmosphere. Earth's surface absorbs solar radiation, mainly in the form of visible light. The surface gets warmer and then emits heat as long-wave **infrared radiation**. Some of the emitted radiation is absorbed by gases in the atmosphere. The energy is then reradiated by the gas molecules, some towards space and some back towards the surface of Earth. It is the radiation directed towards the surface that keeps the atmosphere near the surface warm. Simple models showing the interaction of a surface with

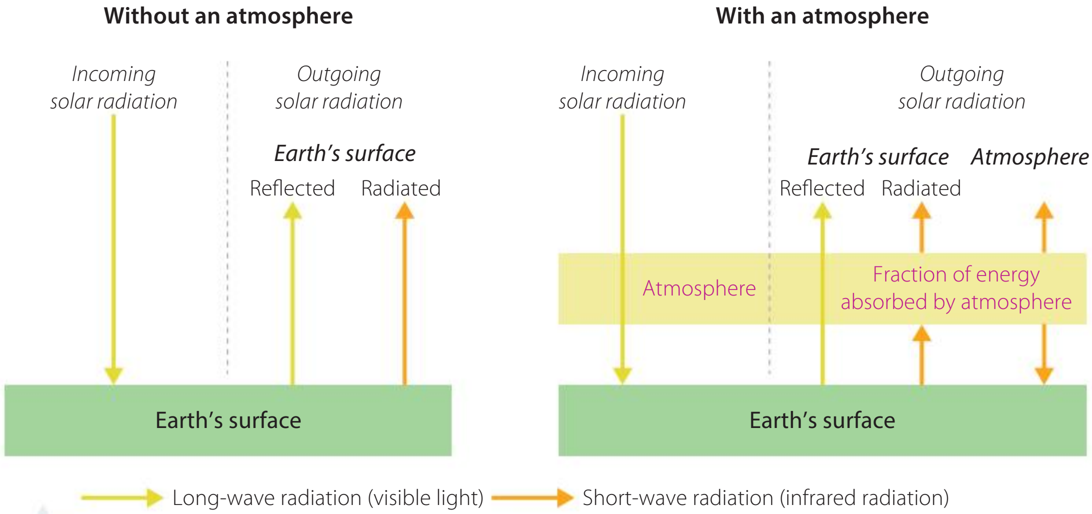
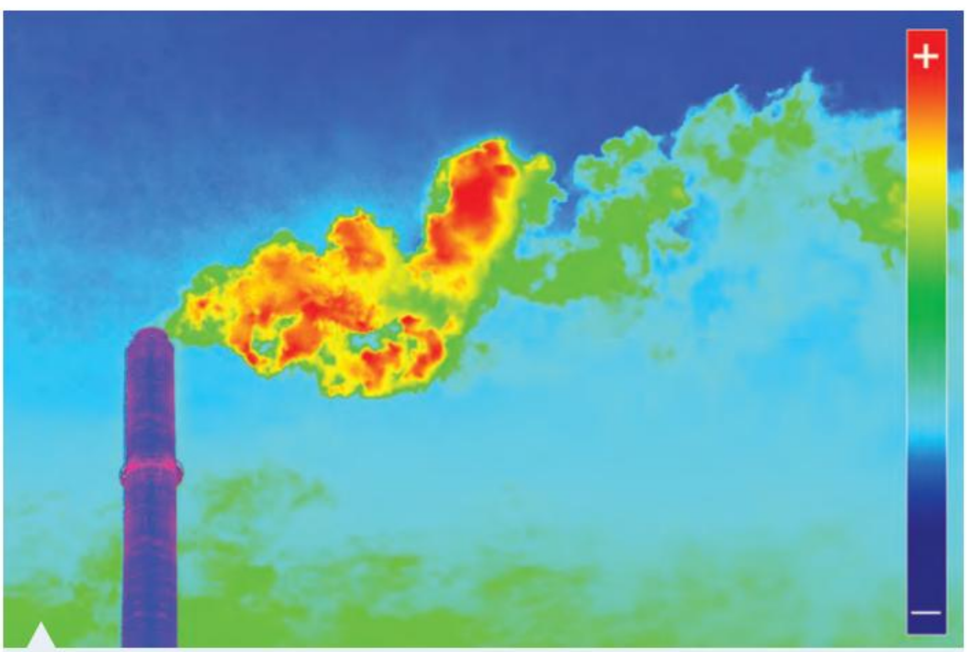


FIGURE 8.4 Simple models of the natural greenhouse effect

WS Interpreting natural greenhouse warming data

and without an atmosphere are shown in Figure 8.4. Scientists can use simple models to calculate the effect of the natural greenhouse effect on Earth's surface. The models agree closely with the observed average global temperature of 15°C.

For any planet or moon to have a constant surface temperature, there has to be a balance between the energy absorbed as light from the Sun and the energy emitted from the surface as infrared radiation, or heat. An object that absorbs all the electromagnetic radiation that falls on it is called a **black body**. Such a body with a constant temperature radiates energy that is termed black-body radiation. Although most materials are not perfect black-body radiators, warm objects emit a range of electromagnetic radiation. Hot gases emit radiation too (Figure 8.5).



Shutterstock.com/Ivan Smuk

FIGURE 8.5 This infrared image shows hot gases being emitted from a power station chimney. The scale on the right indicates which colours represent hot and cold parts of the image. The hot gases put out more infrared light than the surroundings so they are bright red or yellow.

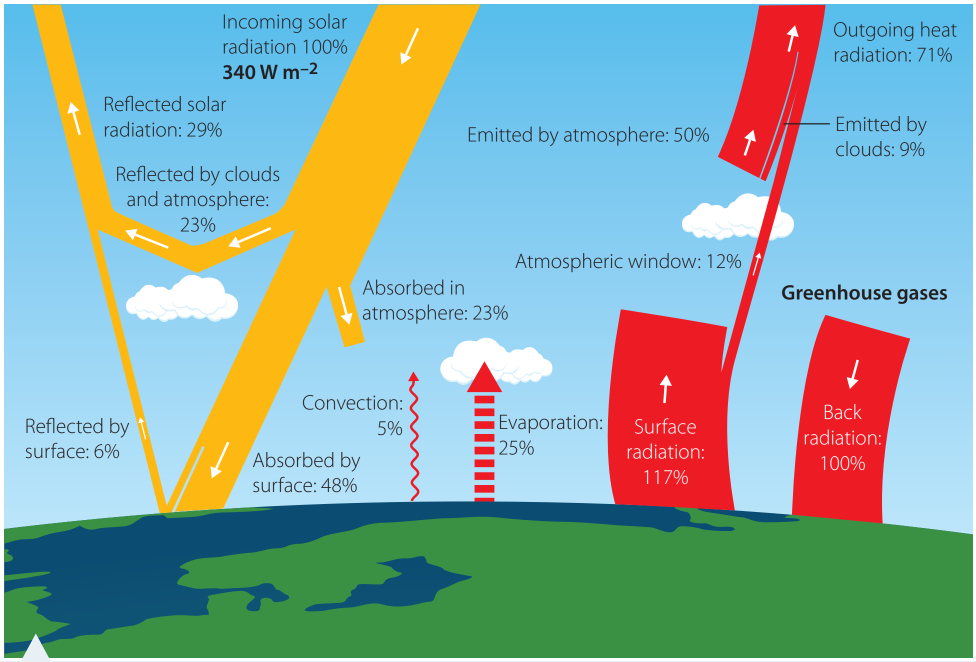


FIGURE 8.6 Earth's energy budget. The fate of incoming solar radiation is shown on the left. The right side of the diagram shows the flow or fluxes of energy.

Measuring Earth's albedo

Read the article to identify how and why NASA measures albedo.

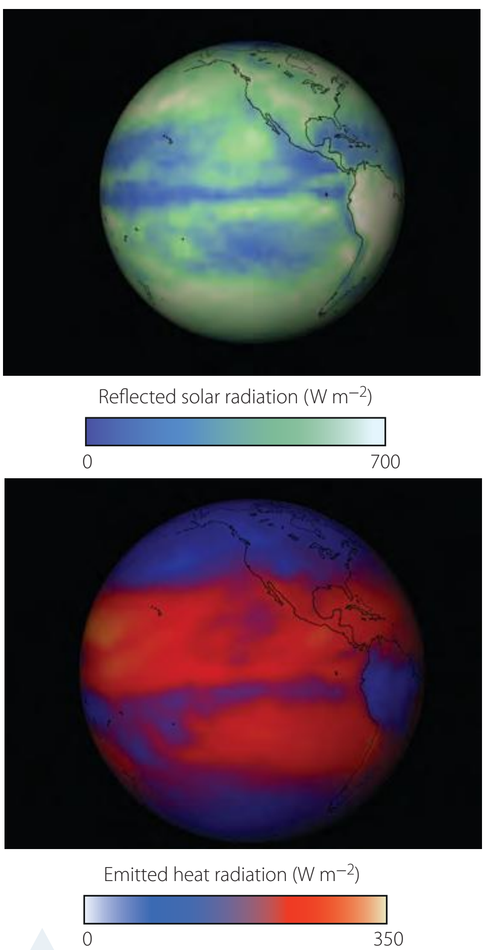


FIGURE 8.7 These NASA images show the radiation reflected from the atmosphere and radiated from the surface.

The amount of light absorbed and the temperature of the surface of a body determines how much infrared radiation radiates from the surface. Not all the light entering the atmosphere reaches Earth's surface. Figure 8.6 shows the possible fates of light entering the atmosphere. Note that clouds are a major cause of light not reaching the surface (see also Figure 8.7). Most of the atmosphere allows visible light to travel through it with only a small amount of light being absorbed. We say that the atmosphere is transparent to incoming light. Of the light that does reach the surface, some is reflected. The proportion of light reflected from a surface is called albedo. Different surfaces have different albedos. Water has a very low albedo but a high heat capacity, so it does not heat up a great deal during the day. The albedo of dry sand is about four times greater than that of water, but sand heats up faster and radiates more heat.

The ground emits more energy than it absorbs as light. This is because the greenhouse gases return energy to Earth's surface from the atmosphere. The surface is heated by solar radiation and back radiation from the greenhouse gases. Therefore, the net surface radiation into the atmosphere is greater than the amount generated by reradiation of solar radiation alone. It is this additional energy that warms Earth's surface and lower parts of the **troposphere**.

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Only some gases absorb infrared radiation. These are greenhouse gases and they include naturally occurring gases such as water, carbon dioxide (CO_2) and methane (CH_4). Greenhouse gases absorb incoming infrared radiation, which we feel as heat, from the Sun.

The term 'greenhouse effect' was first used in the early years of the 20th century and refers to an apparent similarity with the effect of the glass panels of a greenhouse. The glass is **transparent** and allows visible light to pass through. But the glass is **opaque** to infrared radiation, or heat. Infrared radiation cannot escape through glass and so heat generated in a greenhouse is trapped there. The enclosing glass prevents the heat from escaping the greenhouse by convection. The atmosphere operates differently. It absorbs infrared radiation and re-emits some out to space and some back towards Earth, warming the surface.

The natural greenhouse effect only raises the temperature of the atmosphere by about 30°C. Although heat is returned to the surface and the surface warms, the rate of energy emission from a warming surface is greater than the rate of the surface's temperature change. The energy a surface radiates is proportional to the fourth power of temperature ($E \propto T^4$). The increased temperature of the surface does increase the amount of infrared radiation being emitted, but rather than warming just a shallow area of the atmosphere close to the surface, it has the effect of warming a greater depth of the atmosphere.

INVESTIGATION 8.1

Modelling the natural greenhouse effect

Critical and creative thinking

Information and communication technology capability

Numeracy

AIM

To compare warming and cooling in gases with high and low CO_2 content when warmed by light

MATERIALS

- 2 × 250 mL conical flasks
- 2 bamboo skewers
- 2 corks with a hole in the centre to fit the conical flasks
- 4 Alka-Seltzer tablets
- Strip of Blu-Tack
- 2 rectangular strips of slate or a dark solid material that fits in the conical flasks
- 2 data loggers with temperature probes
- Desk lamp with a 100 W bulb
- Stopwatch

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
The desk lamp may become hot and burn you.	Make sure the lamp is not in contact with anything flammable during the investigation and leave it to cool before dismantling the apparatus.
When pressure builds up when the CO_2 is generated in the flask, the cork may pop out.	Make sure the cork is placed on lightly until all the gas has been generated by the dissolving tablets. Then push the cork into the flask to seal the contents. Wear eye protection.

What other risks can you identify in this investigation? How will you manage them?

»

METHOD

1 Copy the table in the Results section.

2 Put 100 mL of cold water into each conical flask.

3 Slide a slate strip into each flask so it lies diagonally across the flask.

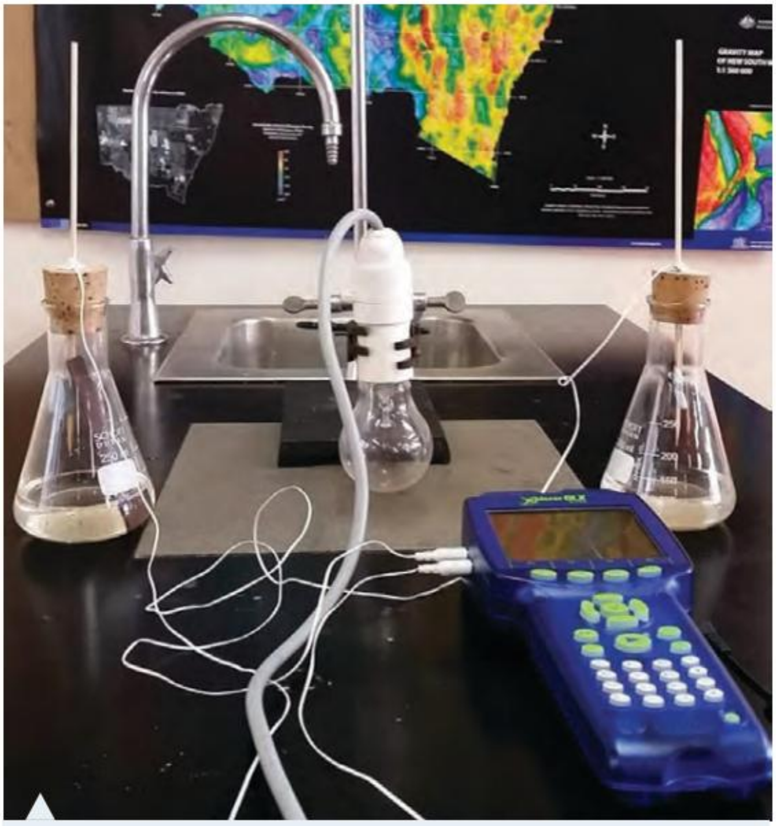
4 Label the bottles as 'Control' and 'CO_2'.

5 Attach a temperature probe to a bamboo skewer. Carefully insert the skewer and probe through the cork about 8 cm.

6 Use some Blu-Tack to make a small shield around the temperature probe so light does not fall directly on the probe.

7 Adjust the temperature probe so that it is centred in the flask above the water. Fit the corks into the flasks.

8 Place the flasks side by side on a bench and set up the lamp so the two flasks receive the same amount of light. The lamp bulb should be approximately 30 cm from the centre of the flasks. Ensure the temperature probes face away from the lamp and that the slate strips are angled towards the light (Figure 8.8).



Chris Huxley

FIGURE 8.8 Apparatus set-up for the investigation

9 Remove the cork and thermometer from the conical flask labelled 'CO_2' and drop four Alka-Seltzer tablets into the conical flask.

10 Replace the cork and thermometer in the flask immediately.

11 Let the flask sit for 10 minutes after more CO_2 bubbles are being produced.

12 Record the air temperature of the room.

13 Slightly loosen the corks to allow the air pressure to adjust so it is the same in both flasks.

14 Record an initial temperature reading for each flask in your results table.

15 Turn on the light and record the temperature in each flask every 5 minutes for at least 20 minutes. (A time of 3 hours produces valuable results.) Record the times and temperatures in your results table.

16 Note any changes in the flasks as the investigation proceeds.

17 Turn off the lamp. Measure and record the temperature every 2 minutes for 10 minutes as the flasks cool.

» **RESULTS**

Copy and complete this table.

TIME (min)		TEMPERATURE (°C)		OBSERVATIONS
		CONTROL	CO_2	
0	Warming			
5	Warming			
10	Warming			
15	Warming			
20	Warming			
22	Cooling			
24	Cooling			
26	Cooling			
28	Cooling			

ANALYSIS OF RESULTS

1 Construct a graph to compare the rate of heating in the control flask with that in the CO_2 flask.

2 Calculate the rate at which the temperatures increased in the control and CO_2 flasks.

DISCUSSION

1 In what ways was the CO_2 flask different from the control flask?

2 Describe the difference in the way the CO_2 flask warmed under the lamp compared with the control flask.

3 Account for the difference in the flask heating rates in terms of the presence of CO_2.

4 How does the stoppered flask model a planet and its atmosphere?

5 Would the lack of a dark body absorbing light in each flask change the results? If so, how?

6 How could this model be improved to demonstrate the greenhouse effect?

KEY CONCEPTS

- The natural greenhouse effect plays an important role in making Earth habitable. Without it, the average temperature of Earth would be –18°C.
- The natural greenhouse effect describes the warming of Earth's atmosphere by greenhouse gases absorbing long-wave radiation emitted by Earth's surface and transferring the energy to the atmosphere.
- A greenhouse gas is a gas that can absorb and reradiate long-wave radiation.
- Important natural greenhouse gases are water vapour, CO_2 and CH_4.
- The amount of light reaching Earth's surface is affected by albedo, reflection and absorption by clouds and the atmosphere.
- Scientists use models to understand and predict processes such as the natural greenhouse effect and their effects.

CHECK YOUR UNDERSTANDING 8.2

1 Refer to Figure 8.4 on page 193. Not all the solar radiation entering the atmosphere is absorbed by the surface. Outline the reasons some light does not reach the surface of Earth.

2 Describe what happens to light absorbed by rock on Earth's surface.

3 Define 'greenhouse gas'.

4 Identify three naturally occurring greenhouse gases.

5 Explain, with the aid of a diagram, how the natural greenhouse effect works.

6 Why is the natural greenhouse effect important for life on Earth?

8.3 Models of carbon movement in Earth systems

To understand how climate changes, scientists use models. Models of processes such as the natural greenhouse effect provide scientists with the tools to understand complex processes and anticipate changes. A **scientific model** is a representation of a phenomenon such as an object, process or system. Scientific models are useful because they use a simplified representation to explain and describe what may be a complex phenomenon. The use of models is a key part of science. By using a simplified representation of something, such as the interplay between greenhouse gases and radiation, scientists can develop useful predictions and experiments to test them. A set of simple models, showing the effect of the natural greenhouse effect, is shown in Figure 8.9. Each flask in Investigation 8.1 was a simple model of a planet.

CO_2 is an important greenhouse gas. A model used to understand the way CO_2 is added or removed from the atmosphere over short lengths of time (seconds to thousands of years) is the **carbon cycle** (Figure 8.9). The carbon in the model may be CO_2 or carbon as part of solid materials such as organic material in soil or phytoplankton in the ocean. The model shows the **reservoirs**, or areas of storage, for carbon. The reservoirs act as both **sources** and **sinks** because they provide or accept carbon to or from other reservoirs in the model. The flow of carbon between the reservoirs is termed a **flux**. The carbon cycle shows the importance of volcanoes, soil, plants and the ocean in adding or removing carbon from the atmosphere.

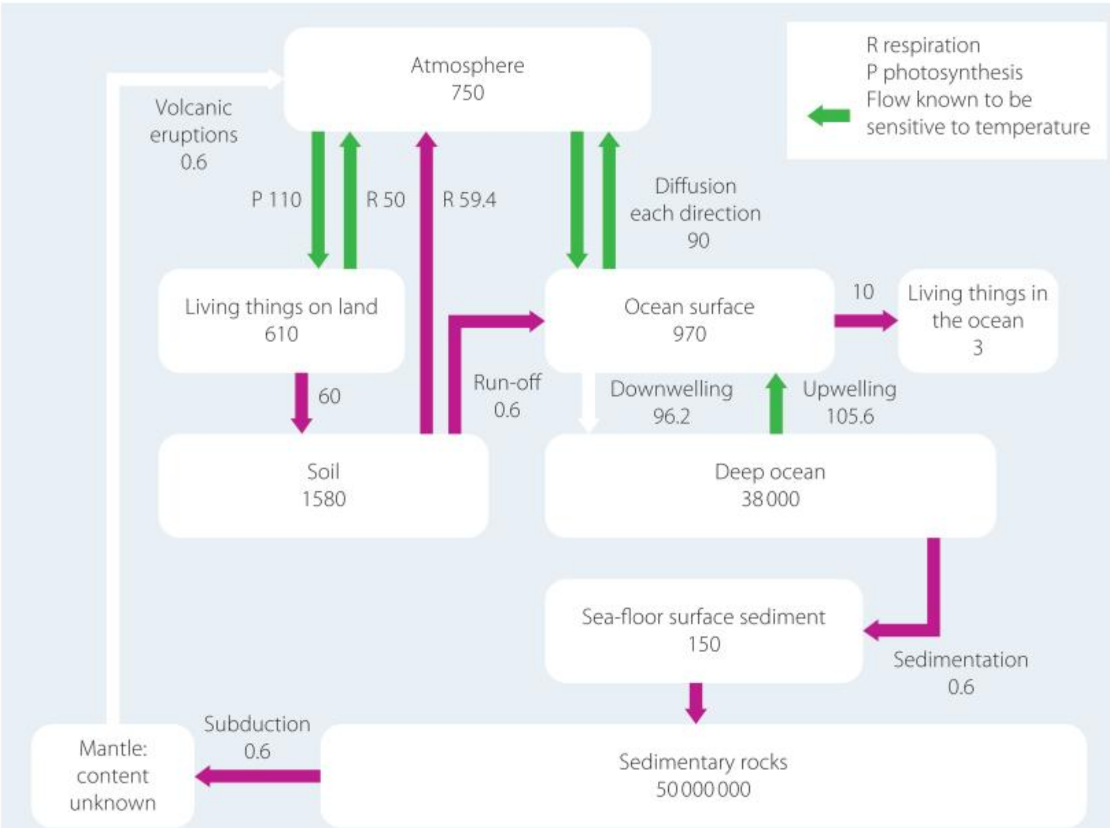


FIGURE 8.9 The global carbon cycle. All flows are measured in gigatonnes (Gt) of carbon (1 Gt = 10^9 tonnes).

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The carbon cycle allows us to consider how changes might occur as climate warms. We can infer that respiration will increase and the absorption of CO_2 by the oceans will slow as the ocean warms. The carbon cycle model also demonstrates the importance of knowing the rate of fluxes if we are to understand how CO_2 levels in the atmosphere change. Carbon can stay in the atmosphere for, on average, several years. Carbon can stay in plant material for a decade or in the ocean for hundreds of years. Measuring fluxes in Earth systems is ongoing to ensure climate models are accurate.

To understand how climate changes over longer timescales (hundreds of thousands to millions of years), a long-term carbon cycle model is needed (Figure 8.10). Like the more familiar short-term model, the long-term model shows carbon cycling through Earth with parts of Earth acting as sources and sinks for carbon. However, the processes in this model are much slower than those in the short-term model. Rock weathering rates are very slow. The total mass of material removed by weathering is 1/150 the rate at which CO_2 is transferred from the air to the ocean. However, the amounts involved seem large to us. In the European Alps, CO_2 is consumed in weathering at the rate of approximately $22\,t\,km^{-2}\,year^{-1}$. Some of this carbon is later released to the atmosphere through chemical reactions in streams and the ocean. Processes such as metamorphism and diagenesis (the processes by which sediments become rocks) also release CO_2 to the atmosphere. Recent modelling suggests that mid-ocean ridges may emit more than 50 million tonnes per year. This is about 1/120 the rate at which humans add CO_2 to the atmosphere each year by burning fossil fuels.

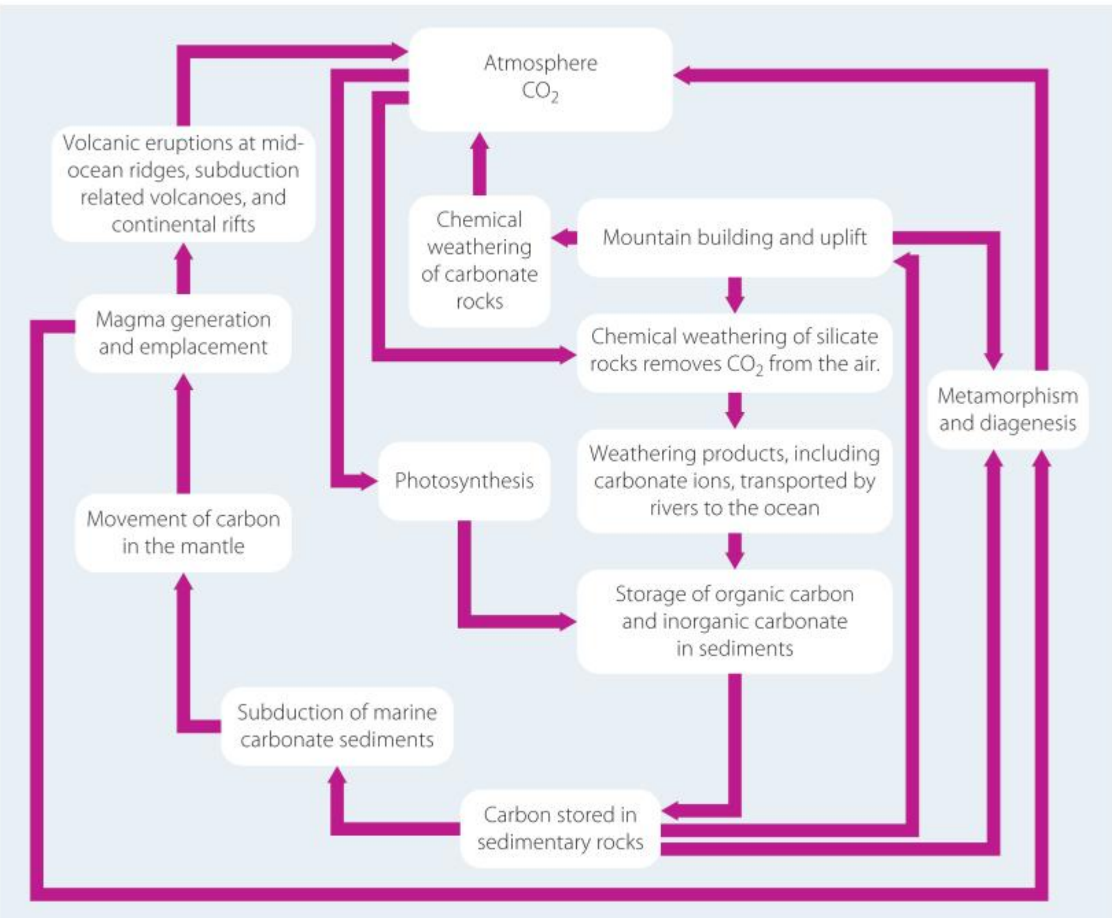

FIGURE 8.10 The long-term carbon cycle

INVESTIGATION 8.2

Mapping the long-term carbon cycle against the tectonic supercycle

Critical and creative thinking

Information and communication technology capability

An important part of science is making and testing predictions. In this investigation, you will apply what you have learnt about plate tectonic processes and the long-term carbon cycle to predict climate at five stages of the plate tectonic supercycle (Figure 8.11). You will then research the climate for each period to see how similar it was to your prediction.

Paleomap Project
Use Christopher Scotese's climate maps to verify your predictions about climate for each period.

AIM

To identify the processes occurring in the plate tectonic supercycle that might contribute to climate change

METHOD

1 Copy the table in the Results section. After a class discussion, you might choose to add additional columns for factors you think might also be important.
2 Review the plate tectonic supercycle in Chapter 3 and then identify and record the stage of the cycle in your table. (The Early Permian has been completed for you as an example.)
3 Use the tectonics present in each stage of the cycle to predict volcanic activity, sea level and tectonic mountain weathering. Record the frequency of these events as high, medium or low (H, M or L).
4 Review Figure 8.9 and estimate the level of CO_2 in the atmosphere. Record your predictions in the table. On average, convergent boundary volcanoes emit more water and divergent boundary eruptions erupt more CO_2.
5 Using the CO_2 level you identified, predict whether the climate was cool, warm or somewhere in between.
6 Having made your predictions, use the weblink *Paleomap Project* to identify the climate during each time period.

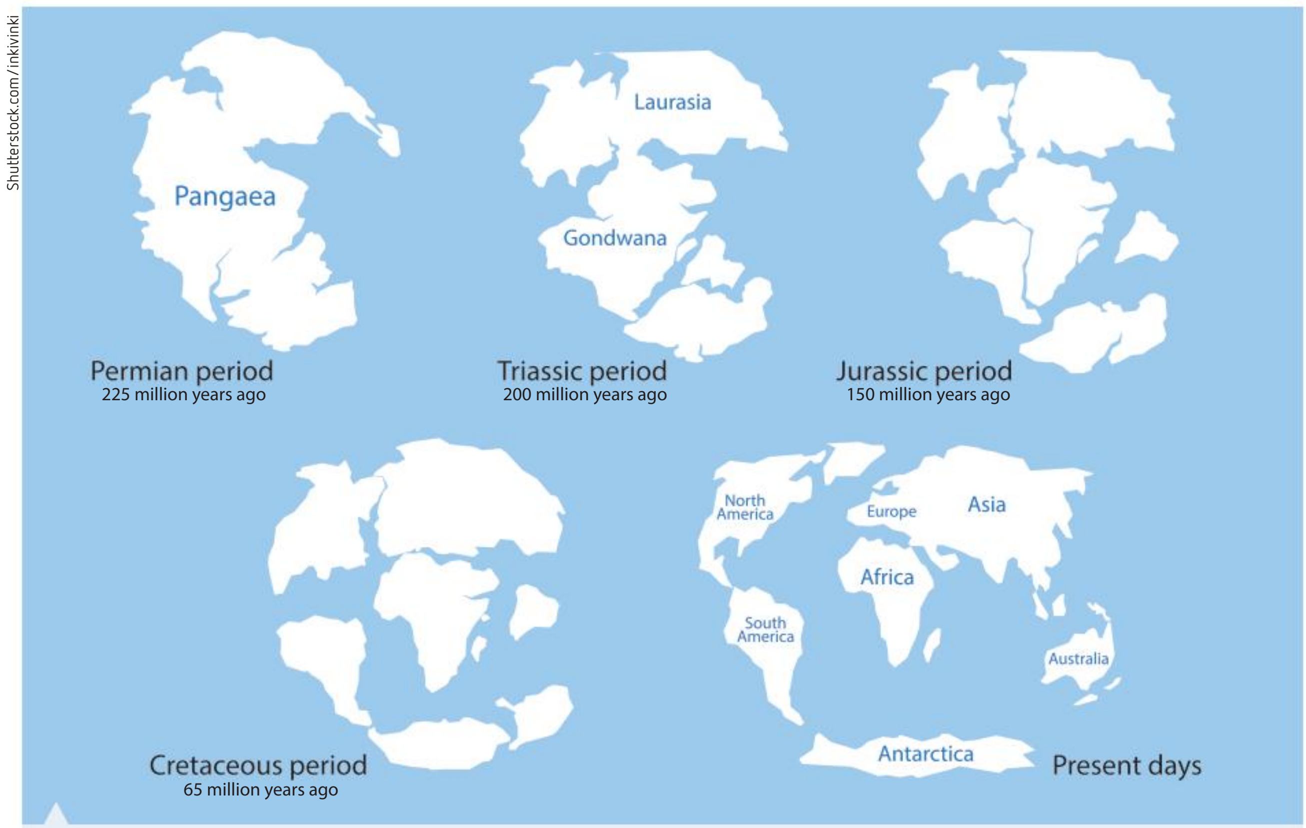

FIGURE 8.11 Distribution of continents during the last 250 million years

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RESULTS

Copy and complete this table (H high, M medium, L low).

TIME	STAGE IN TECTONIC SUPERCYCLE	VOLCANIC ACTIVITY (H, M, L)	ESTIMATED SEA LEVEL (H, M, L)	TECTONIC MOUNTAIN WEATHERING (H, M, L)	ESTIMATED CO_2 LEVELS (H, M, L)	ESTIMATED CLIMATE (WARM, UNSURE, COOL)	ACTUAL CLIMATE
Early Permian	Supercontinent	L	L	H	L	Cool	
Triassic							
Jurassic							
Late Cretaceous							
Present							

ANALYSIS

1 During which stage of the tectonic supercycle is the amount of volcanic activity the greatest? Did the atmosphere have a high CO_2 level at this stage?

2 The early Cretaceous was a period when many coal deposits were laid down and the climate cooled. What does this evidence suggest about the effect of photosynthesis on CO_2 levels?

3 How successful were your predictions when tested against the Paleomap information?

4 Which period stood out as being very different from your prediction based on CO_2 levels?

5 Is long-term climate change influenced by one process, such as tectonics, or by a number of interacting processes? Justify your answer.

6 Assess the role of models in analysing processes such as climate change, using some of your results from this investigation.

CONCLUSIONS

1 Based on your research, does the volcanic activity after a supercontinent break-up lead to a warmer climate?

2 Does tectonics alone predict climates such as the present or in the Late Cretaceous period?

3 Why are models useful for testing scientific hypotheses?

KEY CONCEPTS

- Scientists use models to describe, predict, explain and investigate complex systems and processes.
- The global carbon cycle is a model that allows scientists to predict and explain short-term changes in CO_2 in the atmosphere.
- The long-term carbon cycle shows that changes in carbon reservoirs and CO_2 levels can take thousands or millions of years.
- Rock weathering and the deposition of carbonate sediments are two processes that remove CO_2 from the atmosphere.

CHECK YOUR UNDERSTANDING 8.3

1 What is a scientific model?

2 Why do scientists use models?

3 Identify two sources and two sinks of carbon in the global carbon cycle.

4 How does the rate of CO_2 production from burning fossil fuels compare with the amount of CO_2 produced by volcanic activity?

5 Describe a scientific model you studied in Science before you started your HSC course. How did it aid your learning?

8.4 Long-term changes in Earth's climate

Geological processes are only one of the main factors influencing climate over long periods. Factors influencing climate over geological timescales can be grouped into three types of changes. These are changes in the:

- amount and distribution of solar energy entering Earth's atmosphere
- nature of the surface of Earth caused by plate tectonics
- composition of the atmosphere that influence the natural greenhouse effect.

Each of these changes operates on a slightly different timescale. The climate at any time in Earth's history is the sum of all these processes.

Changes in the solar energy Earth receives

Earth's climate depends on the amount and distribution of solar radiation the planet receives. Variations in solar radiation are due to changes in the Sun's radiation output and to changes in the way Earth orbits the Sun. Together, these changes create variations in climate that show cycles of tens to hundreds of thousands of years.

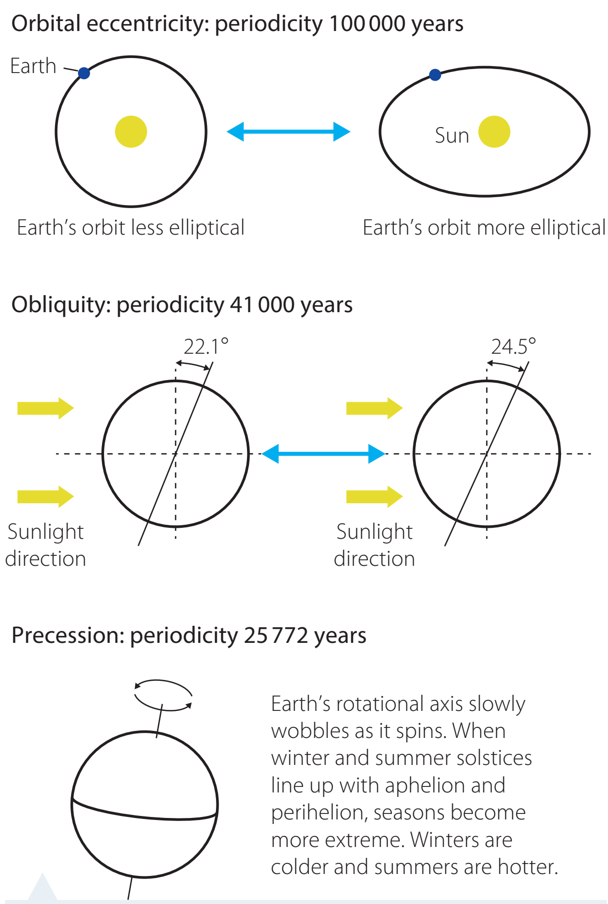

FIGURE 8.12 Three aspects of Earth's orbital behaviour influence the amount of radiation Earth's receives and affect climate: orbital eccentricity, obliquity and precession.

The Sun's energy output changes over time. Over a long time, the amount of radiation emitted by the Sun has increased. The amount of emitted radiation is estimated to have increased by as much as 40% since the Sun formed 4.5 billion years ago. Sunspot activity also affects the amount of solar radiation reaching Earth. Like Earth, the Sun has a magnetic field that changes direction. Unlike Earth's magnetic field, the Sun's magnetic field has a fairly regular cycle of 11 years. There is a slight change in rainfall patterns when the Sun's light emission is greatest because the increase in ultraviolet radiation generates more ozone in the stratosphere. This warms the lower stratosphere and causes the location of tropical convection to move off the Equator. This favours monsoonal effects during summer. Where there is reduced cloud cover, increased solar irradiation increases sea surface temperatures. This, in turn, affects the global atmospheric circulation and moves rainfall away from the Equator.

As Earth orbits the Sun, changes in three aspects of Earth's relationship to the Sun combine to produce variations in the amount of solar radiation entering the atmosphere (Figure 8.12).

Orbital eccentricity

The shape of Earth's orbit around the Sun is an ellipse rather than a circle. The deviation of Earth's orbit from a circle is called its **eccentricity**. This means there is a point in the orbit when Earth is closest to the Sun (**perihelion**) and a point when Earth is furthest from the Sun (**aphelion**). At present, the difference between these points is about 3% of the average orbital radius. The eccentricity changes over time as gravitational attraction between the planets of the solar system acts on Earth. The eccentricity varies in a cycle of 90 000–100 000 years. At present, the eccentricity of Earth's orbit means the solar radiation varies by 6.8% from when Earth is closest to when it is furthest from the Sun. When the eccentricity is at its greatest, the variation is between 20% and 30%. Relative to the effect of Earth's tilt, eccentricity during a year contributes only a small amount to variations in the solar radiation reaching Earth's surface.

Earth's tilt – obliquity

The angle of Earth's rotational axis affects climate. It creates seasons in higher latitudes with summer occurring when the axis is oriented towards the Sun and winter when the axis is oriented away from the Sun. Imagine a line joining the centres of Earth and Sun. During a year, the line would sweep out a flat disc. This is called the orbital plane. Currently, the rotational axis of Earth is inclined at 23.4° to the orbital plane. This tilt is referred to as **obliquity**. The axial tilt changes over time and varies between 22.1° and 24.5° in a cycle lasting 41 000 years. The last time the tilt was at its maximum was in 8700 BCE.

At the greatest axial tilt, more solar radiation reaches Earth's surface in summer and less reaches it in winter. This means that seasons become extreme. Summers are warmer due to the mesosphere receiving more solar radiation and winters are colder because the hemisphere receives less solar radiation. Latitude affects this too. While more solar radiation reaches high latitudes, less arrives close to the Equator. At present, the tilt is gradually declining, which should result in milder summers and winters as well as gradual cooling.

Precession

The direction of Earth's rotational axis varies relative to the stars over time. It is as if the axis gradually draws out a circle in the opposite direction to Earth's rotation. This oscillation of the axis is called **precession** and is caused by the gravitational forces of the Sun and the Moon acting on Earth (Figure 8.12).

The period of the axial precession is slightly less than 25 772 years. Precession affects climate in combination with orbital eccentricity. If the rotational axis of a hemisphere is pointing towards the Sun at perihelion, seasons become more extreme in terms of the solar radiation the hemisphere receives.

Milankovitch cycles

The effect of orbital properties on climate was first formulated by Serbian astrophysicist Miluton Milankovitch in the 1920s. Milankovitch combined eccentricity, obliquity and precession to generate a curve describing the solar radiation arriving at the top of the atmosphere. He calculated his values for a latitude of 65° north because Milankovitch was working to explain the pattern of glaciation in the northern hemisphere, which has a period of approximately 100 000 years.

Two climate proxies have a high correlation with **Milankovitch cycles**. A **climate proxy** is a physical source of evidence that can be used to estimate climate conditions in the past. Oxygen isotopes from fossil benthic forms and information from Antarctic ice cores both correlate well with the Milankovitch cycles (Figure 8.13).

You will learn about the use of oxygen isotopes in determining temperature in Chapter 9.

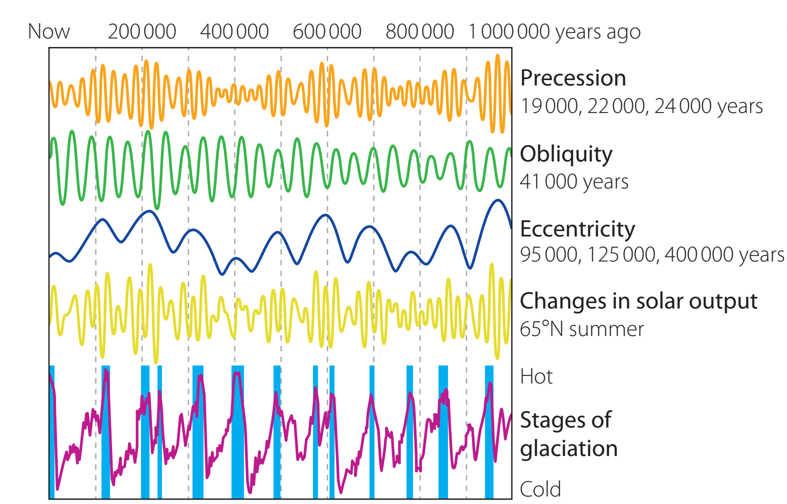

FIGURE 8.13 The Milankovitch cycles

WS
Interpreting natural greenhouse warming data

Changes in Earth's surface caused by plate tectonics

Massive volcanic emissions

Large igneous provinces are extensive accumulations of intrusive and effusive igneous rocks that are emplaced over a short duration (Figure 8.14). Large volumes, frequently more than a million cubic kilometres, of magmas are generated and emplaced by processes unrelated to sea-floor spreading or subduction. The magmas are generally mafic in composition, with effusive eruptions of basalt and the intrusion of mafic dykes being the most common igneous products. However, large explosive eruptions involving silica-rich material can also occur. Such eruptions in the Paraná-Etendeka large igneous province 132 million years ago are thought to have had a volcanic explosive index of 8.

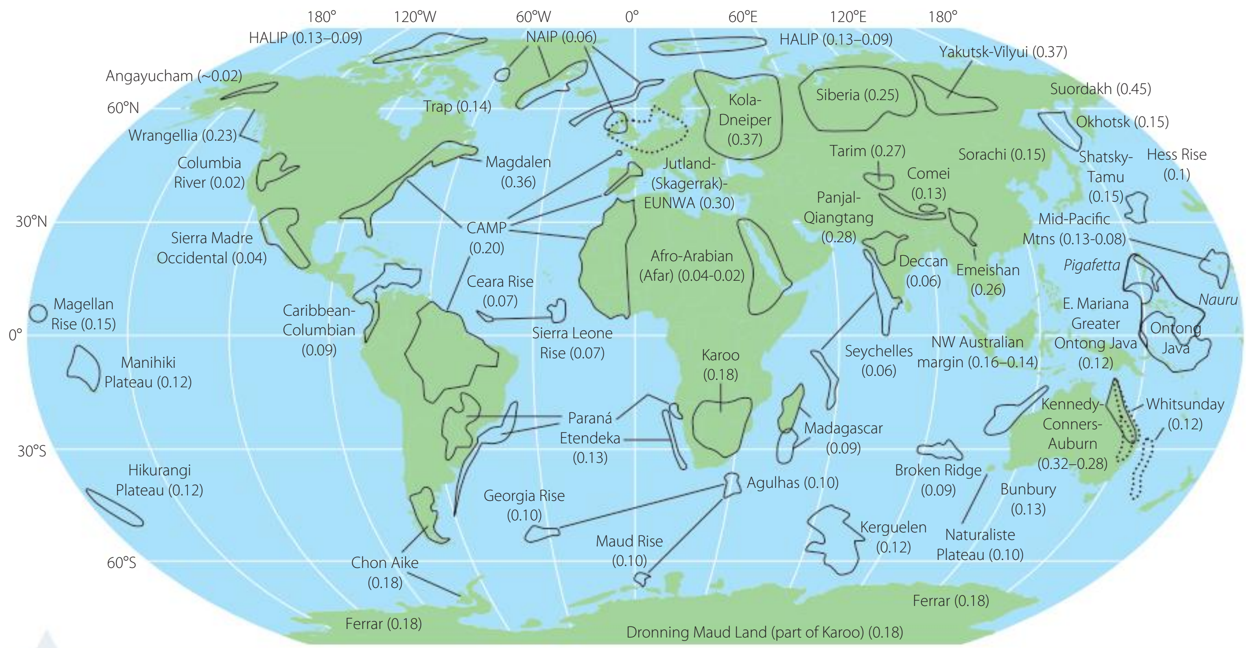

FIGURE 8.14 The distribution of large igneous provinces erupted during the last 500 million years. The numbers in parentheses show age of eruption in billions of years.

When a large igneous province intrudes sedimentary rocks rich in carbonates, a lot of CO_2 is erupted into the atmosphere. The eruption of the Siberian Traps at the end of the Permian and the Deccan Traps at the end of the Cretaceous resulted in the addition of large volumes of greenhouse gas into the atmosphere and increased global temperatures. Together with the generation of mid-ocean ridges, large igneous province generation, associated with continental separation, has added a significant volume of CO_2 into the atmosphere, contributing to the creation of a greenhouse environment.

The Siberian Traps cover more than 4 million square kilometres and consist of lava flows, pyroclastic deposits and intrusive structures. The rocks were formed in less than a million years but it was probably the creation of sills in carbon-rich sedimentary rocks over an even shorter period that led to the end-Permian mass extinction. The contact metamorphism in rocks surrounding the dykes liberated the massive volumes of greenhouse gas that contributed to the extinction event.

Plate tectonic supercycle

The supercontinent cycle creates **icehouse** and **greenhouse climates** on a timescale of hundreds of millions of years. An icehouse climate is marked by low CO_2 levels and low temperatures. Ice sheets wax (grow) and wane (shrink), creating glacial and interglacial periods, respectively. Greenhouse climates have high CO_2 levels and higher temperatures. Ice sheets are small or non-existent. The period of the cycle varies but it is approximately 440 million years long.

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When continents **amalgamate** (come together) to form a supercontinent, conditions favour processes that remove CO_2 from the atmosphere. This results in a colder climate and the presence of ice sheets. When the continents are widely dispersed, the climate is warmer and CO_2 levels are high, creating greenhouse conditions. Over short geological periods, orbital factors can influence climate more strongly than tectonic factors. At present, we are in an interglacial period, with the last glacial period occurring approximately 10 000 years ago, but the continents are well dispersed as part of the tectonic supercycle.

You learnt about the stages of the plate tectonic supercycle in Chapter 2.

Supercontinent amalgamation generates icehouse conditions due to falling CO_2 levels. CO_2 is removed from the atmosphere by rock weathering, particularly in mountains formed by plate convergence. Ageing ocean basins deepen, leading to sea levels falling. This increases land surface area and the albedo. When parts of a supercontinent form at a pole, the likelihood of ice sheet formation increases.

Figure 8.15 shows some of the long-term changes affecting climate from the assembly of Pangaea until its break-up. The age distribution of **zircon** reflects the formation of granites in subduction zones as continents converge and subduction zones develop. As heat builds up under the thick supercontinent, uplift occurs, the surface area of continental shelf covered by ocean falls, and so does the sea level. Note that it is the start of Pangaea when cooling caused ice sheets to form.

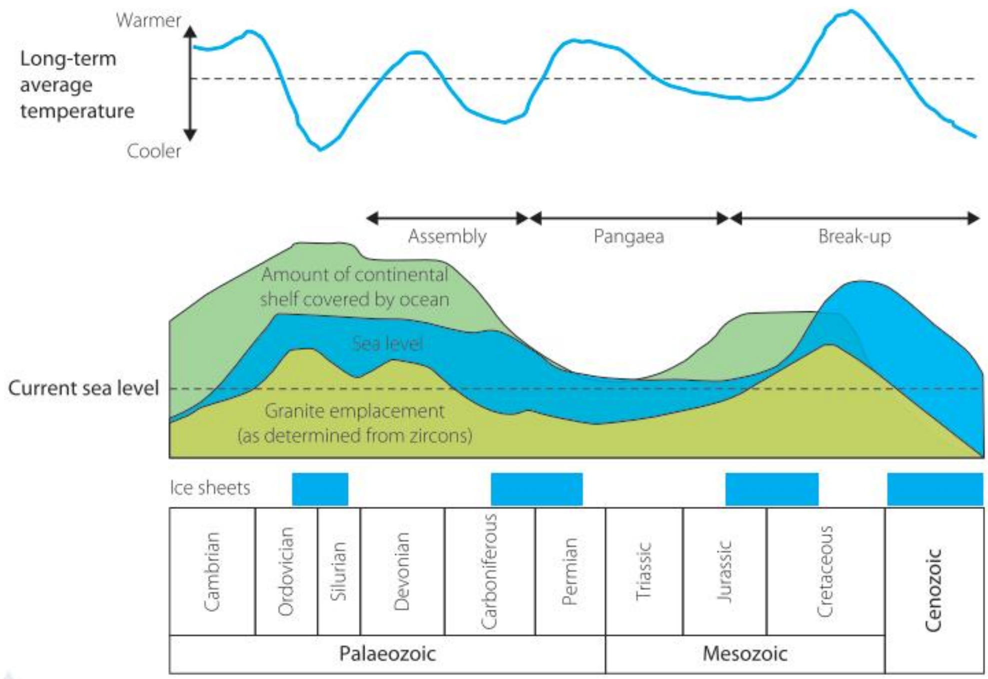

FIGURE 8.15 Climate change and Pangaea's break-up

Supercontinent break-up generates greenhouse conditions because increased volcanic activity adds CO_2 to the atmosphere and enhances the natural greenhouse effect. Other factors creating hothouse conditions include lower albedo due to increased sea levels and reduced land surface area. Lower albedo means more light is absorbed by Earth's surface and the energy is reradiated as infrared radiation. Break-up also changes ocean currents and heat flow as ocean basins are created and destroyed.

Continents influence climate in three important ways over long periods:

- At high latitudes, ice sheets and glaciers can form on the surface of continents. The resulting increase in albedo helps these ice sheets to persist.
- When plate convergence builds mountains, the weathering of newly exposed silicate minerals in rock removes CO_2 from the atmosphere. The dissolved carbon is carried to the ocean and is eventually stored in sediments as carbonate minerals.
- The position of continents in ocean basins affects climate because continents can affect the flow of currents in ocean basins and influence the transfer of heat from low to high latitudes.

Animations of Australian currents

View the animations and create a poster to identify two ways in which currents might affect climate in Australia.

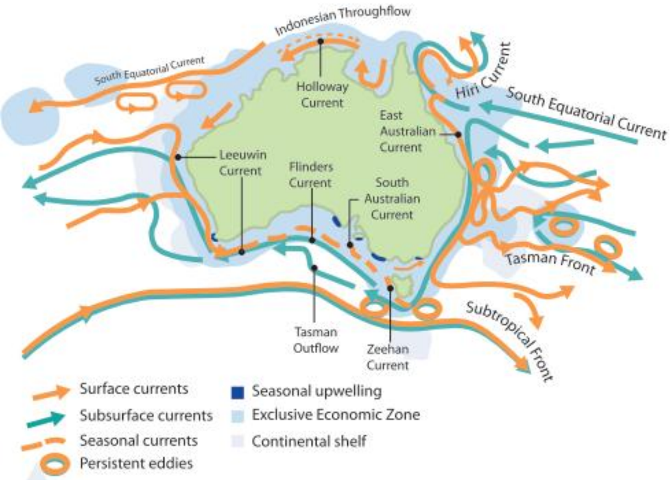

FIGURE 8.16 The ocean currents affecting Australia

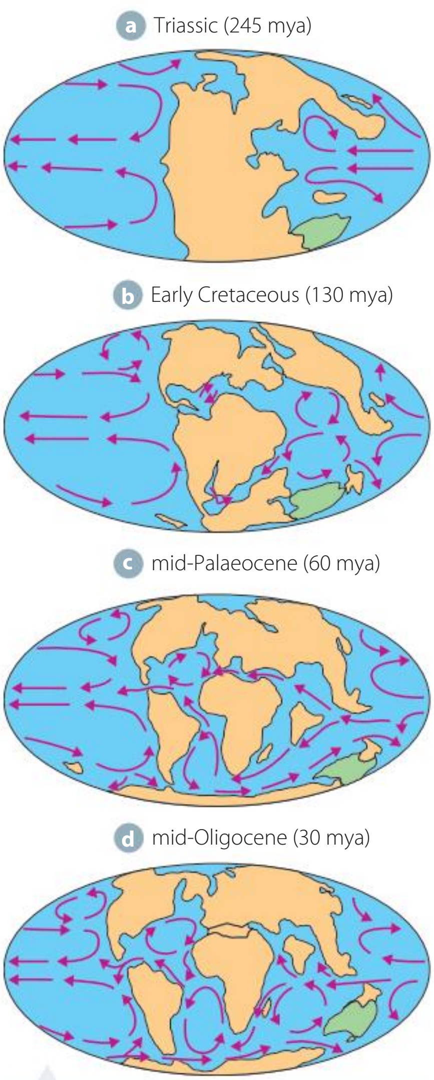

FIGURE 8.17
Generalised continental distribution and probable ocean currents. The location of Australia is shown in green.

Changes in ocean currents and circulation

Currents are a product of many factors: solar radiation, prevailing winds, temperature and salinity differences, continental and seafloor topography. In *Earth and Environmental Science in Focus Year 11*, you learnt how they operate at the surface of the ocean and at greater depths, transferring heat around Earth. Winds create currents that transfer warm or cold water towards or away from the polar regions. Temperature and salinity create density currents that move across the floor of ocean basins.

Ocean currents and circulation have a critical effect on climate. Without them redistributing heat around Earth, climate in different areas would be more extreme. Places near the Equator would be hotter and higher latitudes would be colder. To illustrate how currents moving heat influence climate, consider two currents that affect northern and eastern Australia (Figure 8.16).

To the north of Australia, water from the Pacific Ocean moves into the Indian Ocean between the islands of Indonesia. This current, called the Indonesian Throughflow, transfers heat from the Pacific Ocean and this contributes to the energy required to cause the Asian and Australian Monsoons. Some of this warm water later returns to Western Australia and flows south then east along the coast as the Leeuwin Current. This current modifies temperatures in southwestern Western Australia during winter and contributes to the rainfall in the area.

In eastern Australia, the deflection of the Pacific Ocean's South Equatorial current near Cape Melville in Queensland generates a powerful warm and nutrient poor current that flows rapidly along the coast. This is the East Australian Current. Most of the current moves east towards New Zealand slightly south of Sydney but eddies of warm water can extend as far as Tasmania. The East Australian Current modifies the climate along the New South Wales coast by providing the heat and moisture needed for rainfall and moderate coastal temperatures. As the current intensifies, it can move further south, generating more storms and contributing to heatwaves in Sydney by reducing the effects of onshore sea breezes.

Continental drift due to plate tectonics has affected the nature of ocean currents and the climate they produced in the past. Continents influence ocean currents and the winds that create them by forming barriers. The continents deflect currents carrying heat south or cooler waters north. During the Triassic, the continents forming Pangaea extended from one pole to the other (Figure 8.17a). The giant ocean basin called Panthalassa would have allowed strong **gyres** to move heat to high latitudes and the westerly flowing equatorial currents would have provided warm water to the Paleo Tethys ocean on the eastern side of Pangaea. Rocks that formed in this area, which is now part of the Mediterranean, are rich in fossil reefs. This suggests that the area once had warm, shallow and clear waters. As a result of the

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ocean currents, you might expect that Earth's climate did not vary as strongly with latitude as it does today, and this is what some of the evidence shows. The Triassic rocks do not contain evidence of ice sheets near what were the poles, and reptiles and amphibians seem to have lived over a wider range of latitudes than such animals do today.

As Pangaea split apart, new seaways allowed ocean currents to move in different directions. For example, in the mid-Palaeocene (60 million years ago), Australia was still attached to Antarctica, India was moving north towards Asia and the Atlantic Ocean had begun to open (Figure 8.17c). West-flowing currents could move north and south of Africa to form a continuous equatorial flow. This is termed the **circumequatorial current**. The resulting gyres led to warm surface waters in high latitudes. The currents, coupled with high CO_2 levels in the Palaeocene, led to a much warmer world than the one we live in today.

The closure of the Tethys seaway 40–50 million years ago disrupted the circumequatorial current. The equatorial waters cooled and the climate began to cool. About 30 million years ago, the **circumpolar current** around Antarctica became established. This prevented warm water from reaching the Antarctic coast and ice began to accumulate on the Antarctic continent (Figure 8.17d). Ice in the northern hemisphere is also a result of ocean currents. The closing of the Isthmus of Panama 3 million years ago led to the intensification of the **Gulf Stream**, a current moving along the east coast of North America that transports heat and moisture towards the north. The precipitation that resulted led to the establishment of the northern polar ice cap (Figure 8.18).

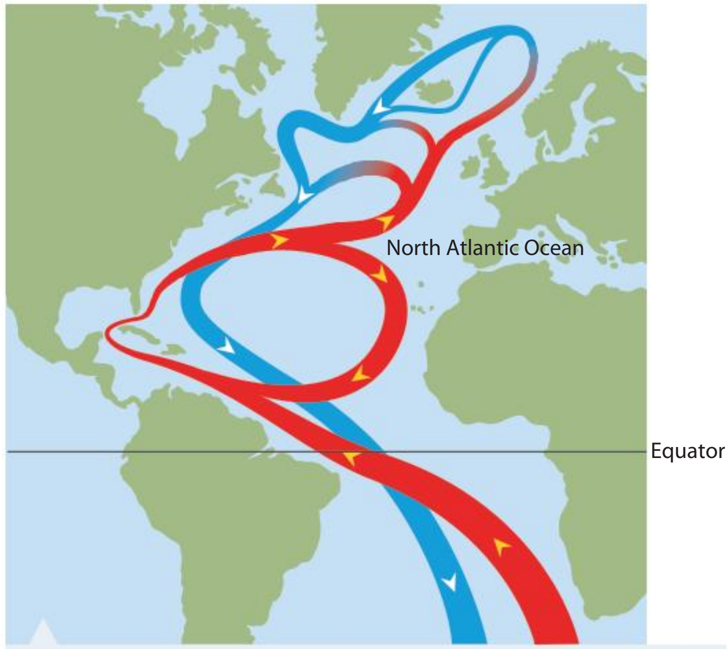

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FIGURE 8.18 The Gulf Stream transfers heat from the Equator to the North Atlantic Ocean. Red shows surface currents. Blue shows deep currents.

INVESTIGATION 8.3

Factors affecting climate

Critical and creative thinking

AIM

To summarise the factors affecting climate and compare their effects

METHOD

1. Copy the table in the Results section.
2. In your table, list the factors described in the chapter that affect climate.
3. Working alone, or as part of a group, identify the timescale over which the factor acts. Is it cyclic? How variable is it?
4. For each factor, describe how it causes a change in temperature in an area. Describe heating or cooling changes.
5. To complete the table, identify and record those factors that human activity might change.

»

» **RESULTS**

Copy and complete this table.

FACTOR	PERIOD OVER WHICH IT ACTS	HOW IT CAN LEAD TO WARMING	HOW IT CAN LEAD TO COOLING	CAN HUMAN INTERVENTION AFFECT THIS FACTOR?

ANALYSIS OF RESULTS

1 Which factors do you think are the most important in changing climate over long periods?
2 Do the factors interact with each other?
3 What combination of factors could lead to Earth cooling?
4 Which combination of factors could lead to Earth warming?

CONCLUSION

Explain why climate varies over long periods and why the nature of climate change is complex.

KEY CONCEPTS

- Factors influencing climate over geological timescales include plate tectonics, changes to the composition of the atmosphere and changes to the amount of solar radiation Earth receives.
- The supercontinent cycle influences climate through changing rates of volcanic emissions and weathering, together with changing positions of continents.
- The assembly of supercontinents has led to icehouse conditions in the past and continental dispersal is correlated with warm periods known as greenhouse conditions.
- Large igneous provinces have contributed large volumes of greenhouse gases to the atmosphere.
- Solar radiation received by Earth is influenced by changes in the Sun's output and changes due to Earth's orbital behaviour.
- Three features of Earth's orbit that create variations in the amount of solar radiation entering the atmosphere are eccentricity, obliquity and precession.
- Changes in ocean currents cause changes in local and global climate.
- A strong circumequatorial current distributes heat to high latitudes and has generated warmer global conditions in the past.
- The isolation of Antarctica by the formation of the circumpolar current and changes to the Gulf Stream contributed to the formation of the current ice caps.

CHECK YOUR UNDERSTANDING 8.4

1 What are the key factors that have influenced climate during the last 500 million years?
2 Outline the relationship between the stages in the plate tectonic supercycle and global climate.
3 Explain two reasons why the assembly of a supercontinent can lead to a cooler global climate.
4 Compare the effects of Earth's orbital eccentricity and obliquity on long-term climate.
5 Describe the role of massive volcanic eruptions in modifying climate.
6 How does an ocean current influence climate on a continent?
7 Describe how ocean currents influence global climate.
8 Explain how the formation of the circumpolar current around Antarctica led to a cooling of Antarctica.

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8 CHAPTER SUMMARY

- Climate is a long-term description of the weather system.
- Climate is described in terms of averages and variations of characteristics such as temperature, precipitation, winds and atmospheric pressure.
- The climate system consists of five parts and their interactions: atmosphere, hydrosphere, lithosphere, cryosphere and biosphere.
- An area's climate is affected by a range of factors, including latitude, altitude, wind patterns, topographic relief and the nearness to the ocean.
- The natural climate changes over a wide range of timescales – from hundreds to millions of years.
- The natural greenhouse effect plays an important role in making Earth habitable. Without it, the average temperature of Earth would be –18°C.
- The natural greenhouse effect describes the warming of Earth's atmosphere by greenhouse gases absorbing long-wave radiation emitted by Earth's surface and transferring the energy to the atmosphere. It makes Earth suitable for life.
- A greenhouse gas is a gas that can absorb and reradiate long-wave radiation.
- Important natural greenhouse gases are water vapour, CO_2 and CH_4.
- The amount of light reaching Earth's surface is affected by albedo, reflection and absorption by clouds and absorption by the atmosphere.
- Scientists use models to describe, explain, predict and investigate complex systems and processes such as those that create climate.
- The global carbon cycle is a model that allows scientists to predict and explain short-term changes in CO_2 in the atmosphere.
- The long-term carbon cycle shows that some changes in carbon reservoirs and CO_2 levels can take thousands or millions of years.
- Factors influencing climate over geological timescales include plate tectonics, changes to the composition of the atmosphere and changes to the amount of solar radiation Earth receives.
- The supercontinent cycle influences climate through changing rates of volcanic emissions and weathering, together with changing positions of continents.
- The assembly of supercontinents has led to icehouse conditions and continental dispersal is correlated with warm periods known as greenhouse conditions.
- Large igneous provinces have contributed large volumes of greenhouse gases to the atmosphere in the past resulting in climate warming.
- Solar radiation received by Earth is influenced by changes in the Sun's output, and changes due to Earth's orbital behaviour.
- Three features of Earth's orbit that create variations in the amount of solar radiation entering the atmosphere are eccentricity, obliquity and precession.
- Changes in ocean currents cause changes in local and global climate.

8 CHAPTER REVIEW QUESTIONS

Review quiz

1 Contrast weather and climate.

2 Outline an interaction between the hydrosphere and atmosphere that affects climate.

3 Explain why central New South Wales experiences more variation in daily temperatures and rainfall than towns along the coast.

4 Summarise the natural greenhouse effect.

5 Create a flowchart to show how the natural greenhouse effect helps to maintain a warm temperature at Earth's surface.

6 Explain how an increased greenhouse gas concentration would affect surface temperature.

7 Why does the weathering of silicate minerals remove CO_2 from the atmosphere?

8 A warming climate might lead to higher rainfall in some areas. How could this lead to the removal of CO_2 from the atmosphere?

9 How does the albedo of a surface influence the natural greenhouse effect?

10 Outline the factors influencing climate over geological timescales.

11 Describe three factors affecting the amount of solar radiation arriving at the surface of Earth.

12 Draw a diagram to illustrate the nature of Earth's orbital eccentricity and obliquity.

13 At present, the orbital eccentricity of Earth is nearly at the minimum of its cycle. Explain what will happen to Earth's climate as the orbit becomes more elliptical.

14 Describe how the tectonic supercycle influences global climate.

15 Contrast the effects of volcanic CO_2 and sulfide emissions on global climate.

16 Table 8.1 summarises satellite measurements of the albedo and the extent of sea ice in the Arctic over a 6-month period.

TABLE 8.1 Albedo and sea ice cover in the Arctic

MONTH	CLEAR-SKY PLANETARY ALBEDO	SEA ICE COVER (%)
March	0.58	99
April	0.57	95
May	0.54	90
June	0.41	75
July	0.32	68
August	0.23	39

a Graph the albedo against sea ice cover and draw a line of best fit.

b Describe the relationship between albedo and sea ice cover.

c If light is absorbed by water rather than being reflected by ice, what will happen to water temperature and the probability of ice formation?

17 Describe the effects on climate of one Australian ocean current.

18 Assess the role of heat transfer by surface currents in reducing temperature extremes between high and low latitudes on Earth.

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9 Evidence for climate variation

OUTCOMES

In this chapter you will learn about:

- the concept of climate proxies
- types of evidence for climate change in Earth's past CCT L
- various types of evidence for recent climate variation. CCT ICT L N

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To be confident that Earth's climate has varied in the past, we must understand the evidence of Earth's historical climate record. Today, different aspects of the climate are measured, at least daily, in many areas, and technology allows scientists to collate that information into a climate picture very rapidly. To know what the climate in an area was a thousand or a million years ago takes longer. Scientists need to interpret evidence preserved in Earth materials that have accumulated over long periods. In this chapter, you will learn that it is rarely possible to measure ancient changes shorter than years or even centuries.

Science Photo Library/British Antarctic Survey

FIGURE 9.1 Ice cores can contain records of climate spanning thousands of years.

Alamy Stock Photo/redbrickstock.com

FIGURE 9.2 A dust storm passing over Sydney in September 2009. Most of the dust was deposited in the Tasman Ocean.

9.1 The nature of climate proxies

Evidence of climate change exists in many forms and places on Earth – ocean sediments, caves, tree rings, ice (Figure 9.1) and the sediments that glaciers create. Evidence of climate change can be seen in underwater shells, sea level displacements and oxygen isotope percentages in water. All of these are forms of proxy data.

A climate proxy is anything that is preserved, can be measured and from which some aspect of climate can be inferred. Changes in a proxy reflect changes in the environment in which the proxy formed. An example of a climate proxy is windblown dust deposited in marine sediments or on ice. The presence of dust in sediment or ice tells us about the climate where it originated. During droughts and dry conditions, dust is blown from land into the ocean and as far as Antarctica. When conditions are cool and wet, less dust is transported long distances.

The **span** of time that a climate proxy covers and the **resolution** of the data provided are important factors in choosing a climate proxy. Resolution refers to how well two closely associated events can be separated. Some proxies, such as coral growth ridges, detail time intervals of days; others, such as deep marine sediments, may have a resolution with intervals of thousands of years.

Analysis of a climate proxy provides evidence of the climate during a specific span of time, when direct measurements of the climate at the time are impossible. Mineral particles in windblown dust contain evidence of their origin and the climate conditions that deposited them (Figure 9.2). The size and surface features of quartz grains, together with the distance of the sediment sample from land, allows scientists to infer wind speeds. The presence of rare earth elements and lead isotopes in the dust can help determine where the dust came from. The conditions needed to generate the dust are reasonably well understood and provide reliable evidence of extensive dry conditions on the continent.

Another example of a climate proxy is changes in rock type. Some rock types reflect particular climatic conditions. For example, windblown sands form sandstones with characteristic grain size distributions and structures. These rocks reflect climates that are dry and warm. Changes in rock type reflect a change in environment and climate.

Fingerprinting aeolian dust in marine sediment: Australian examples

Read Patrick De Deckker's summary of how aeolian dust provides evidence of climate history.

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Rock types often change as a result of sea level. Sea level rise can be due to tectonic factors but it also reflects climate temperature change. In warm periods, as ice melts, sea levels rise. In cool periods, ice re-freezes and sea levels fall. During a **transgression**, sea levels rise and the ocean covers more land and moves the sediment (Figure 9.3).

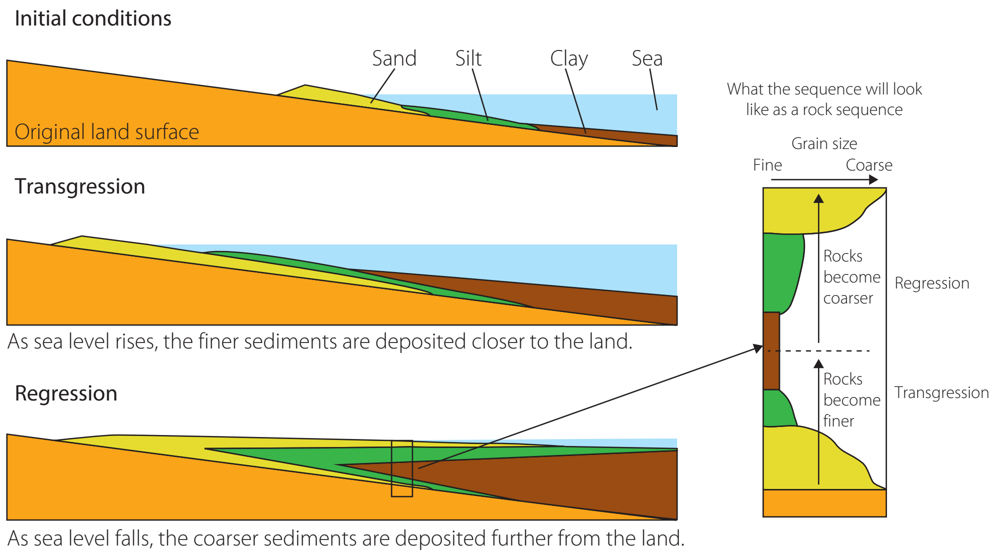

FIGURE 9.3 Transgressions and regressions result in rock sequences with changing sediment sizes.

The distance that sediment is transported from land depends on grain size. Larger particles, such as sand, are deposited close to shore; fine particles, such as clays, are deposited further from shore. During a transgression, the boundary between sands and finer sediments moves towards the shore. During a **regression**, the sea level lowers and the boundary between sediment types moves away from the coast. When the layers of sediment are exposed later in a cliff or drilled core, the sequence of sedimentary rocks allows geologists to reconstruct the changing sea level. Although not all sea level changes are due to climate change, this evidence helps to support other climate change evidence.

Oxygen isotopes as a proxy for temperature

Oxygen is the most widely used climate proxy for studying how climate has changed. Oxygen atoms exist in three forms, or **isotopes** – oxygen-16, oxygen-17 and oxygen-18. The isotopes vary only in the number of neutrons the atoms contain (Figure 9.4). Oxygen-16 is the most abundant form (99.76%). Oxygen-18 has an abundance of 0.20% and oxygen-17 has an abundance of 0.040%.

Water molecules that contain oxygen-16 and oxygen-18 are affected differently by evaporation and precipitation because of their different masses. At a warm ocean surface, more water molecules containing lighter oxygen-16 evaporate than heavier water molecules containing oxygen-18. This means that in warmer weather, water vapour contains a higher ratio of oxygen-16 to oxygen-18 atoms. Due to its slightly higher mass, a water molecule containing oxygen-18 is more likely to precipitate from water vapour. As a result, water vapour is further enriched in oxygen-16. This process is referred to as **fractionation**. There is a relationship between latitude and the amount of oxygen-18 in rain. Rain falling closer to the poles contains less oxygen-18.

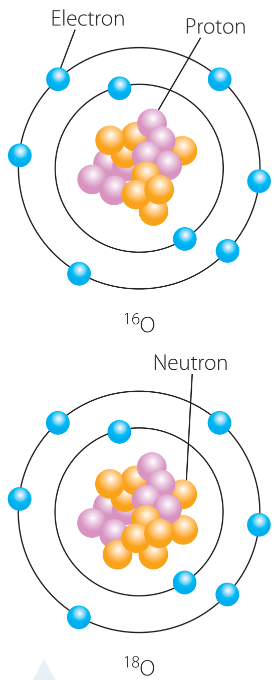

FIGURE 9.4 Oxygen-16 and oxygen-18 have different numbers of neutrons. Oxygen-16 has 8 neutrons and oxygen-18 has 10 neutrons.

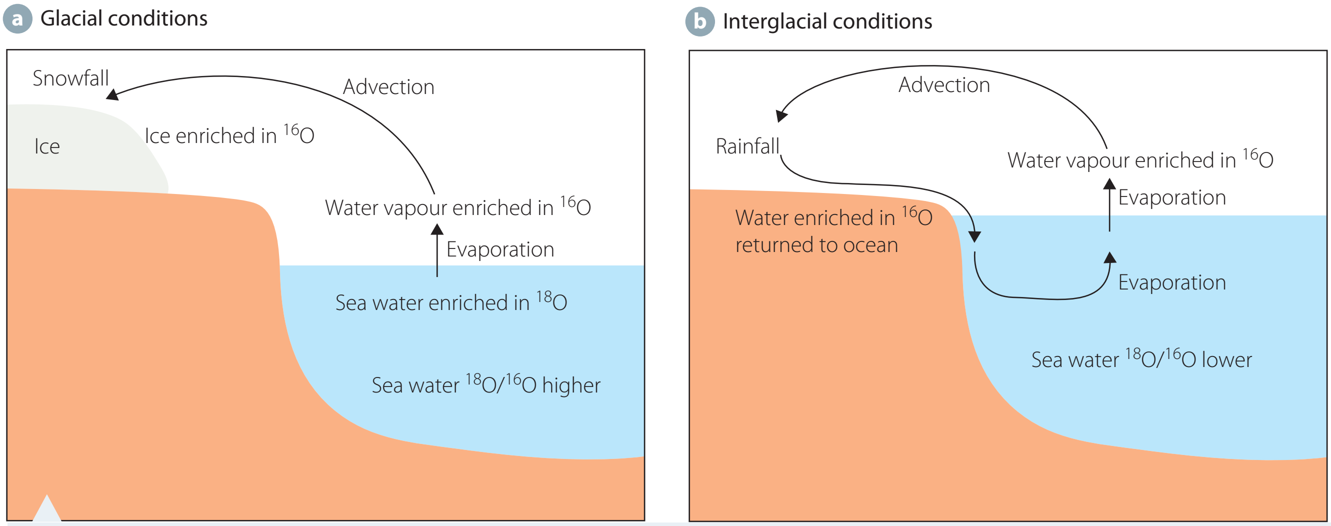

FIGURE 9.5 How oxygen isotopes are fractionated

Temperatures from fossil shells

Read the history of how microfossils came to be used as climate proxies.

When water rich in oxygen-16 precipitates and falls as snow, oxygen-16 is locked up in the ice and the relative amount of oxygen-18 in the ocean slightly increases (Figure 9.5a). When conditions are warm, the oxygen-16-rich water precipitates and falls as rain and eventually runs back to the ocean, maintaining a higher oxygen-16 to oxygen-18 ratio in the ocean (Figure 9.5b).

Scientists describe the ratio of oxygen-18 to oxygen-16 as **delta-O-18** ($\delta^{18}O$). Delta-O-18 is calculated as a ratio of ratios. The ratio of oxygen-18 to oxygen-16 in a sample is divided by the ratio of these isotopes in a standard sample and then multiplied by a thousand. The resulting number is described in units of parts per thousand (‰). An increase of about 0.2‰ in $\delta^{18}O$ corresponds to a temperature decrease of approximately 1°C.


Alamy Stock Photo/E.R. Degginger

FIGURE 9.6 Living foraminifera in water. Their diversity is used to determine past climate.

Scientists who study past climate, **palaeoclimatologists**, can measure $\delta^{18}O$ directly in ice cores. They can also analyse $\delta^{18}O$ values in fossils: both large fossils, such as corals, and **microfossils**. Microfossils are very small fossils, usually less than 1 mm in diameter. Microfossils called foraminefera, usually referred to as **forams** (Figure 9.6), build their **tests** (shells) from calcium carbonate. Oxygen isotopes in the tests are analysed to determine the temperature at which the forams built their shells. The growth rings of corals can be analysed in a similar way. Using carbonate for temperature measurements is slightly more complicated because other factors affect the growth of hard parts, but other isotopes, such as strontium or magnesium, which replace calcium, can be measured to verify the temperatures at which the shells or skeletons formed.

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INVESTIGATION 9.1

Interpreting $\delta^{18}O$ data

AIM

To interpret $\delta^{18}O$ data to identify major changes in climate and possible reasons for those changes during the last 67 million years

Critical and creative thinking

Numeracy

Literacy

ANALYSIS OF DATA

Consider Figure 9.7.

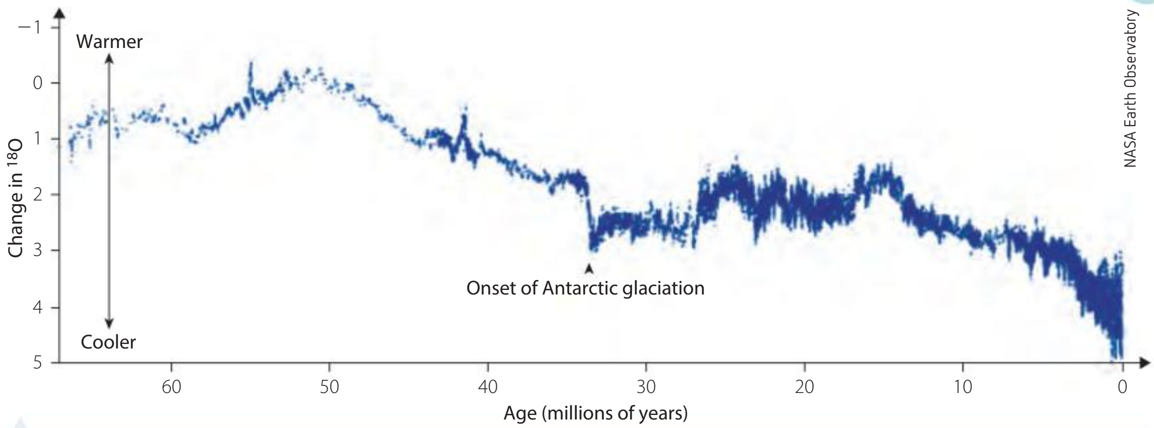

FIGURE 9.7 The change in $\delta^{18}O$ values compiled from more than 40 deep ocean drill cores by US palaeoclimatologist James Zachos and his colleagues demonstrates the decrease of ocean temperature over the last 50 million years.

General trends

1. What is the trend in $\delta^{18}O$ values from 68 million to 50 million years ago?
2. Describe the general trend in $\delta^{18}O$ values from 50 million years ago to the present.
3. If a change of 0.22‰ in the $\delta^{18}O$ value represents a change of 1°C, calculate the decline in temperature since the highest $\delta^{18}O$ value 50 million years ago.

Rapid changes

4. Identify the two spikes in $\delta^{18}O$ values at 55 million years ago and 40 million years ago. These are the Palaeocene–Eocene Thermal Maximum (PETM) and the Middle Eocene Climatic Optimum (MECO). Estimate the change in $\delta^{18}O$ levels for these events above the trends they rise from.
5. Are the rapid changes associated with the PETM and MECO events likely to be due to plate tectonic events or rapid change in greenhouse gas levels? Why do you think so?
6. Table 9.1 shows the timing of some events during the last 50 million years. Copy and complete the table using Figure 9.7.

»

TABLE 9.1 Events and their climate consequences during the last 50 million years

APPROXIMATE TIME (mya)	EVENT	TREND SHOWN ON THE GRAPH	EXPLANATION FOR THE TREND
50	Uplift of the Himalayas		
34	Establishment of the Antarctic Circumpolar Current		
25	Uplift of the Andes		
15	Columbia River Vulcanism		
12	East Antarctic ice sheet forms		
6	West Antarctic ice sheet forms		

DISCUSSION

Climate change involves changes on several timescales. Slow, gradual trends of warming and cooling are due to tectonic processes on timescales of tens of millions of years. Orbital behaviour of Earth and the Sun produce changes on the scale of tens to hundreds of thousands of years. Very rapid climate changes can occur in timescales of thousands to tens of thousands of years.

1 Which timescales are most obvious in Figure 9.7?
2 Why are the intermediate and rapid changes not clearly visible on the graph?
3 Can $\delta^{18}O$ data from deep sea cores provide evidence of the intermediate and rapid changes?
4 Why is oxygen isotope data such a valuable tool for investigating past climate?

KEY CONCEPTS

- Evidence of climate change exists in many forms.
- A climate proxy is a preserved part of Earth that can be used to infer some aspect of past climate.
- An important climate proxy for temperature is variations in the proportion of oxygen-18 to oxygen-16 isotopes in fossils and sediments.

CHECK YOUR UNDERSTANDING 9.1

1 Identify three sources of evidence about climate in the past.
2 Compare sedimentary rock types and fossils as evidence of past climate.
3 Describe, using an example, a climate proxy.
4 How are $\delta^{18}O$ values used as a proxy for global temperature?
5 Describe two sources of the oxygen isotopes used to determine past global temperatures.
6 The graph in Figure 9.8 shows changes in $\delta^{18}O$ over a 22 000-year period derived from fossil foraminifera.
   a Copy the graph and label it to show times of cooler and warmer climate.
   b Estimate the rate of temperature change between points A and B.

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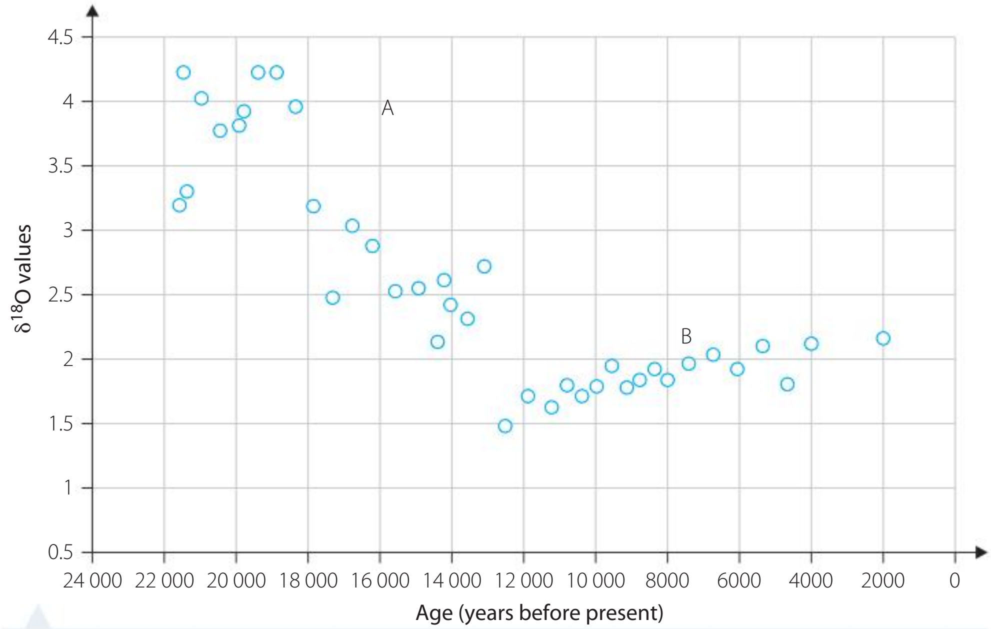


FIGURE 9.8 Changes in $\delta^{18}O$

7 Why can high $\delta^{18}O$ values in oceans be used to infer cold global climates and higher ice volumes?

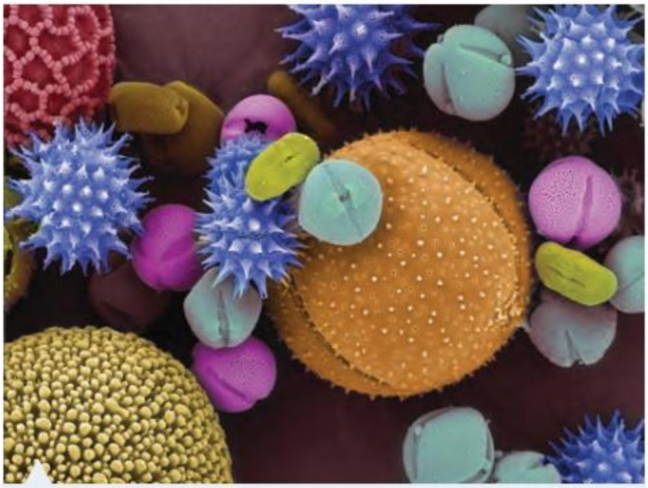
8 A cliff contains rock layers that become finer grained as the layers become younger: coarse sandstone, fine sandstone, siltstone, mudstone. Explain how a change in climate could lead to this sequence of rock layers.

9.2 Ancient evidence of climate change

Biological evidence – pollen, microfossils and macrofossils

Pollen is the microscopic grains containing the male reproductive cells of a plant. Pollen has existed on Earth since the late Devonian. Flowering plants appeared much later during the Cretaceous. Modern plants produce vast amounts of pollen. Because pollen grains are small, they are widely distributed by wind. Pollen grains are highly resistant to decay and they persist in sediment for long periods. Pollen from different plant species has different structures, which make it easily distinguishable (Figure 9.9). This makes pollen a valuable tool for dating sediments and rocks.

On land, fossilised pollen and spores have been used to establish changing climates over long periods. When pollen is washed or blown into a lake, it becomes part of the sediment and records the types of vegetation living around the lake. As the climate and environment around the lake changes, so does the composition of the pollen preserved in the lake sediments.



Alamy Stock Photo/Cultura Creative Ltd

FIGURE 9.9 Pollen grains (magnified) provide evidence of climate change. The colours have been added by computer to this image.

Spores and pollen

Read about the nature of pollen and how samples are prepared for examination.

The study of pollen and other spores in archaeology and geology is called **palynology**. To analyse pollen, scientists separate the pollen from other parts of the sediment and then examine the pollen grains under a high-powered microscope. Sediment from a lake is acquired as a core. The core is separated into samples and the depth of each sample from the top of the core is recorded. The sediment is dried and some carbon material may be used to determine the age of the sample by radiocarbon dating. Next, the sample is treated with hydrochloric acid to remove any carbonate minerals and then with hydrofluoric acid to dissolve any silicate minerals. The residue is then washed and mounted on microscope slides. The types and numbers of pollen grains are counted and recorded; then a summary, or pollen diagram, is constructed.

INVESTIGATION 9.2

Information and communication technology capability

Critical and creative thinking

Numeracy

Interpreting pollen data

This investigation involves a model of palynology data reflecting the trends shown in pollen counts from sediment cores in central New South Wales. The pollen has been divided into five major groups. Four of the groups are families of plants with particular ecological requirements and a fifth group contains other types of pollen. The amount of charcoal found in the sediment at each level is also shown.

Details of the four major plant families are as follows.

- *Nothofagus* (Antarctic beeches): This group of plants requires warm temperate conditions and does not cope well with long dry periods. These plants are heavy pollen producers and their pollen is dispersed by wind.
- Myrtaceae: This large family of flowering plants includes eucalypts and many familiar Australian shrubs and trees. Plants of this family are found in tropical and warm temperate regions. Many are insect pollinated and many today tolerate dry conditions.
- Asteraceae: This large family consists of almost 33 000 species worldwide today. The plants of this family are mostly annual or perennial herbs that have compound flowers, such as the daisy. They can survive in a variety of environments, including arid conditions. Many of the flowers that suddenly appear in Central Australia after rain belong to this group.
- Poaceae (grasses): This diverse family today includes approximately 12 000 species. The grasses are found in diverse habitats and are wind pollinated. Grasses colonise areas after rain and cope well with grazing mammals that appeared at the beginning of the Cenozoic era.

AIM

To describe the changes in a plant community based on pollen data from lake sediments and then infer changes in the climate over time

METHOD

1. Table 9.2 summarises data from a series of sediment cores. Real palynology data would include more detail of individual pollen types and more samples. Not all the levels would be dated. These data are simplified to help you concentrate on key aspects.
2. Create a series of graphs to show how the frequency of major pollen types changed over time. If you use a spreadsheet program for this task, you might try creating a stacked area graph.
3. Draw another graph showing how the proportion of charcoal in the sediment changes over time.

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TABLE 9.2 Major pollen groups collected from a number of lake sediment cores in central New South Wales

DEPTH (m)	AGE (mya)	MAJOR POLLEN TYPES					CHARCOAL OCCURRENCE (%)
		NOTHOFAGUS (%)	MYRTACEAE (%)	ASTERACEAE (%)	POACEAE (%)	OTHERS (%)	
2	3	0	52	14	20	14	1.3
40	5	15	61	3	6	15	0.1
65	10	0	70	7	12	11	1.1
100	13	12	64	5	8	11	0.7
135	18	47	41	0	0	12	0.2
162	29	73	16	0	0	11	0.1
200	36	72	20	0	0	8	0.06

ANALYSIS OF THE DATA

1. Describe the trend shown by the *Nothofagus* data.
2. Describe how the Myrtaceae proportion of the pollen changes as the amount of *Nothofagus* pollen decreases.
3. In what ways are the trends of the Asteraceae and the Poaceae similar?
4. If *Nothofagus* plants grow well in warm temperate conditions, what does their decline suggest about the rainfall in the area?
5. *Nothofagus* and Myrtaceae are thought to have comprised the rainforests that covered much of Australia before it separated from Antarctica. What does the increase in Asteraceae and Poaceae suggest about the plant community in the area near the lakes?
6. Suggest a climate-related reason for the sudden changes in the data at 5 million years before the present.
7. Assuming that the fires that generated the charcoal were created by lightning strikes, what does the changing amount of charcoal suggest about the amount of moisture present in the area?
8. It appears that no pollen was deposited after about 3 million years ago. What might have happened to the lakes to prevent deposition of pollen and sediment?

CONCLUSION

Write a summary of the ways pollen records in lake sediments help us understand past climate.

A number of microfossils are used as climate proxies. The important role of foraminifera was described earlier, but other microfossils such as dinoflagellates, diatoms, forams and coccoliths are also used to study paleoclimate. Microfossils are found in rock cores and outcrops and can be extracted by methods such as sieving, chemical reaction with other parts of rock or density separation.

Calcareous microfossils build their tests from calcium carbonate ($CaCO_3$). They include foraminifera, coccoliths and some dinoflagellates. All these microfossils can provide oxygen isotopes from which past temperatures can be inferred. Forams and coccoliths make good index fossils because they occur over short geological periods and are widely, often globally, distributed. Research has found that particular species exist in specific temperature ranges and the occurrence of these species indicates probable temperatures when they were incorporated into sediment.

Fossils as indicators of past climatic conditions

Read this article about fossils and summarise the information acquired about climates.

Diatoms

Read about the diversity and uses of diatoms at University College in London.

Siliceous microfossils built their tests from silica (SiO_2). Diatoms are an important member of this group (Figure 9.10). They are photosynthetic, have very diverse forms (Figure 9.11) and are sensitive to changes in environmental conditions. Diatoms are planktonic and information such as oxygen isotope data from their tests tells us about conditions in the surface of the ocean or lakes. Nutrients from the land as run-off or as wind-blown dust can cause diatoms to rapidly reproduce, forming **blooms**. The diatoms then die and sink, leaving large numbers of their tests in ocean and lake sediments. We know from studying the modern diatom that their growth and abundance is affected by wind strength, upwelling and light availability. This knowledge is used to infer climate conditions from the remains of diatoms in ocean and lake sediment cores.

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FIGURE 9.10 Living diatoms. Note the outer surface, which is the test made of glass (SiO_2).

Shutterstock.com/Dr Norbert Lange

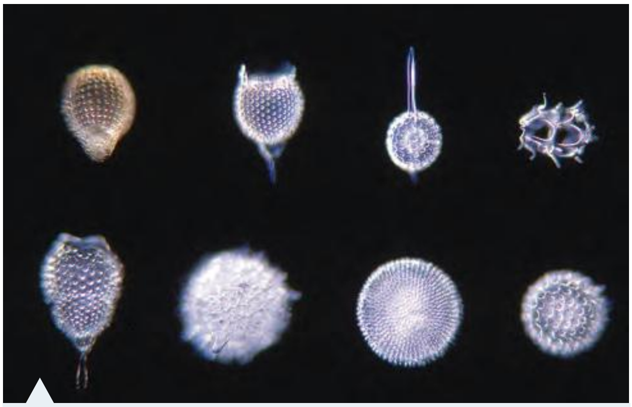

FIGURE 9.11 These diatom tests (shells) show the variety of ornamentation within the group.

Macrofossils are fossils that can be examined without the aid of a microscope. By understanding the adaptations of a fossil, scientists can make inferences about the environment the living organism inhabited. **Palaeontologists**, scientists who study past life, also see what is known of living species to understand the features of fossil organisms. For example, the marsupial lion (*Thylacoleo carnifex*) fossils from the Naracoorte Caves in South Australia was established as a carnivore by comparing its shearing teeth, enlarged thumb claw and massive jaws with modern carnivores (Figure 9.12). The plant group *Nothofagus* has a long fossil record in Australia and is found today in places that are cool and with high rainfall (Figure 9.13). The appearance and disappearance of *Nothofagus* fossils over time reflects changing temperature and rainfall conditions through parts of Australia.

AAP Photo/Flinders University

FIGURE 9.12 Note the head of the marsupial lion (*Thylacoleo carnifex*). It has many similar features to modern carnivores.

The number and distribution of any organism is controlled, in part, by climate conditions. Some groups of organisms are particularly sensitive to climate and their fossils are valuable indicators of past climate. Corals have a long fossil record and we know that these organisms require particular temperatures and depths to survive. Corals make their skeletons from calcium carbonate, which means they can also be used as sources of oxygen isotopes for temperature measurements. Some corals add growth to their skeletons in annual rings, similar to annual rings in trees. These growth rings provide evidence of climate on an annual basis when the oxygen isotopes are extracted from each growth ring.

The fossils of plant communities have provided a great deal of evidence about climate during the Cenozoic in Australia. Rainforest plants in Australia have a common ancestry with similar rainforest plants in India.

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This implies a common ancestry before Australia, Antarctica and India separated. Antarctica has a very rich fossil plant record extending back 100 million years, and together with fossil deposits in Australia, the plant fossils demonstrate plant communities being affected by changing climate. The use of plant macrofossils, together with pollen studies, has allowed scientists to build up a picture of how Australia's climate has changed since Australia first began to rift from Antarctica during the late Cretaceous (Table 9.3).

Shutterstock.com/Manuel Soler Mayor

FIGURE 9.13 Leaves and flowers of a *Nothofagus* tree. Its fossils can be used to establish past temperature and rainfall conditions in particular locations.

Animals and fossils of Naracoorte

Summarise some of the fossil organisms found in the Naracoorte caves and the types of environments in which they lived.

TABLE 9.3 Climate and plant communities in Australia during the Cenozoic

PERIOD	STARTING TIME (mya)	EPOCH	PLANT COMMUNITIES INTERPRETED FROM FOSSILS	IMPLIED CLIMATE
Quaternary	0			
	0.01	Holocene	Vegetation was similar to now but affected by firestick farming and more recently by European land clearing for farming.	Slightly wetter until 5000 years ago; since then it has dried. Temperatures similar to now.
	2	Pleistocene	Patterns of forests, grasslands and deserts changed fairly rapidly.	Climate was cycling rapidly between cold, dry conditions and warm, wet conditions.
Neogene	5	Pliocene	Forests reappeared briefly in south-eastern Australia at start followed by grasslands, shrublands and open forests becoming common.	Increasing fluctuations in climate.
	24	Miocene	End of Miocene characterised by decreases in forests and increases in dry-land vegetation. Middle to Late Miocene saw changes from closed forests to wet sclerophyll forests and in other areas dry forest gave way to open woodlands. Many plant groups dominating inland Australia became common. Early Miocene characterised by temperate forests with a high proportion of *Nothofagus*.	Vey arid conditions. Middle to Late Miocene climate was cooler and more seasonal. Early. Miocene was warm and wet.
Paleogene	37	Oligocene	*Nothofagus* became a more common part of the forests. Temperate rainforests showed lower species diversity.	Climate more seasonal and cooler.
	58	Eocene	Rich and diverse rainforests of different types covered most of Australia with *Nothofagus* being a relatively small component in some areas.	Wet and warm. Rainfall fairly high. Temperature about 18–19°C.
	66	Palaeocene		

Geological evidence

The composition and structure of rocks provide a long record of climate change. In section 9.1, you learnt about rocks being used as an example of a climate proxy. Sedimentary rocks are sources of climate evidence because the weathering processes that generate sediment and the agents of erosion that transport and deposit the sediment are a consequence of climate conditions. For example, **silcrete** is a rock formed when silica dissolved in groundwater precipitates in soil to form a silica-rich layer of minerals

You learnt about how Aboriginal peoples valued silcrete as a tool-making resource in Chapter 5 of *Earth and Environmental Science in Focus Year 11*.

surrounded and cemented together by the precipitated silica. Silcretes form under warm arid conditions with occasional periods of waterlogging, possibly due to flooding. Silcrete is common in Australia. Fossilised plants in silcretes are used to date the rocks' formation in the Cenozoic throughout Australia.

Sedimentary rocks contain structures that reflect the climates in which they form. A common structure in sedimentary rocks is cross-bedding. The structure forms in dunes produced by flowing air or water. Sand dunes on land lead to large cross-beds with characteristic fine sand compositions. They are often iron stained, reflecting the arid environments in which they form (Figure 9.14). Cross-beds are common in river-deposited sandstones (Figure 9.15). The height of the ripples and dunes containing the cross-beds are determined by the speed of the water moving the sediment. Large sets of cross-beds reflect the movement of high volumes of water, and the resulting rocks, as part of a sequence, can be used to interpret the environment and climate in which they formed.

Shutterstock.com/PhotoGeo111

FIGURE 9.14 Cross-beds formed by wind-blown dunes. This structure formed in an arid environment and the cross-bedded units are measured in metres.

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FIGURE 9.15 Cross-bedding in a water-deposited sandstone. Each cross-bed is approximately 30 cm high.

Rocks and rock formations can also be shaped by forces that are a product of climate. Figure 9.16 shows a rock surface covered in scratches or **striations**. It is also polished. The polishing and the striations are caused by glacial ice moving over the rock surface, reflecting a time when the climate was cold and glaciers were present.

Chemical evidence

Isotopes in rocks and sediments provide information about age, the origin of material and climate processes. Radioactive isotopes of uranium, potassium and carbon can be used to date material in a geological sequence or sediment core. Proportions of rare earth elements can be used to identify where mineral material comes from. Biological and physical processes in environments also change the proportions of isotopes of some elements in meaningful ways.

When sediment sinks in an ocean or a lake, it often carries climate proxy data that can later be used to reconstruct past climate information. You have already learnt how $\delta^{18}O$ ratios are used as a climate proxy to investigate temperature. However, $\delta^{18}O$ data can be used to infer many other aspects of past climates; for example, ice volumes and the behaviour of processes such as evaporation and precipitation in the water cycle. Magnesium to calcium ratios in forams provide evidence about sea surface temperatures. Barium to calcium ratios have been used to infer the amount of freshwater added to the ocean as rain or continental run-off. Dust deposited in water far from land reflects dry conditions.

Oxygen and hydrogen fractionation provides similar information about past climates. Hydrogen, like oxygen, has a heavier form – hydrogen-2 (deuterium) – that can be separated, or fractionated, from hydrogen-1 in a similar way to the fractionation of oxygen isotopes. The ratio of hydrogen-2 to hydrogen-1 is used to calculate a value referred to as δD. The values of δD vary in a similar way to values for $\delta^{18}O$ and provide similar information.

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Living systems also fractionate isotopes. Isotope ratios of carbon and nitrogen have been used to understand the interaction between life and climate. The main isotopes of carbon are carbon-12 and carbon-13. The major fractionation process for carbon is photosynthesis. During photosynthesis, carbon-12 is preferentially used to build carbonates and the proportion of the heavier carbon-13 atoms decreases. This process is affected by ocean surface temperature and possibly the type of photosynthesis used by marine plants called **phytoplankton**. The ratio of carbon-13 to carbon-12 is used to calculate a value called **delta-13-C** ($\delta^{13}C$). $\delta^{13}C$ values are interpreted as a CO_2 proxy and their measurement in sedimentary rocks and deep-sea sediments provides valuable evidence about changing CO_2 levels in ocean surface waters in the past.

The fractionation of nitrogen isotopes occurs in a similar way. The two isotopes of nitrogen are nitrogen-14 and nitrogen-15. Phytoplankton preferentially take up nitrate ions containing nitrogen-14 rather than nitrogen-15. **Delta-15-N** ($\delta^{15}N$) values are used to understand how the nitrogen cycle operated in oceans in the past. Nitrogen availability limits the growth and productivity of phytoplankton. High levels of nitrogen can cause high levels of photosynthesis and CO_2 uptake. It is possible that nitrogen availability could influence transitions between interglacial and glacial climates. In cores from the Pacific Ocean, there is evidence that $\delta^{15}N$ values do vary between glacial and interglacial sediments, but this is not true for sediment cores from other areas. There is ongoing research to understand the relationship between nitrogen isotope ratios and climate.

Getty Images/Wolfgang Gaehler

FIGURE 9.16 Glacial striations and polishing on a rock surface

KEY CONCEPTS

- Evidence of ancient climate change can exist at the scale of annual change and change over long periods.
- Evidence from older periods generally has lower resolution than evidence from more recent time periods.
- Variations in a range of isotopes provide strong evidence of climate change.
- Fossils provide evidence of climate change in terms of their chemical composition, the nature of species present and changes in species over time.
- Changes in sea level reflect global climate and evidence of such change exists in changing sediment composition in rocks.
- Deep ocean sediments are important sources of evidence of the ancient climate because of the presence of a range of climate proxies and a long record of change.

CHECK YOUR UNDERSTANDING 9.2

1 What is the difference between the span and resolution of palaeoclimate proxy data?

2 Make a table to summarise the span and resolution of:
- coral rings
- ice cores
- deep sea sediments
- continental coastal sediments.

3 Describe an isotope system other than oxygen, and how it is used as a climate proxy.

4 Outline the role of foraminifera in determining past climates.

5 Outline how a cooling climate leads to falling sea levels and changes in coastal sediment deposition.

6 How can a study of diversity in fossil assemblages be used to infer climate change?

7 Describe the variations in ocean sediments and the climate variation those changes imply.

8 **a** Why do deep ocean sediments provide a long time span of data but a resolution measured in hundreds of years?

b Explain the high resolution but relatively limited time span of data from fossil corals.

Climate variation evidence

9.3 Recent evidence of climate variation

Ice cores

Ice in glaciers retains a record of the climate when it forms. As snow falls in glacial areas or on ice sheets, it is compacted by later snowfall to form ice. The ice traps bubbles of gas together with windblown dust, isotopes created in the atmosphere by cosmic rays, windblown pollen, ash from fires, salts from the atmosphere and ocean, and volcanic ash. Annual layers can be identified in the ice, as they can for rings in a tree. Ice is particularly deep in Antarctica (Figure 9.17) and in Greenland.

FIGURE 9.17 Ice at Antarctica has an average thickness of 2 km and reaches a maximum thickness of 4.7 km.

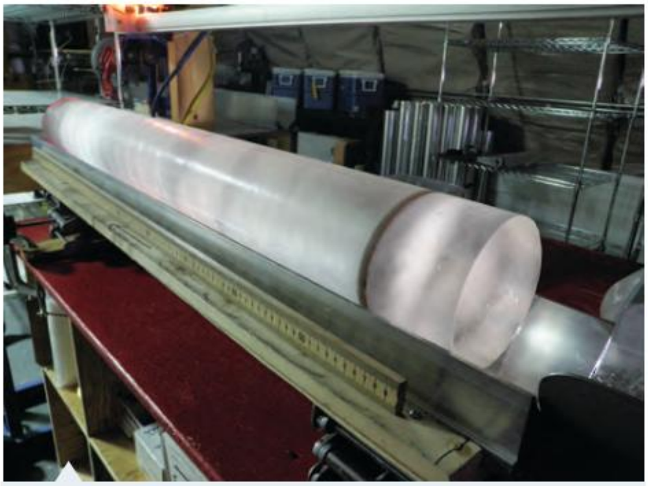

FIGURE 9.18 An ice core from west Antarctica. The dark band is a layer of volcanic ash that settled on the ice sheet approximately 21 000 years ago.

Ice is collected as an **ice core** (Figure 9.18). Ice cores are obtained using a hollow drill that cuts a cylindrical core 5–13 cm in diameter. Individual sections of an ice core are 1–3 metres long. Ice cores have been obtained from drill holes up to 3 km deep.

The age of the ice increases with depth. In 2017, an ice core from Allan Hills in Antarctica contained ice 2.7 million years old but the ice core was not continuous for that length of time. The Dome C ice core from further inland is a continuous record of the last 800 000 years. An ice core in Greenland is a continuous record of 123 000 years.

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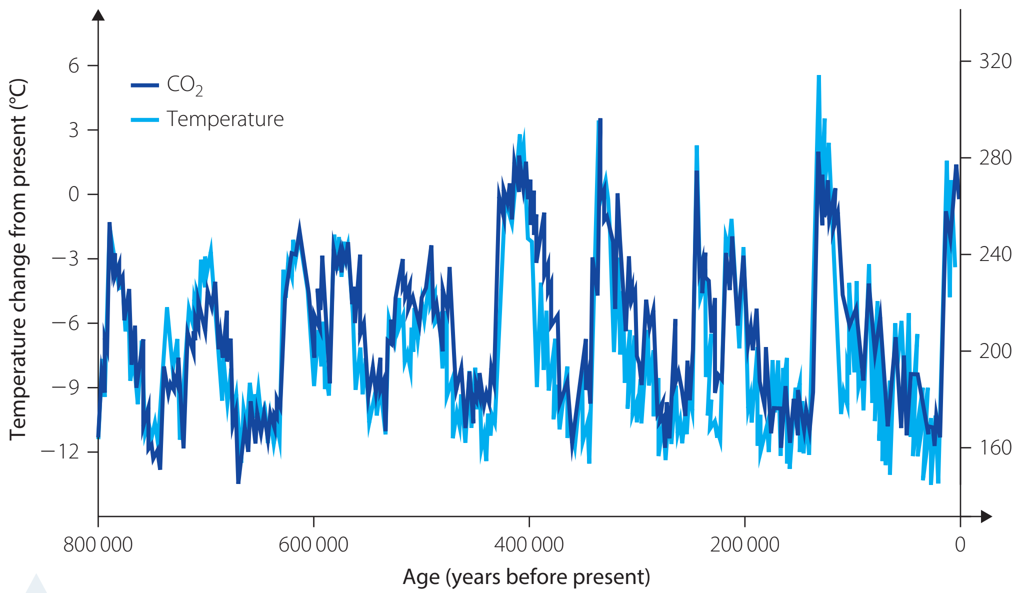
There are many ways to date ice cores. One method is to count the annual layers, but this is not always possible. Scientists sometimes measure changes in electrical conductivity and assay radio nucleotides. Scientists also use computer models that predict how ice depth changes with age. Radiocarbon dating can also be used on carbonate minerals and CO_2 trapped in the ice.

A range of useful climate proxies can be extracted from ice cores. Gas in the ice can be extracted under a vacuum hood as a slice of the ice core is melted. Scientists can then directly measure CO_2 levels at a time in Earth's past. Instruments such as mass spectrometers can analyse oxygen isotopes to identify past temperatures. Dating of volcanic ash allows scientists to correlate the age of layers between ice cores drilled in different areas. Oxygen isotope ratios in the ice, like those in forams, indicate the temperature of the air when the ice fell. The correlation between CO_2 levels and temperature is quite striking (Figure 9.19).



Figure, Temperature change (light blue) and carbon dioxide change (dark blue) measured from the EPICA Dome C ice core in Antarctica. National Centers for Environmental Information/National Oceanic and Atmospheric Administration (NOAA)

FIGURE 9.19 These graphs show how temperature and CO_2 levels in the atmosphere have corresponded during the past glacial cycles.

Ice cores have provided important evidence about climate change over the last half a million years. We know that for most of that time, CO_2 levels did not exceed 300 parts per million (ppm) (Figure 9.20). Today, the atmospheric level is approximately 415 ppm and it increases by 2 ppm per year.

Interpreting data from the Vostok ice core

Information from ice cores also suggests that climate change is due to the complex interaction of several factors. Figure 9.19 shows the close correlation of CO_2 levels and temperature. However, the graph does not prove causation. The glacial–interglacial changes are due to Earth's orbit and reflect Milankovitch cycles. Small changes in the energy reaching Earth causes ice surface area to increase which then increases albedo. This, in turn, causes changes in temperature that affect CO_2 exchange with the oceans and rates of photosynthesis. These changes create feedback loops that produce more temperature change. Indeed, if we could see the relationship between CO_2 levels and temperature at a larger scale, as in Figure 9.20, we would see that the CO_2 lags slightly behind the temperature change.

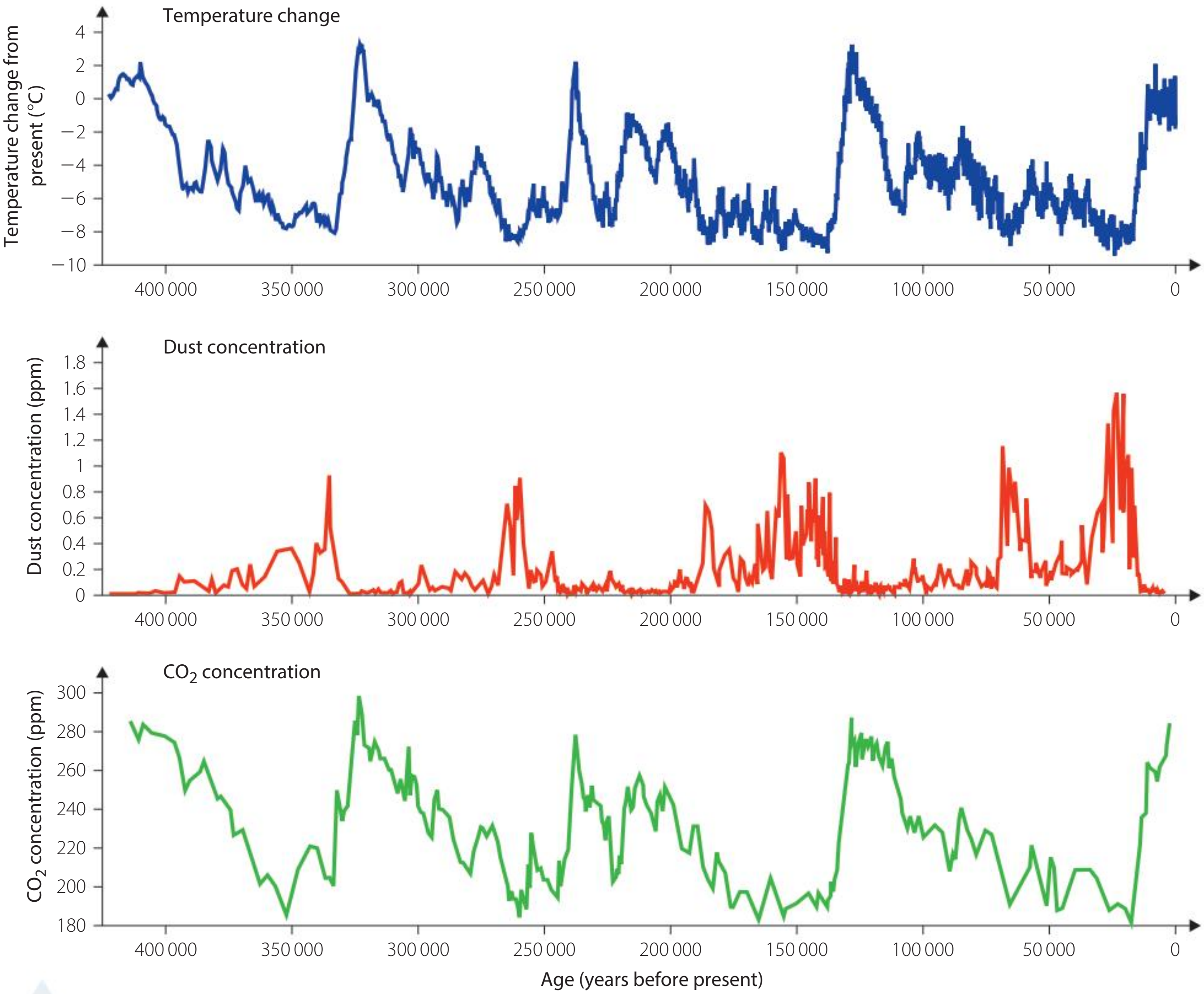


FIGURE 9.20 Temperature variation, CO_2 concentration and dust concentration from the Vostok ice core in Antarctica

Dendrochronology

In **temperate** areas where temperature and rainfall are seasonal, woody plants produce growth rings. A growth ring is a set of cells forming a recognisable ring in the trunk of a woody plant. Large cells with thin walls form at the start of a growing season as the plant grows quickly, and as the year proceeds and water becomes scarce, the cells become smaller and thicker walled. Figure 9.21 shows a cross-section of a woody plant with two growth rings. Note how the cell size changes in a ring as the

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cells move outwards. The red colour of some of the cells is due to the staining of cells with additional thickening.

Towards the end of the 19th century, scientists began studying the pattern of tree rings to describe changing climate and date artefacts made of wood. The scientific study of growth rings is referred to as **dendrochronology**. Tree rings have the great advantage of being produced annually, and by averaging the growth rings in an area to create a master pattern for the trees, scientists can compile long sequences of data by matching overlapping tree ring histories. In some areas, climate records recorded in tree rings extend to more than hundreds or even thousands of years.

The width of a growth ring in a tree varies from year to year, depending on temperature, rainfall, light availability, length of the growing season and available water in the soil. An abrupt change in conditions disturbs the gradual change in cell diameter in a growth ring, and more than one growth ring can be created for a particular year. This results in errors in calculations. The growth of a single plant is affected by several factors. For example, a tree growing next to a creek has better access to water than a tree of the same species growing on a ridge. You would not expect the tree ring pattern from the two trees to be exactly the same.

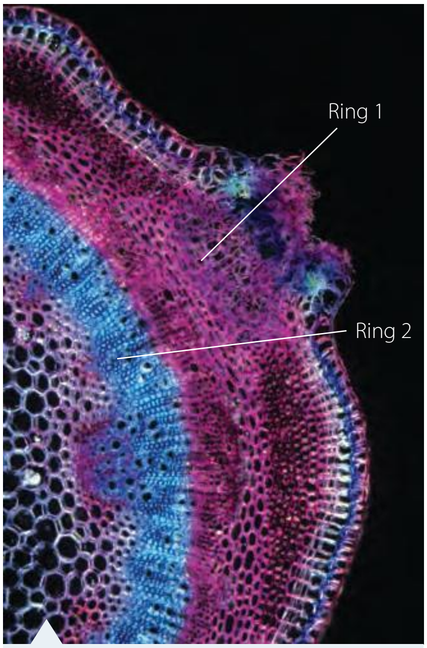

FIGURE 9.21 A cross-section of a woody stem with two annual growth rings viewed through a microscope. Tree rings can give information about past climate.

Tree ring data for long periods is compiled by matching patterns from trees of different ages. Some trees are incredibly long lived.

- Mountain plum-pines (*Podocarpus lawrencei*), which are native to the Snowy Mountains, live for as long as 600 years.
- Bristlecone pines in California, USA, can live for more than 4500 years. Some trees reach great age by cloning themselves.
- Aspen trees in Utah, USA, have growth records as long as 80 000 years, although individual trees live, on average, 130 years.
- A Huon pine clonal colony in Tasmania records 10 500 years of growth.

By matching the growth ring patterns of living and preserved dead trees, histories for an area can be extended over a very long time. In Europe, oak trees provide accurate records because they produce a growth ring each year. Scientists have used preserved timber recovered from bogs and swamps to create a data series from the present to a little more than 8000 BCE.

Dendrochronology data have been used to study a range of recent climate issues. Over the last 2 million years, before industrialisation, two key factors affected climate: variations in solar output and volcanic activity. Tree-ring data from bristlecone pines and trees in Asia and Europe have shown reduced ring growth in years where volcanic activity cooled the climate. More than 20 volcanic events have been identified in the tree-ring data.

Dendrochronology was used to resolve the nature of a controversial climate phenomenon. The Medieval Warm Period (Medieval Climate Optimum) was a period of warm conditions that occurred between 950 and 1250. Establishing whether this was a global event has been important for climate modellers, and dendrochronology data have helped to show that it was a period of climate change but not uniform warming. It is thought that the changes globally were due to an increase in solar output coupled with a decline in volcanic activity. In Europe, the warming might have been caused by a change in the North Atlantic Oscillation, a weather system that causes warm winds from the Atlantic to move over Europe.

In Australia, dendrochronology studies look at aspects of climate that have occurred in eastern Australia. Preliminary research on a native conifer (*Callitris intratropica*) from northern Australia suggests that it may be a suitable species for studying the Australian monsoonal system.

INVESTIGATION 9.3

Interpreting climate using dendrochronology

Critical and creative thinking

Numeracy

Using tree rings to identify periods of wet or dry climate is a valuable tool in determining climate over thousands of years. In years when water is scarce, tree rings are narrower than in years when water is readily available. In this investigation, you will correlate information from three tree cores to identify drought periods and critically analyse the quality of the data tree rings can provide.

The data you will use is shown in Figure 9.22. It shows skeleton plots from three trees distributed over a 4 km^2 area in the southern part of central New South Wales. A skeleton plot is created by marking the narrow rings in a tree ring sample. The length of the mark is inversely proportional to the width of the ring. This means that long lines represent very narrow annual rings and short lines represent wider rings. The absence of a line means there is no noticeable narrowing in an annual tree ring.

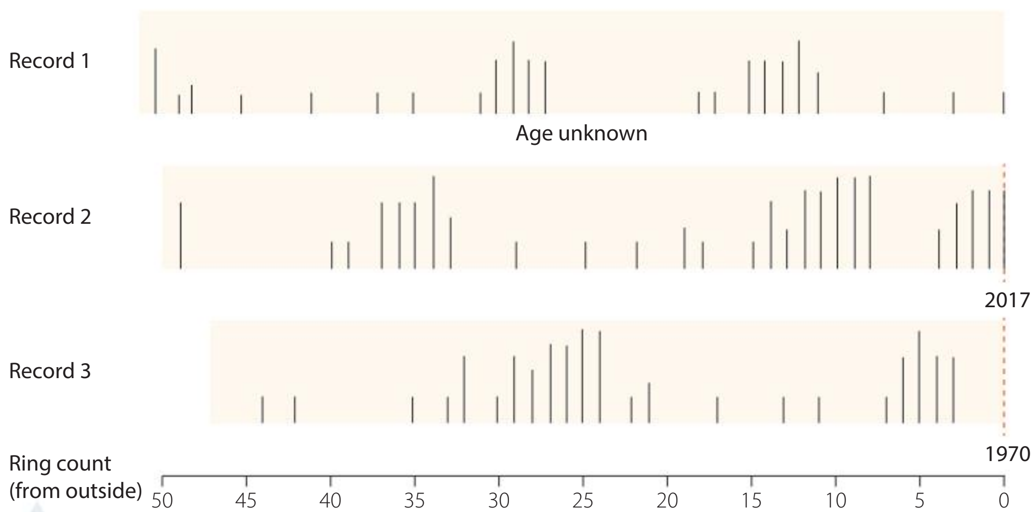

FIGURE 9.22 Skeleton plots from three trees of the same species

AIM

To compile a history of dry or wet conditions by using dendrochronology data and to compare the picture generated with other climate data to access its accuracy and utility

METHOD

1. Examine the three skeleton plots. Determine how many years are represented by each graph using the ring count scale at the bottom of the diagram.
2. Cut out the three skeleton plots from a copy of Worksheet 9.3. Line up the three plots so that similar patterns of lines lie under each other. Record 2 is the youngest. It was sampled from a living tree in 2017.
3. Copy the skeleton plots you have assembled onto graph paper to make a master record of the information from all three plots.
4. Working backwards from 2017, mark the decades on your master plot (2017, 1997, 1987 etc.). The years for some plots may not match.
5. On your master plot, identify periods of dryness. Assume that a drought is represented by three or more consecutive lines on your master plot. Work out the years over which the droughts or dry periods occurred and mark the drought periods on the master plot.
6. Use the weblink *Interactive: 100 years of drought in Australia* to identify years of drought in the southern area of central New South Wales. Mark the periods of below average rainfall on your master plot so you can compare the rainfall patterns.

Interactive: 100 years of drought in Australia

Identify years of drought in the southern area of central New South Wales.

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ANALYSIS OF RESULTS AND DISCUSSION

1. What period of time do the overlapping skeleton plots cover?
2. Why does the use of data from plants of the same species in a similar area make the information more reliable?
3. Why do narrow annual rings reflect dry periods?
4. The rings of Record 1 show less narrowing on average than the other records. What are possible reasons for this?
5. How well do the periods of dryness you identified in the tree ring data match the rainfall patterns you identified?
6. Would you expect similar data from trees of the same type in another area to produce exactly the same pattern? What would it mean if data from different areas produces similar patterns?
7. Not all species of woody plants produce a growth ring each year. Sometimes stressed plants produce more than one ring in a year. How does using data from a large number of trees help to overcome this problem?
8. Explain how similar data could be used to identify the years of El Niño and La Niña climate patterns in Australia before European colonisation and official records were kept.
9. How could measuring $\delta^{18}O$ values and carbon-14 dating of rings provide more reliability to the data gathered from tree rings?

CONCLUSION

Summarise the accuracy and value of dendrochronology as a method of studying past climate in Australia.

Stalagmites, stalactites and corals

Cave structures and corals, like trees, produce annual growth rings that can be dated. Variations in growth rates give rise to layers that reflect annual growth. In caves, water saturated with dissolved CO_2 precipitates calcium carbonate as it drips from a cave roof onto the floor, creating structures called **speleothems** (Figure 9.23). Speleotherms include stalactites (columns that grow downwards from the cave roof), stalagmites (columns that grow upwards from the cave floor) and a range of other structural forms.

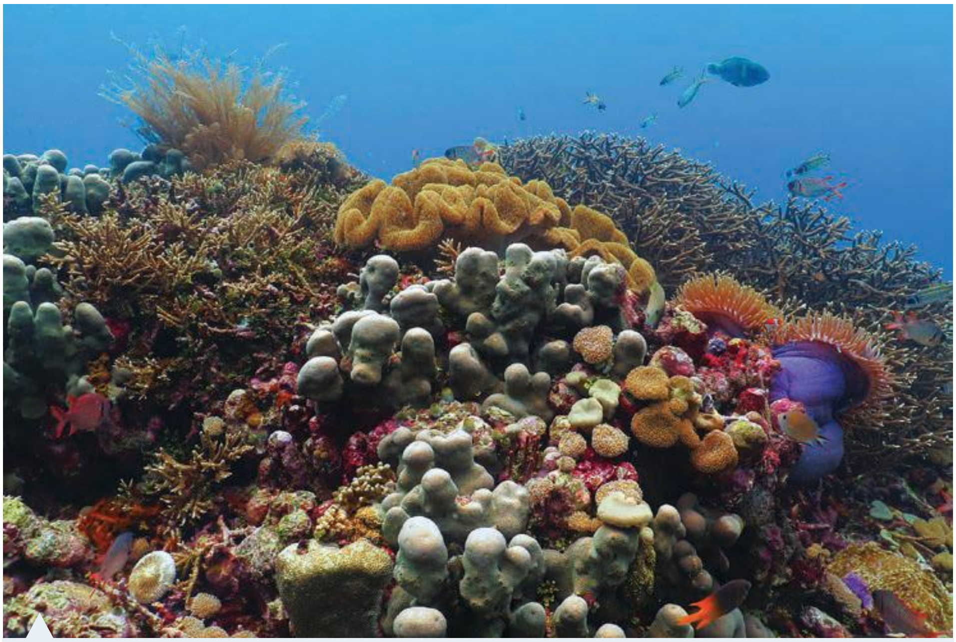
Dreamstime.com/Giovanni Gagliardi

FIGURE 9.23 Speleotherms, like these in the Jenolan Caves near Sydney, provide climate proxies.

Speleothems provide climate proxies detailing changes in precipitation and temperature from quite recently back to almost half a million years ago. Oxygen and carbon isotopes from caves provide information about temperature in similar ways to forams and ice cores. Carbon isotopes can be analysed to infer growth in plants above the caves. Scientists use uranium–thorium dating techniques to accurately determine the age of layers in a speleotherm. Together with the annual growth rings, this produces very detailed information about temperature and precipitation.

Corals provide information about the climate of the shallow oceans in which they live. Some coral ridges on the surface reflect daily additions of new skeletal material. The layers are very thin with about 200 ridges per centimetre. Coral growth ridges are a key piece of evidence for the slowing rotation of Earth. Today, corals generate about 360 rings per year, but in the Devonian, corals grew 400 ridges per year. By collecting coral skeletons of different ages and matching the ridge patterns, a long history of climate variation can be determined. Oxygen isotopes are also analysed from the layers of the coral to determine temperature.

Coral climate proxy data has provided useful information about climate change over tens of thousands of years. The corals you can see today in the Great Barrier Reef (Figure 9.24) grow on top of the remains of older reef platforms. The living corals and the buried remains represent 8000 years of uninterrupted coral growth and recorded climate information. The Great Barrier Reef began to form about 18 million years ago but glacial and interglacial cycles caused sea levels to rise and fall. This interrupted the growth of corals at different times in the reef's history. In 2014, scientists working as part of the Integrated Ocean Drilling Program ran Expedition 325, which recovered corals in drill cores from the reef. The corals spanned a range of 12 000–20 000 years. Information from the older corals showed that the ocean had been more than 4°C cooler than at present. This information supported conclusions obtained from Lynch's Crater peat sediment in the Atherton Tablelands in northern Queensland about dry cold conditions on the Australian continent. As the glacial period ended, the temperature of the ocean increased, reaching current temperatures about 12 000 years ago.



Shutterstock.com/blue-sea.cz

FIGURE 9.24 Corals of the Great Barrier Reef can provide information about past climates.

Aboriginal art sites

NASA Climate Close-up; Coral Reefs
Read more about how corals record climate and identify other proxies from corals to describe past climates.

Aboriginal and Torres Strait Islander histories and cultures

Indigenous people have lived in Australia for a very long time and they have recorded changes in Australia's climate. Evidence in a rock shelter on the western edge of Arnhem Land places people in Australia 65 000 years ago. Many Indigenous rock art sites depict ordinary life, including humans and animals, and abstract symbols (Figure 9.25). The art is sometimes engraved into stone but many images are painted in ochre or charcoal. The age of the art is not always easy to determine. Modern techniques measure the age of thin films of dirt that form over the artwork. By determining the age of the material, scientists set an upper date on the age of the painting. Dating of artwork has shown some artwork in Queensland to be between 13 000 and 15 000 years old. In the Northern Territory,

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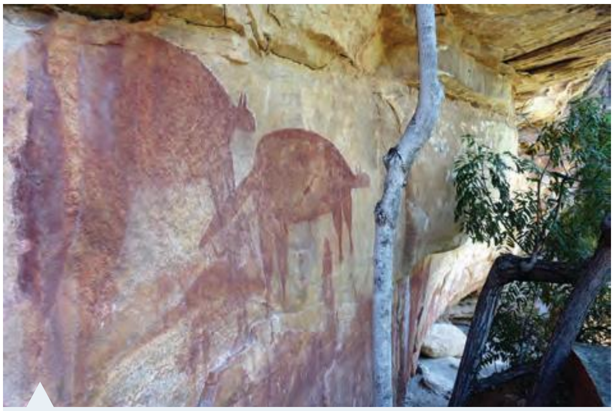
some sites have been dated as being up to 28 000 years old.

The animals depicted in Aboriginal art provide evidence about the climate when the paintings were made. For example, in the Wollemi National Park, New South Wales, a wide range of animals are shown in charcoal rock art. Dingos, possums, gliders, wallabies, kangaroos, quolls and wombats are all represented. By dating the images, it is possible to build up a picture of the ecology of the area at different times, before and after European settlement. The art helps to understand the climate that existed when the art was made. Changing fauna over time may help to identify changing climate conditions.



Alamy Stock Photo/Suzanne Long

FIGURE 9.25 Aboriginal rock art from the Northern Territory

Is this the world's oldest rock art?

Watch the video from the ABC and summarise how the artwork is being dated.

In the Northern Territory, there are rock drawings of megafauna and other animals that are no longer found in the area. Megafauna are large animals of 40 kg or more. *Genyornis*, a giant bird, the marsupial tapir *Palorchestes* and the marsupial lion *Thylacoleo* are examples of extinct megafauna depicted at sites in the Northern Territory. It is believed that a changing climate and possibly human activity led to the disappearance of these animals.

Instrumental and historical records

Instrumental records made with scientific instruments such as thermometers, barometers and rain gauges provide important data about climate but they only provide information over large areas for the last few hundred years. Although thermometers were invented in the mid-1600s, it was not until the early 18th century that reliable instruments and appropriate temperature scales were developed.

Shutterstock.com/Envirosense

FIGURE 9.26 This derelict Stevenson screen is near Scott's Hut in Antarctica. A Stevenson screen is a protective shelter for meteorological instruments, while allowing air to freely circulate around them.

In Australia, weather stations and telegraph networks to transmit the weather data existed across the continent by the end of the 19th century. The national Bureau of Meteorology was established in 1908. Nationwide standardised measurements began in 1900 for rainfall and 1910 for temperature. Protective structures such as the Stevenson screen increased the reliability of the data collected (Figure 9.26). Weather balloons have been used to gather temperatures in the high atmosphere since 1963 and satellite measurements date from the 1980s.

The first non-Aboriginal weather recorder was Lieutenant William Dawes, after whom the point near the southern pylon of the Sydney Harbour Bridge is named. Dawes brought with him on the First Fleet a barometer and thermometer and he used them to record pressures and temperatures for 4 years. Dawes' data showed the seasonal extremes we take for granted in Australia and that many early European colonists noted. There are many historical written comments about weather events since European colonisation, but as a scientific database, these descriptions may show a bias by focusing on extreme events such as hot days, storms and floods. However, this information adds another set of data to the many other sources of climate information you have explored in this chapter.

South Eastern Australia Recent Climate History (SEARCH) site

Explore this project that gathered palaeoclimate, historical and early instrumental climate records to describe the last 200 years of Australian climate.

INVESTIGATION 9.4

Information and communication technology capability

Literacy

Climate Data Online

A comparison of weather records

AIM

To use data from the Bureau of Meteorology (BOM) to compare weather data from where you live and a place some distance from you

METHOD

Part A

1. Copy the table in the Results section.
2. Access the BOM data from the weblink *Climate Data Online*.
3. Use the 'Select using Text' tab and select 'Temperature', 'Daily observations' and 'Maximum temperature'.
4. Type in the name of the town where you live and select 'Find'.
5. A set of nearby stations will appear. Click on one and a graph of available data will appear. Record the station code, name and earliest recording date in Part A of your data table.
6. Leave the year and click on 'Get Data'.
7. A new page of data will open. Look at the table of data for the year. What do the blanks mean?
8. Use the 'Summary statistics for all years' table to record the highest monthly mean temperature, the lowest monthly mean temperature, the highest daily temperature and lowest daily temperature for January and July into your table.
9. Use a map to identify a town that is at least 400 km away from you. Repeat steps 3–8 for this new location.

Part B

10. Go back to the starting page and change the type of data to rainfall. Generate the data for the two towns and fill in Part B of the data table.

If you wish to see all years' data, click on 'View all monthly data' at the bottom of the Daily rainfall table.

RESULTS

Copy and complete this table.

PART A: TEMPERATURE DATA								
TOWN	STATION NUMBER	STATION NAME	MONTH	EARLIEST DATE	HIGHEST MONTHLY MEAN	LOWEST MONTHLY MEAN	HIGHEST DAILY	LOWEST DAILY
1			January					
			July					
2			January					
			July					
PART B: RAINFALL DATA								
TOWN	STATION NUMBER	STATION NAME	MONTH	EARLIEST DATE	WETTEST MONTHLY MEAN	DRIEST MONTHLY MEAN	WETTEST MONTHLY MEDIAN	DRIEST MONTHLY MEDIAN
1			January					
			July					
2			January					
			July					

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ANALYSIS

1. For each location, identify the hottest and coldest times of the year.
2. Are daily extremes (hottest or coldest) similar to the averages?
3. Compare when data collection began and the consistency of data collection for the two locations.
4. For each location, identify the times of year when it is driest and wettest.
5. How do the two locations compare in terms of climate?
6. Can you suggest reasons for differences in temperature and rainfall based on where the two stations are situated?

DISCUSSION AND CONCLUSIONS

1. Were there differences in the completeness of data for the locations you examined? Why do you think this was the case?
2. Were there clear differences between rainfall and temperature for the two locations you examined?
3. Suggest reasons for the differences you identified.
4. Do you think the amount of data available for where you live would allow accurate short-term weather prediction?
5. Describe how you might compare your current climate with the climate 50 years ago to identify any long-term changes.
6. How does the length of data collected for your location affect the confidence of long-term trend analysis?
7. Why is the use of climate proxies an important complement to instrumental records?

KEY CONCEPTS

- Ice cores provide evidence of both temperature change and CO_2 levels over the past thousands of years.
- Dendrochronology is the study of growth rings in trees and provides evidence of seasonal changes and water availability.
- Layers of sediment from lakes and growth rings in cave structures such as stalactites and stalagmites provide year to year evidence of changing climate.
- Aboriginal art records changing environments over a time range of tens of thousands of years.
- Instrumental records provide reliable records of recent climate change globally since the 1840s and in Australia since 1900.
- Historical documents are an additional source of evidence for climate change since European settlement in 1788.
- Direct measurements of ocean temperatures and shrinking ice sheets provide recent evidence of climate change.

CHECK YOUR UNDERSTANDING 9.3

1. What is the temperature proxy extracted from an ice core?
2. Why is temperature and CO_2 data from ice cores valuable evidence for climate change?
3. Three types of climate evidence obtained from ice cores are thickness, past air temperatures and melt layers. How are these types of evidence measured, and what do they tell us about climate?
4. Describe the variations in tree rings that reflect changes in climate.
5. Compare the origins of layers of sediment in lakes and cave precipitation growth rings. How do these structures act as climate proxies?
6. Describe the evidence of past climates contained in Aboriginal rock art.
7. How can the diaries of early European settlers in Australia be used to estimate changing climate conditions?

9 CHAPTER SUMMARY

- Evidence of climate change exists in many forms.
- A climate proxy is a preserved part of Earth that can be used to infer some aspect of past climate.
- An important climate proxy for temperature is variations in the proportion of oxygen-18 to oxygen-16 isotopes in fossils and sediments.
- Evidence of ancient climate change can exist at the scale of annual change and change over long periods of time.
- Evidence of older periods generally has lower resolution than evidence from more recent periods.
- Variations in a range of isotopes provide strong evidence of climate change.
- Fossils provide evidence of climate change in terms of their chemical composition, the nature of species present and changes in species over time.
- Changes in sea level reflect global climate and evidence of such change exists in changing sediment composition in rocks.
- Deep ocean sediments are important sources of evidence for ancient climate because of the presence of a range of climate proxies and a long record of change.
- Ice cores provide evidence of both temperature change and CO_2 levels over the past thousands of years.
- Dendrochronology is the study of growth rings in trees and provides evidence of seasonal changes and water availability.
- Layers of sediment from lakes and growth rings in cave structures such as stalactites and stalagmites provide year to year evidence of changing climate.
- Aboriginal art records changing environments over a time range of tens of thousands of years.
- Instrumental records provide reliable records of recent climate change globally since the 1840s and in Australia since 1900.
- Historical documents are an additional source of evidence for climate change since European settlement in 1788.
- Direct measurements of ocean temperatures and shrinking ice sheets provide recent evidence of climate change.

9 CHAPTER REVIEW QUESTIONS

Qz Review quiz

1 Define 'climate proxy'.

2 Explain why tree rings are a climate proxy.

3 Compare the information obtained from ice cores and deep-sea sediments.

4 Explain the relationship between an increasing δ^{18}O and temperature change.

5 Assess the importance of δ^{18}O data in our understanding of past global climate.

6 Assess the role of corals and foraminifera in estimating past global climates.

7 Explain how thicknesses of ice cores can be used to infer changes in climate.

8 Summarise the types of evidence that can be derived from deep ocean sediment cores.

9 In Tasmania, some Huon pine trees may be at least 3000 years old. Assess their potential for providing evidence of past Tasmanian and global climate.

10 Outline how a drying environment influences the precipitation of carbonates in a cave system.

11 Assess the use of cave deposits in measuring past global temperatures.

12 Explain the concepts of span and resolution using examples of climate proxy evidence.

13 Compare the evidence of climate change that is provided by Aboriginal art and early European settler documents.

14 Table 9.4 shows some δ^{18}O data from a cave speleotherm.

TABLE 9.4 δ^{18}O data from a cave speleotherm

AGE (THOUSANDS OF YEARS AGO)	δ^{18}O VALUE
4.0	–5.4
4.5	–5.6
5.0	–5.5
5.5	–5.0
6.0	–5.6
6.5	–6.0
7.0	–6.5

a Graph the data in an appropriate form.

b Describe the trend shown in the data.

c Assess the evidence as reflecting increased temperature.

d What additional information would support the hypothesis of increasing temperature?

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15 Outline the types of evidence you might use to study past climate change in the area where you live during the:

- **a** last 200 years
- **b** last 2000 years
- **c** Cenozoic (last 65 million years).

16 Discuss the role of climate proxies in understanding climate change over the last 400 000 years.

17 Recent changes in global climate attributed to human action span less than 500 years.

- **a** Why is evidence from ocean sediment cores unlikely to provide climate data with the resolution needed to compare past climates with current changes?
- **b** Why are ice cores a better proxy for studying climate changes on the scale of thousands of years?

18 Evaluate the use of multiple sources of past climate data in understanding past global climate change.

10 Human activities and climate change

OUTCOMES

In this chapter you will learn about:

- anthropogenic greenhouse effects CCT ICT
- how human activities have caused environment change CCT EU ICT N
- flow-on effects of changes to climate in the atmosphere, cryosphere and biosphere. S AAEA CCT EU ICT L

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Humans rely heavily on fossil fuel resources for energy and the many products of the petrochemical industry. A petrochemical plant can generate fuels or produce materials for making plastics, drugs and other products that society uses every day (Figure 10.1). Fossil fuels have provided many benefits for society, but their use has also contributed to a range of environmental problems. One of those environmental problems is the changing climate.

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FIGURE 10.1 Industrial plants like this petrochemical plant produce many raw materials that are important to society.

In this chapter, you will examine how human activities influence changes in climate. In previous chapters, you examined the processes and factors that have changed Earth's climate over long periods. Scientists have recognised that Earth's atmospheric temperature and CO_2 levels have climbed rapidly over the last few centuries. In this chapter, you will assess the evidence for climate change over the last 200 years, how human activity has contributed to climate change and the effects of those changes on Earth systems.

10.1 Natural and anthropogenic greenhouse effects

Natural greenhouse effect: the warming Earth

WS Increasing greenhouse gases and temperatures

Scientists have been building a picture of how Earth's temperature has changed since the discovery of ice ages in the first half of the 19th century. John Tyndall and Svante Arrhenius first described the natural greenhouse effect in the second part of the 19th century and used their understanding to try to explain the end of the last ice age. The growing understanding of ice ages stimulated scientists such as Alfred Wegener and Milutin Milanković in their research to understand climates of the past.

Today, scientists have reached a consensus about the way temperature has changed over the last several thousand years. In the last 50 years, scientists have developed reconstructions of past climate for the whole Earth using the climate proxies described in Chapter 9. The scientists have tested their understanding with sophisticated computer models. Most of the early reconstructions used land-based data from the northern hemisphere, particularly tree ring data. In the last 20 years, the variety of proxies, the use of marine data, and the sophistication of methods and technologies for working with multiple sources of data has improved dramatically.

Examples of some land-based proxy data

A wide range of land-based proxy data tell a consistent story of Earth's climate warming. Data from ice cores, speleothems, pollen, sediment cores, coral and glacial ice all describe a global change. Before the late 19th century, all Earth's continents, with the exception of Africa, showed a steady cooling trend of 0.1–0.3°C per 1000 years. Africa is an exception because there is very little proxy evidence available to build a reliable picture of the continent's past climate history.

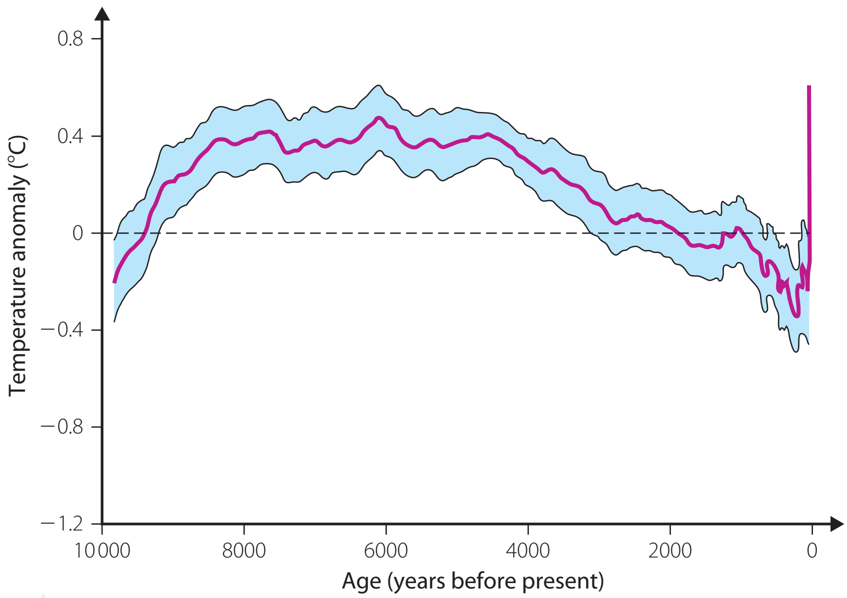

FIGURE 10.2 Global temperature change during the last 10 000 years compared with the global average from 1961 to 1990

Scientists studying Earth's climate using ocean sediment cores have reached the same conclusion. The evidence shows that Earth's temperature is increasing today at a rate that has not occurred during the last 1000 years. Figure 10.2 plots temperature anomaly against time. The **temperature anomaly** is the difference between the temperature at a particular time and an average temperature (or baseline). In Figure 10.2, the average temperature used is that from 1961 to 1990. A positive anomaly means the temperature was higher than the average temperature; a negative anomaly means the temperature was lower than the average. The graph shows a rising temperature until approximately 9000 years ago followed by a fairly constant temperature for several thousand years before a steady decline until 200 years ago. Since then, Earth's temperature has rapidly risen. Since 1880, when the coverage of weather stations provided reliable data, the average global temperature, including land and ocean surface temperatures, has risen by 0.8°C. Two-thirds of that change has occurred since the middle of the 1970s.

You will explore the nature of temperature anomalies in Investigation 10.1.

In the past 150 years, both global land surface and marine air temperatures have increased significantly. Figure 10.3 shows how global temperature has changed over land and the ocean since 1850, according to global instrument records. The graphs show a similar trend with a change of approximately 1°C over land and a smaller change of 0.6°C over the ocean. The difference between land and ocean surface temperatures is mainly due to the thermal capacity of water. The ocean absorbs similar amounts of solar radiation to land but changes temperature more slowly. Both graphs show a fairly constant average temperature until approximately 1900 and then a steady increase, a dip between 1940 and 1970, and then a constant increase to the present.

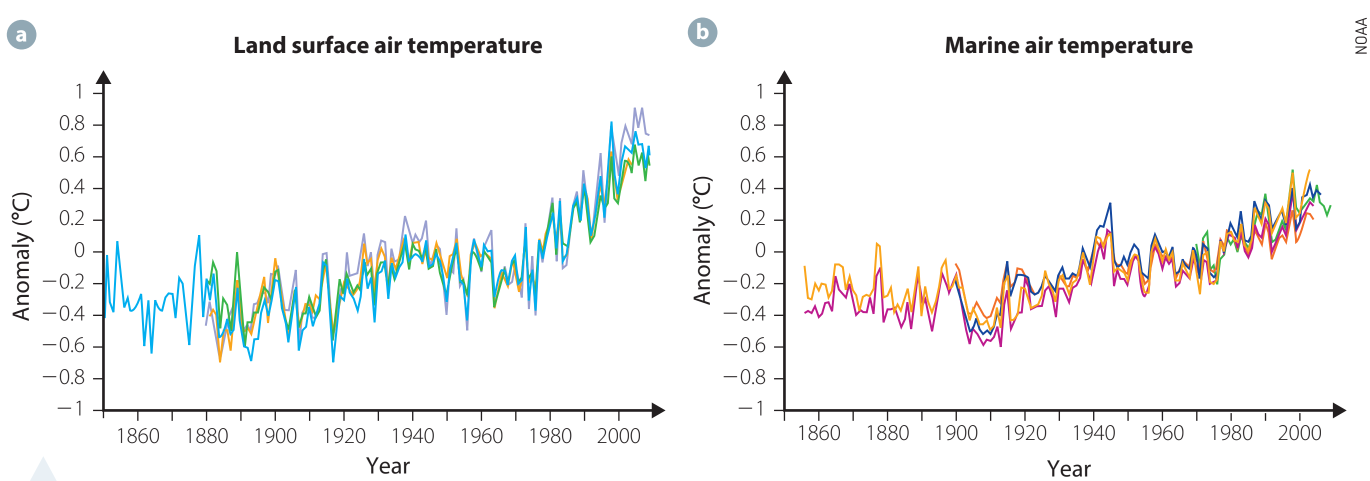

FIGURE 10.3 Global temperature change since 1850 for **a** land surface air temperature and **b** marine air temperature. The different coloured lines represent different climate models.

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Changes in greenhouse gas levels

CO_2 levels have shown a similar increase to temperature. Since 1958, the Mauna Loa Observatory on Hawaii has made continuous measurements of CO_2 levels in the atmosphere. A graph of the data is shown in Figure 10.4. The curve is known as the **Keeling curve** after Charles Keeling who started the monitoring program and supervised it until his death in 2005. The curve shows a steady rise in CO_2 levels. In 1958 when the program began, the concentration of CO_2 was 313 parts per million (ppm). In mid-May 2019, the concentration was 415 ppm. The cyclic nature of the curve is due to seasonal variations in CO_2 levels. In the northern hemisphere, CO_2 levels fall in summer because of plant growth and rise as winter approaches. The seasonal variation is approximately 5 ppm.

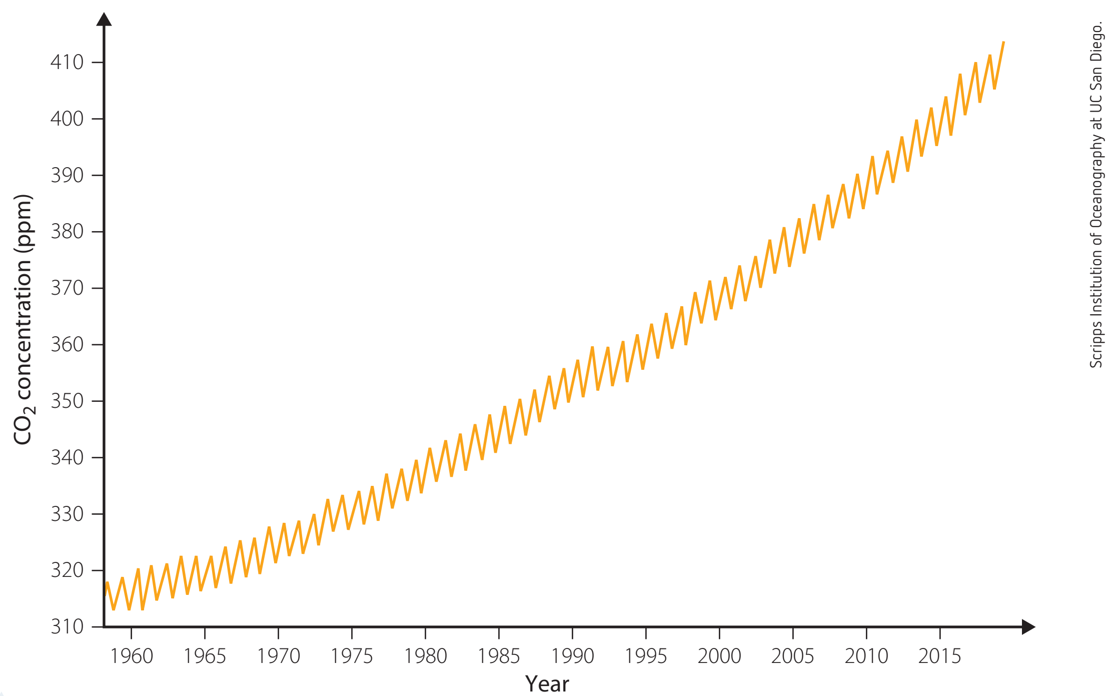

FIGURE 10.4 This Keeling curve shows changes in atmospheric CO_2 levels from 1958 to May 2019 (415 ppm) at Mauna Loa Observatory, Hawaii.

Since the 1970s, the US National Oceanic and Atmospheric Administration (NOAA) has monitored CO_2 levels using a worldwide network. Today, about 100 stations make up the Global Greenhouse Gas Reference Network. The data shows a similar continuous rise to that of the Mauna Loa Observatory. When direct measurements such as the Keeling curve data are combined with ice core measurements, it shows that CO_2 levels are rising much faster today than in the past (Figure 10.5).

Ice cores, direct measurements and data from speleothems all show similar patterns for other greenhouse gases.

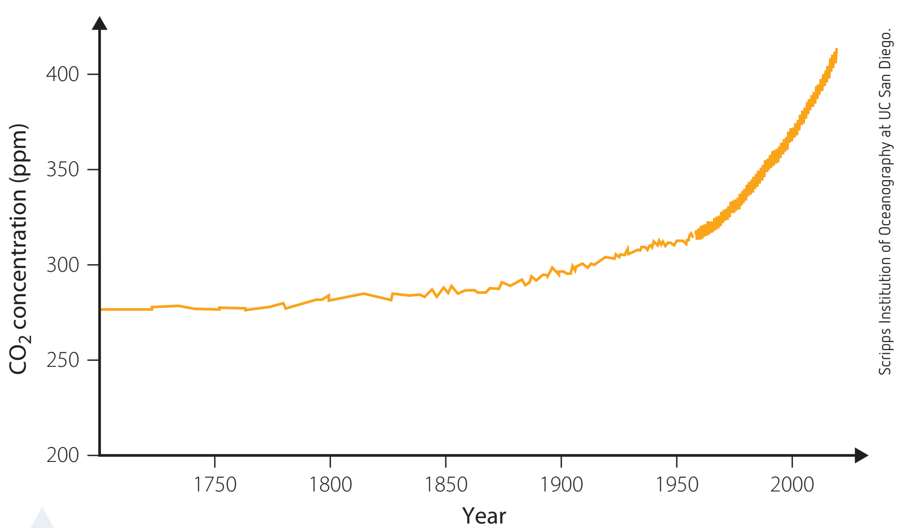

FIGURE 10.5 This Keeling curve shows changes in atmospheric CO_2 levels from 1700 to May 2019 (415 ppm) at Mauna Loa Observatory (from 1968) and from ice core data (before 1968).

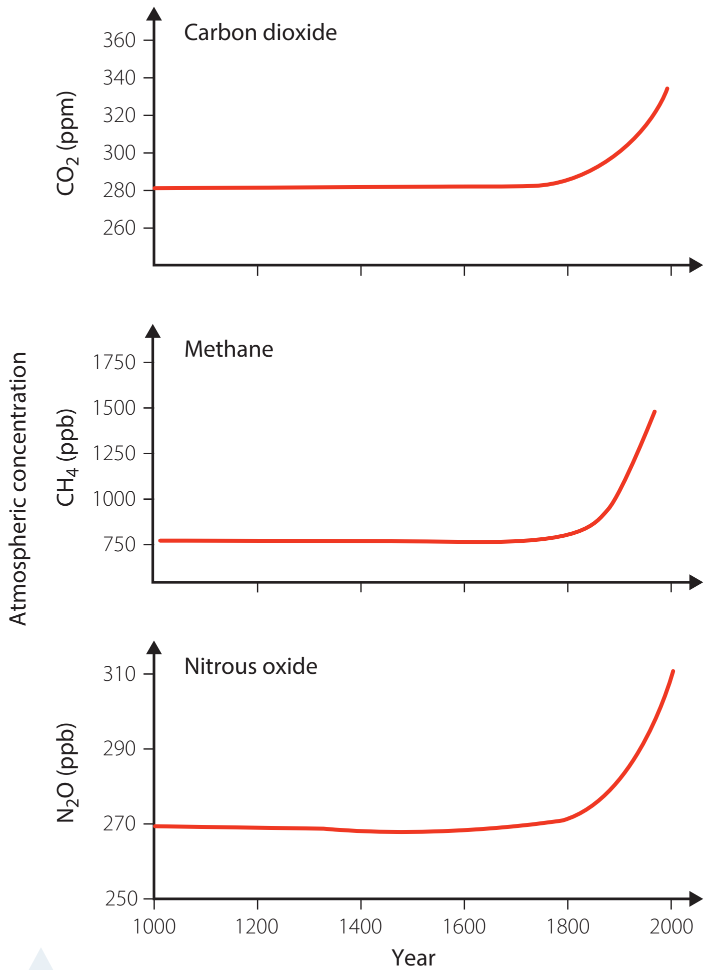

FIGURE 10.6 Global atmospheric concentrations of three greenhouse gases (CO_2, CH_4 and N_2O) over the last thousand years (ppm = parts per million, ppb = parts per billion)

University of Michigan

Figure 10.6 shows changes in the concentrations of CO_2, methane (CH_4) and nitrous oxide (N_2O). Note the similarity in the trends of all three gases. Levels for all three were fairly constant until the early 19th century when they began to rise. Today, the levels are significantly higher than at any time in the preceding 800 years.

Anthropogenic greenhouse gases and global warming

Scientists have good reasons to think that the changes in global temperature and CO_2 level in the last 200 years are due to human activities. In 2019, scientists published news of a computer model that had accurately modelled the main features of climate variability over the last 3 million years. The model linked ocean and atmosphere through a global carbon cycle with ice sheets in the northern hemisphere. Change was driven by changes in Earth's orbital behaviour, and CO_2 variations occurred as a result of volcano outgassing and the weathering of rocks on the continents. The model accurately described the occurrence and timing of ice ages and interglacials, but it could not model the rapid changes in temperature during the last 200 years. The model did not take into account the effects of the Industrial Revolution of the late 18th and early 19th centuries.

The Industrial Revolution resulted in the widespread use of fossil fuels and the emission of large amounts of CO_2 into the atmosphere. The Industrial Revolution started in the United Kingdom and involved rapid changes in manufacturing systems as coal began to be widely used to supply energy for transport and manufacturing. Since the start of the Industrial Revolution, the burning of fossil fuels has increased to 1300 times the rate that occurred in 1800. In the early 20th century, the types of fossil fuels used diversified with the development of oil and natural gas (Figure 10.7). Today, coal accounts for less than 30% of global fossil fuel consumption, with crude oil being the largest energy source. Human emissions are currently approximately 26 gigatonnes (Gt) of carbon per year. In 2015, Australia's share of CO_2 emissions was 380.93 million tonnes of carbon. This represents 15.83 tonnes for each Australian in that year. In terms of our fossil fuel exports, we export the equivalent of 44 tonnes of CO_2 emissions per person.

One tonne of carbon emissions equals 3.7 tonnes of CO_2 emissions because the mass of CO_2 also includes the mass of the oxygen in the molecule.

Anthropogenic greenhouse gases are the gases generated by human activity that capture and reradiate infrared radiation. Greenhouse gases include CO_2, CH_4, N_2O and a range of synthetic chemicals. CO_2, CH_4 and N_2O also have origins in the natural world. Table 10.1 shows that different greenhouse gases have different warming potentials and stay in the atmosphere for different lengths of time. The time that a material stays in a location is referred to as its residence time. While CH_4 has a greater ability to absorb energy than CO_2, it has a shorter residence time in the atmosphere and its concentration is much lower. Synthetic gases are potential problems for global warming because they have high energy-absorbing potential and long residence times in the atmosphere.

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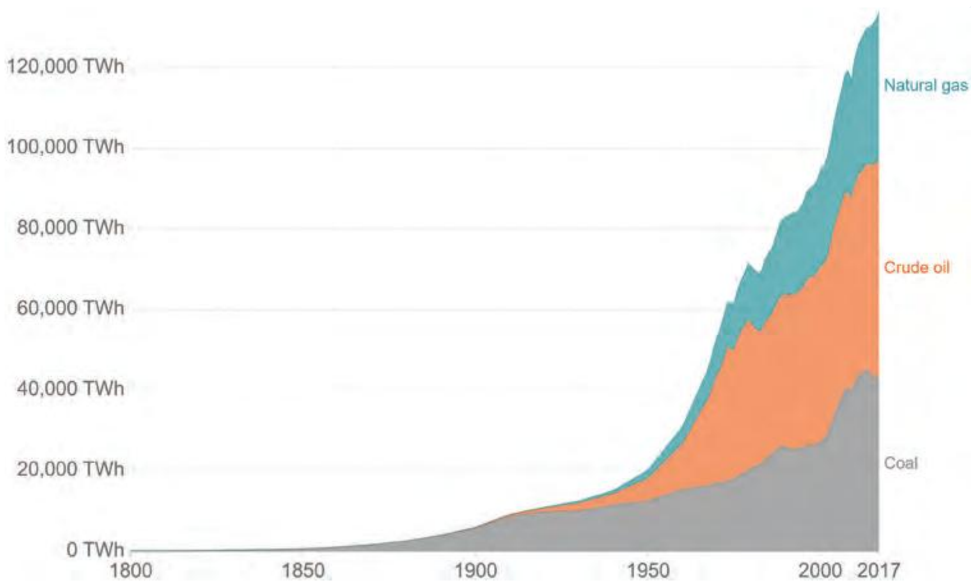

FIGURE 10.7 Global fossil fuel consumption since 1800. One terawatt-hour (TWh) is equivalent to 150 million tonnes of carbon

TABLE 10.1 Major anthropogenic greenhouse gases and their characteristics

GREENHOUSE GAS	FORMULA	MAJOR ANTHROPOGENIC SOURCES	GLOBAL WARMING POTENTIAL (BASED ON ENERGY ABSORPTION OVER 100 YEARS)	AVERAGE TIME IN THE ATMOSPHERE (YEARS)	PRE-INDUSTRIAL REVOLUTION CONCENTRATION (ppb)	2016 CONCENTRATION (ppb)	INCREASED RADIATIVE FORCING (W/m^2)
Carbon dioxide	CO_2	Fossil fuel combustion Cement manufacture Deforestation	1	100	278 000	403 000	1.82
Methane	CH_4	Fossil fuel production Agriculture Waste disposal	25	12	272	1842	0.48
Nitrous oxide	N_2O	Fossil fuel and biomass combustion Fertiliser application Industrial processes	298	114	271	329	0.17
Chloroflurocarbon-12 (CFC-12)	CCl_2F_2	Refrigerants	10 200	100	0	0.516	0.17
Hydroflurocarbon-23 (HFC-23)	CHF_3	Refrigerants	12 400	270	0	0.024	0.0045
Sulfur hexafluoride	SF_6	Electricity transmission	22 800	3200	0	0.0086	0.0041
Nitrogen trifluoride	NF_3	Semiconductor manufacture	17 200	740	0	0.00086	0.0002

The influence of the natural greenhouse effect on the temperature of the atmosphere changes over time. In Chapter 8 you learnt how the natural greenhouse effect leads to a balance between the energy Earth receives from the Sun and the heat energy radiated back into space. Some changes alter this balance, or **equilibrium**. For example, increased ice cover reflects more light so there is less heating of land and the atmosphere. The difference between the incoming and outgoing energy is referred to as **climate forcing** or radiative forcing. It is measured in watts per square metre ($W\,m^{-2}$).

Factors that change Earth's climate system are referred to as climate forcings. Figure 10.8 shows a range of climate forcings. Climate forcing is divided into anthropogenic forcings and natural forcings. Anthropogenic climate forcings are of human origin; natural climate forcings originate in natural Earth processes. Note that some of the anthropogenic forcings also have a natural origin. A positive value means that the energy received from the Sun is greater than the energy leaving the troposphere, and therefore the climate forcing creates a warming effect. A negative value means that the balance between solar input and heat loss favours cooling.

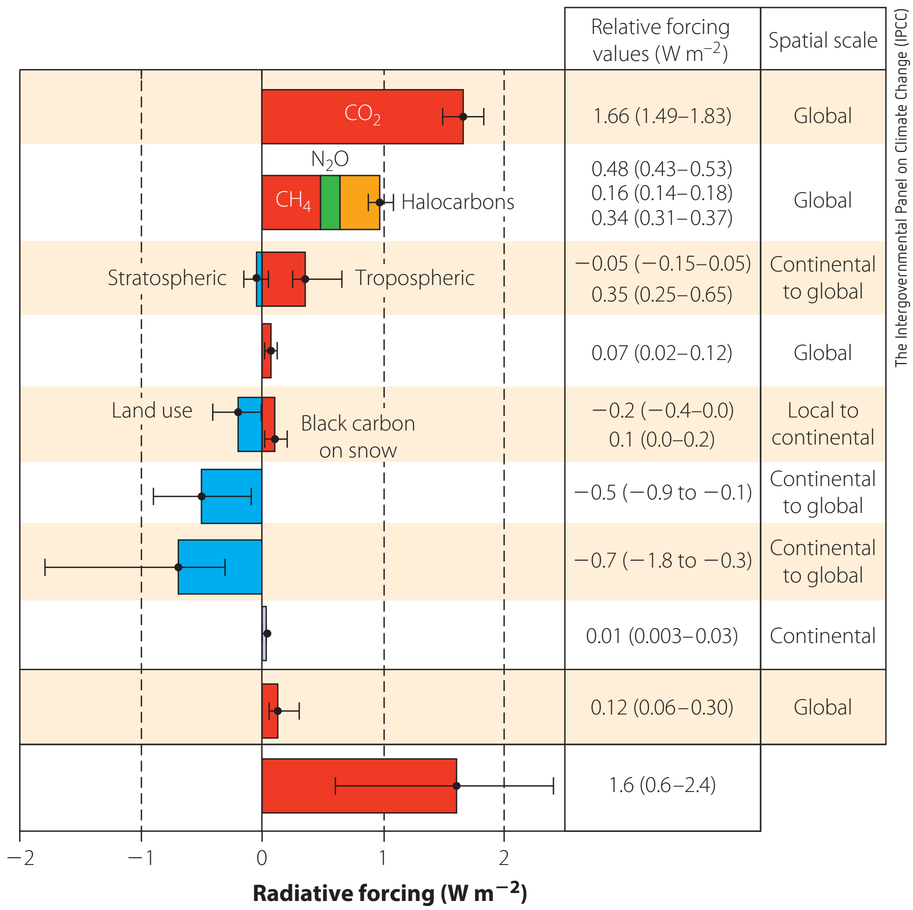

FIGURE 10.8 Natural and human-generated climate forcings. The relative forcing range in brackets is the interval for which researchers have a confidence of 95% for the values.

The role of greenhouse gases in warming the atmosphere is a critical part of the greenhouse effect. Albedo from surfaces and clouds tends to have the opposite effect, reducing the amount of energy that is absorbed as light and reradiated as infrared radiation. The error bars in Figure 10.8 indicate the degree of uncertainty scientists have in the forcing measurements. The largest uncertainty is about the role clouds and aerosols play in cooling the atmosphere. Water condenses around aerosols to form clouds but aerosols themselves can reflect visible light or heat.

By adding greenhouse gases to the atmosphere, humans have changed the equilibrium of the natural greenhouse effect. The increased capacity of the atmosphere to hold heat has added climate forcings to the system and warmed the atmosphere. Figure 10.8 shows that some anthropogenic forcings have a positive warming effect while others have a negative cooling effect. However, the sum of the forcings is a radiative forcing of 1.6 W m^{-2}.

Natural forcings over the past 50 years have been very small. Most climate scientists agree that most of the 0.8°C global temperature increase during that time is due to human activities. The global average temperature in 2017 was 14.9°C, which means that 5% of the global temperature has been added to Earth in less than a century. While 0.8°C may not seem much, you will see later in this chapter that a warming world has serious effects.

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Climate attribution is a field of science that aims to establish cause and effect relationships in the climate system. Finding a correlation between two parts of the climate system is not the same as establishing that one thing causes the other. The two parts being examined might both be caused by other factors we do not know about or understand. To establish the cause of global temperature rise, scientists use a combination of observation and models. By changing a component of a climate model and testing the result against instrument and proxy data, the effect of the component can be determined. At present, climate attribution is most successful in attributing changes over large areas because when studying relatively small areas, such as New South Wales, it is harder to separate long-term changes from natural climate variability.

There are three types of evidence that support anthropogenic greenhouse gases as the cause of our warming climate: accounting, isotopes and climate models.

Accounting

Simple accounting and an understanding of the carbon cycle allows us to determine how much carbon is absorbed by the lithosphere, hydrosphere and atmosphere because we know how much fossil fuel is burned each year. What remains must be resident in the atmosphere. Calculations of the heat absorbed by the CO_2 and its effect on temperature are consistent with what is being measured.

Isotopes

Changes in the relative amount of carbon isotopes implicate fossil fuels as the source of rising CO_2 levels. Just as oxygen isotopes are fractionated by evaporation and precipitation, carbon isotopes are fractionated by photosynthesis. Plants preferentially take up carbon-12 rather than the rarer carbon-13. As a result, fossil fuels are also rich in carbon-12 relative to carbon-13.

You can review the sources and sinks of carbon in the global carbon cycle in Chapter 8.

Figure 10.9 shows that the proportion of carbon-13 in the atmosphere is falling. The data comes from Arrival Heights, Antarctica. Regular measurements have been occurring there

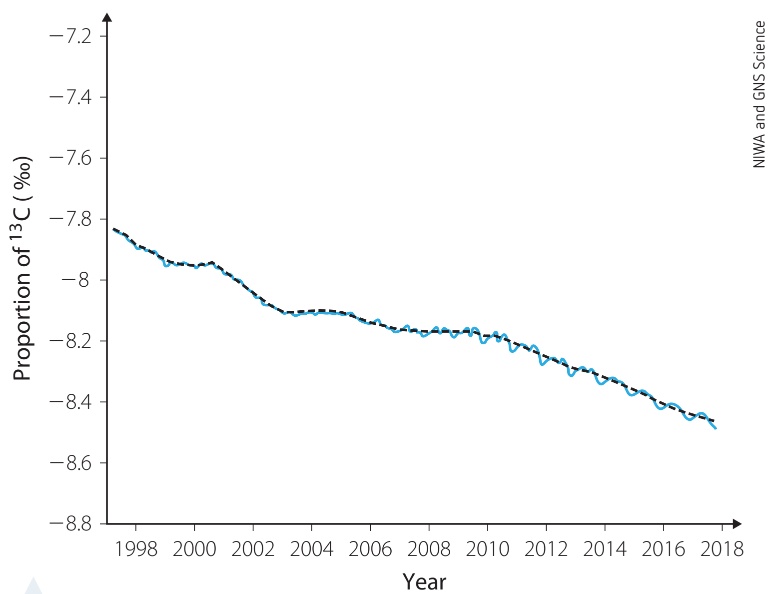

FIGURE 10.9 Change in the proportion of carbon-13 in atmospheric CO_2 over time

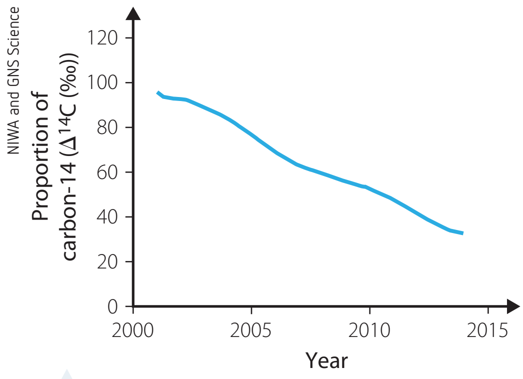

FIGURE 10.10 Change in the proportion of carbon-14 in atmospheric CO_2 over time.

since 1989. Burning fossil fuel releases carbon-12 into the atmosphere, reducing the proportion of carbon-13. In a similar way, the proportion of radioactive carbon-14 is also falling (Figure 10.10). Carbon-14 is produced in the upper atmosphere and is very rare. Carbon-14 accounts for only 1–1.5 atoms in every 10^{12} carbon atoms. Carbon-14 decays relatively quickly (half-life 5730 years) and is not present in fossil fuel carbon. As more carbon-12 enters the atmosphere from combustion, it reduces the concentration of carbon-14. Together, the declining proportions of carbon-13 and carbon-14 indicate that the rising atmospheric CO_2 levels are due to our use of fossil fuels. Carbon-14 is used in carbon dating and measurements in materials are compared to the background levels of carbon-14 in the atmosphere. Scientists think that the falling levels of carbon-14 may limit the use of radiocarbon dating by 2050.

Climate models

A third source of evidence that fossil fuels are the source of increasing CO_2 levels comes from the climate models scientists have developed. Scientists have identified 50 essential variables, which has resulted in modern global climate models being quite complex. Some of the process variables and scales over which they act are shown in Figure 10.11. Modern models generate reasonably accurate long-term descriptions of the climate. Figure 10.12 shows the predictions for two sets of models composed by the Intergovernmental Panel on Climate Change. The sets of models are called Climate Model Intercomparison Projects (CMIP). CMIP4 was released in 2010 and CMIP5, a more advanced set, was released in 2013. Figure 10.12a shows the measured temperature trend in blue and

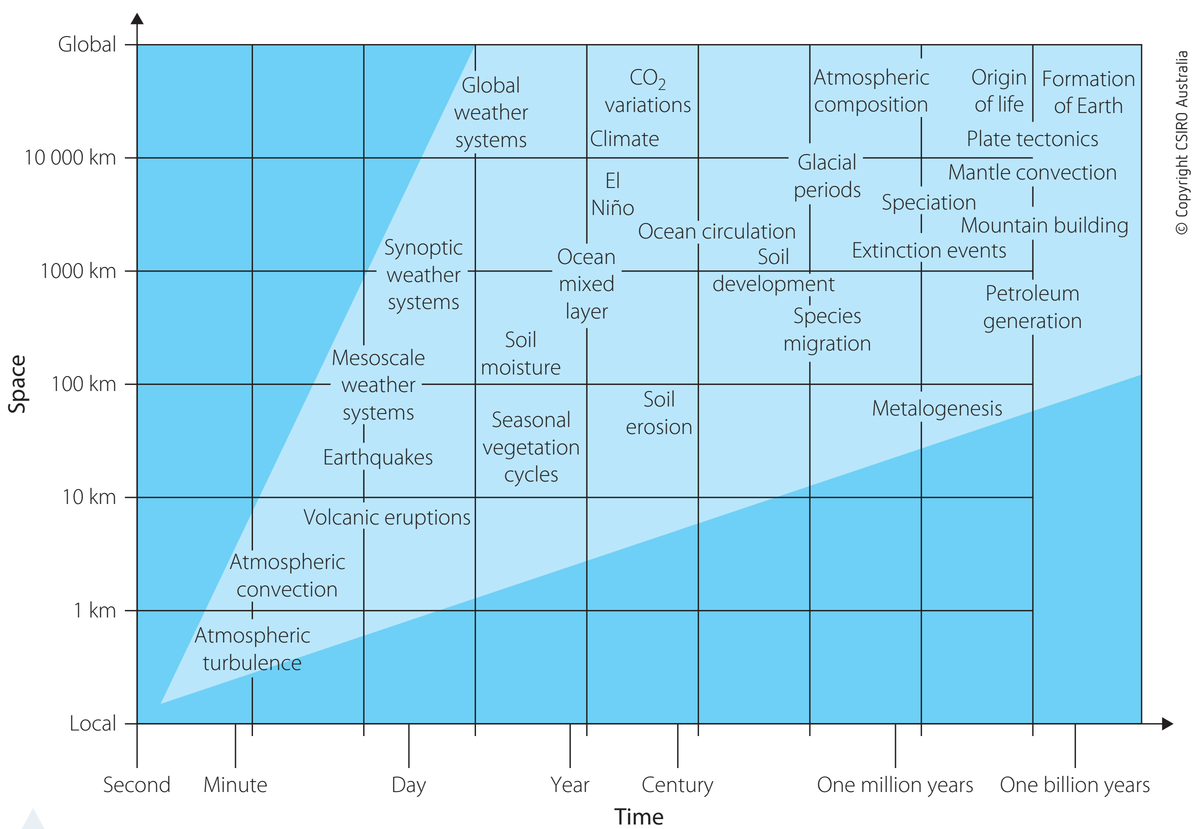

FIGURE 10.11 The timescales and distances across which Earth processes act. These processes are used in models to predict and describe climate change.

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the computer models are shown in orange and red. Note how the models, using only natural forcing parameters, underestimate the temperature change from about 1960. In Figure 10.12b the effect of accounting for human forcing is taken into account and the model results correlate closely with what has been observed.

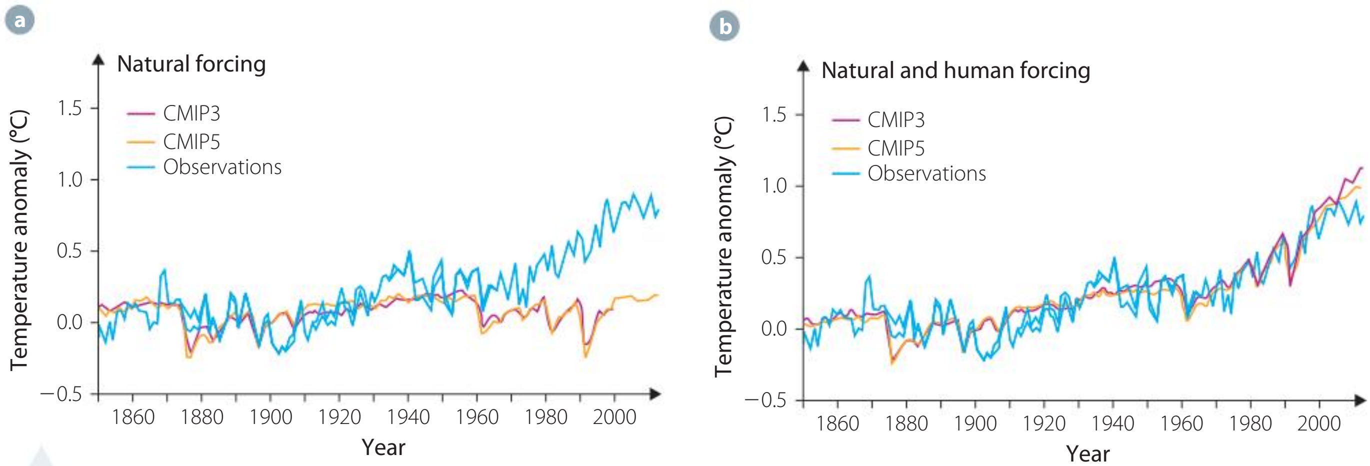

FIGURE 10.12 Model predictions for **a** natural forcing and **b** human forcing on atmospheric temperature

INVESTIGATION 10.1

Representing and interpreting climate data

When you study evidence for climate change, you will often find graphs that use an anomaly – a deviation from an average for a certain period.

In this investigation, you will look at some of the factors that affect such graphs and their interpretation. You will use temperature data for December to February in the southern hemisphere. This data is extracted from a surface temperature analysis dataset compiled by the Goddard Institute for Space Studies (GISS).

Critical and creative thinking

Numeracy

Information and communication technology capability

AIM

To prepare a temperature anomaly graph and use it to calculate rates of temperature change

METHOD

WS Investigation 10.1 spreadsheet

Part A: Initial survey of the data

1. Download Investigation 10.1 spreadsheet.
2. Open the spreadsheet. It has two tables for you to use during this investigation.
3. Using the Year and Average temperature columns in Table 1, graph temperature versus time. Label this graph 'Graph 1'.
4. Describe the trend shown in your graph. Break it up into parts that show a similar trend and record your description by either labelling the graph or writing your description in point form.

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Part B: Calculating averages

5 Calculate average temperatures for the periods 1990–2010 and 1951–1980.

In Excel you can calculate an average using =AVERAGE(cell range), where cell range is something like A2:A5 (cell A2 to, and including, cell A5).

6 Record your averages in Table 2 of the spreadsheet.

7 Calculate the range for each period (range = maximum value – minimum value). Record your data in Table 2.

Part C: Calculate anomalies

8 Calculate the anomaly for each year by subtracting the 1951–1980 average of 14.2 from each year's average temperature. In Excel the function to do this looks like = B2-14.2.

9 Graph the temperature anomaly for the years 1881–1920. Label this 'Graph 2'.

10 Graph the temperature anomaly for the years 1951–2018. Label this 'Graph 3'.

Part D: Estimating temperature increase

11 Apply a line of best fit to Graph 2 and Graph 3. To do this, right click on a data point or Control-click and choose 'Add trend line'.

12 Use the lines of best fit to calculate the rate of change of temperature over time for each graph. If you do not know how to display the equation of the line or the meaning of the line gradient, ask your teacher to explain this.

RESULTS

Keep your results and graphs in the spreadsheet you use. Don't forget to save your work.

ANALYSIS OF RESULTS

1 Are there sections of Graph 1 that show a declining trend? Over what period does this occur?

2 In Graph 1, over what period has the temperature been trending upwards?

3 Compare the trends in Graph 2 and Graph 1.

4 What advantage does Graph 2 have over Graph 1 in terms of working out temperature changes?

5 Compare the average temperatures and ranges in Table 2. Which period shows the greatest variation of values?

6 a Compare the trends and temperature variations in Graph 2 and Graph 3.

b How do the rates of temperature change differ for the 1881–1920 and 1951–1980 periods?

7 At the current rate of warming, when will the temperature have increased by 1°C relative to the average temperature in 1951?

DISCUSSION

1 Suggest reasons why the 1951–1980 period was used as the average for calculating anomaly graphs.

2 What advantage does the use of anomalies have in calculating temperature change?

3 Is there evidence that the southern hemisphere's average temperature is increasing? How much has it warmed since 1950?

4 If you analysed the data for the northern hemisphere, what similarities and differences would you expect to see?

5 This data set from GISS is based on a wide coverage of stations. Why would a small number of stations possibly produce a different trend over time compared with this set?

GISS surface temperature analysis
Learn more about this data set and how it was compiled.

CONCLUSION

What is your estimate of temperature change using the 1951–1980 data? How confident are you in this value?

EXTENSION

In this activity, you used summer data. Is the same trend true for winter temperatures?
Over time, has the average difference between summer and winter temperatures changed? Would you expect this to happen?

KEY CONCEPTS

- Global average temperature has increased since the 1950s with many observed climate changes being greater than any recorded during the last 1000 years.
- The anthropogenic greenhouse effect is changes to the greenhouse process caused by humans.
- Anthropogenic greenhouse gases are those that trap infrared radiation and that are generated by human activity.
- A range of instrumental records and climate proxies show that atmospheric CO_2 concentrations have rapidly increased since the start of the Industrial Revolution.
- Climate forcing refers to influences that change the climate system and cause it to warm or cool.
- Factors that create climate forcing include albedo changes and changes in atmospheric gases.
- It is highly likely that global warming is due in large part to anthropogenic greenhouse gases.
- Evidence that anthropogenic greenhouse gases have affected the climate includes isotope changes, climate models and accounting for the carbon created by burning fossil fuels.

CHECK YOUR UNDERSTANDING 10.1

1 Describe how Earth's average global temperature has changed over the last 1000 years.
2 Describe the change in CO_2 levels and temperature since the beginning of the 20th century.
3 What is the anthropogenic greenhouse effect?
4 How is the anthropogenic greenhouse effect different from the natural greenhouse effect?
5 Describe the properties and origins of two anthropogenic greenhouse gases.
6 Define 'climate forcing'.
7 Outline how CO_2 from burning fossil fuel creates a climate forcing.
8 Why does more CO_2 or CH_4 in the atmosphere lead to a warming climate?
9 Outline the evidence that supports the idea that increasing global temperatures are the result of human fossil fuel use.

10.2 Changes in the ocean and cryosphere

As humans continue to add greenhouse gases to the atmosphere, the world continues to warm and the changing climate creates changes in other parts of the Earth system. In this section, you will learn about some of the effects of climate change on two important features of the ocean and on the cryosphere.

Changes in the ocean

Thermal expansion and sea level rise

As CO_2 levels in the atmosphere rise, there is a constant transfer of CO_2 and heat from the atmosphere into the ocean. Water has a very high heat capacity so the ocean temperature rises slowly as heat is transferred from the atmosphere. But ocean temperatures do rise (Figure 10.13, page 248). About 93% of the heat imbalance generated by greenhouse gases is transferred to the ocean. This means that the global air temperature change represents only 7% of the energy being added to Earth. The energy stored in the ocean is called the **ocean heat content**. The amount of heat stored in the ocean is enormous. One unit of heat content in Figure 10.13 is approximately equal to 18 times the energy used by humans on Earth every year.

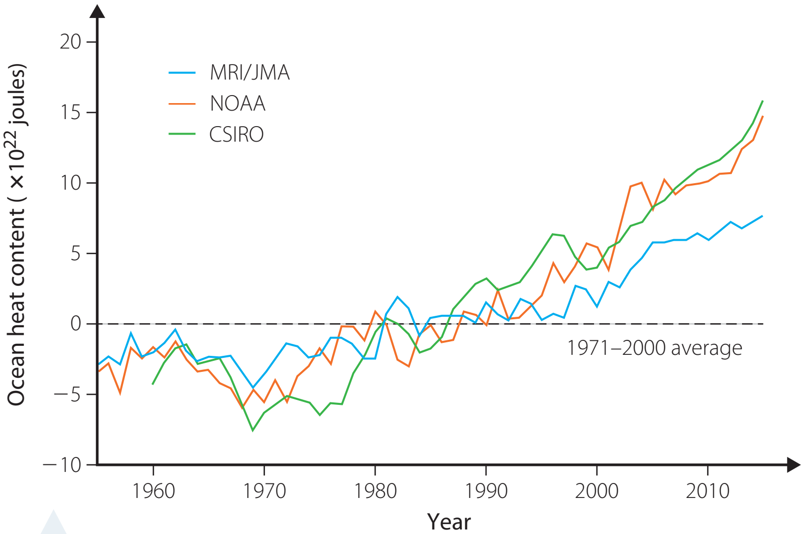

FIGURE 10.13 Ocean heat content for the period 1955–2015 as calculated by three national science agencies: CSIRO, Commonwealth Scientific and Industrial Research Organisation (Australia); MRI/JMA, Japan Meteorological Agency's Meteorological Research Institute; NOAA, National Oceanic and Atmospheric Administration (USA)

In recent years, the rate at which the oceans have warmed has increased. The average rate of heat added to the ocean for the period 1971–2010 was 0.36–0.39 $W\,m^{-2}$ (**watts** per square metre). However, after 1991 the rate increased to 0.55–0.68 $W\,m^{-2}$. These rates are calculated for the upper 2000 metres of the ocean. The recent data is based on the **Argo network** of floating buoys. There are more than 4000 buoys floating in the world's ocean where they periodically sink up to 2000 metres, drift for a while and then take temperature measurements as they rise again to the surface. The data is then transmitted to a satellite. Scientists at the CSIRO are one of the international groups that use Argo data to understand the warming ocean. The heat added to the ocean contributes to a changes to currents and weather patterns but the effect on **sea level** is particularly important.

A watt is a rate of 1 $J\,s^{-1}$. If you wish to calculate the energy added to the ocean each second, use a surface area of the ocean of 3.6×10^{14} m^2

As the ocean warms, water particles move more and move further apart so that they occupy more space (thermal expansion). This is a factor in the rise of sea levels. As water volume expands, it increases the volume of the ocean. Because the shape of the ocean basin is constant, the height of the ocean surface rises. **Thermal expansion** is not the only cause of sea level rise (Figure 10.14). The melting of ice sheets and glaciers contributes significantly to sea level rise. Terrestrial storage refers to the amount of water that is added to the ocean from land or removed as rain captured or stored on the continents. Estimates of these contributions for the period 1993–2003 added were an average of 2.8 mm $year^{-1}$. Direct measurements from satellites for the same period averaged a little more at 3.1 mm $year^{-1}$ but the errors in both measurements suggest a very similar effect.

The consequences of sea level rise are significant. Low-lying areas are more likely to flood. Low-lying islands in the Pacific Ocean may disappear due to flooding and the increased erosion caused by rising sea level. For example, Tuvalu is a country consisting of low-lying reef islands and atolls (Figure 10.15). Islands in Micronesia, Polynesia and Melanesia are all threatened by rising sea levels. Low-lying islands may be periodically flooded, causing problems for food production and saltwater intrusion of fresh water supplies. Damage to **infrastructure**, structures and facilities such as roads and buildings is also a cost on these islands. These events can affect health and have major social and cultural effects when islanders are **displaced**.

In Australia and around the world, rising sea levels increase beach erosion and cause the shoreline to retreat landward. This is called **shoreline regression**. Worldwide, approximately 70% of beaches are eroding and only 10% are growing seaward. A rule of thumb used by geographers and sedimentary geologists is that shoreline regression occurs at a rate of 100 times the rate of sea level rise. The projected sea level rise for Australian cities from Perth to Brisbane by 2030 range from 7 to 18 cm.

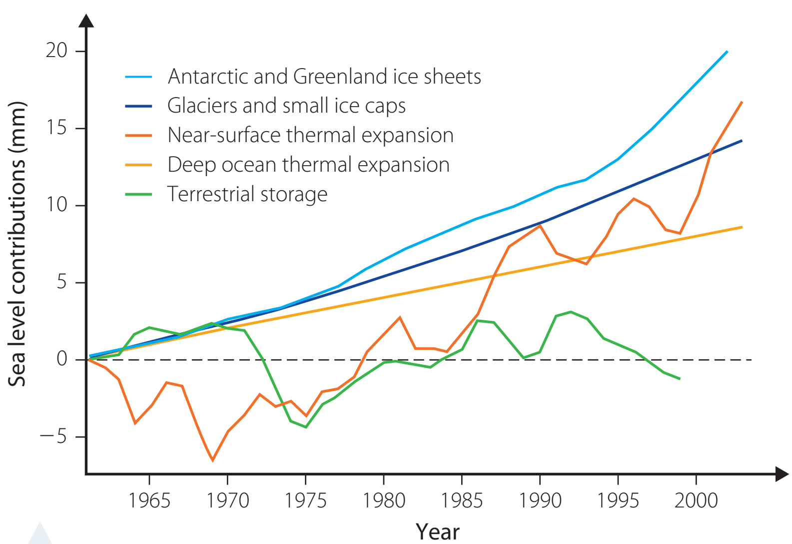

FIGURE 10.14 Ocean heat content 1960–2005 as calculated by three national science agencies

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Extreme weather events are made worse by sea level rise. Extreme weather events are unexpected, severe or unseasonal weather, such as cyclones and east coast lows. Coupled with high tides, increased sea level allows storm surges to affect more of the shoreline. Damage to seashore properties such as occurred at Collaroy in Sydney in 2016 (Figure 10.16) is likely to become more frequent.

Sea level does not rise evenly around the world. Tectonic changes lead to land rising or sinking. Some areas are rising due to isostatic uplift following the removal of ice after the last ice age. Wind patterns, ocean circulation and tides also affect local sea level. These factors add to, or subtract from, the global sea level rise. Satellite observations using lasers to measure the height of the ocean allow scientists to measure global averages for sea level rise. Tide measurements around the world give details about local rates of change.

Alamy Stock Photo/robertharding

FIGURE 10.15 Tuvalu is an island nation in the South Pacific Ocean. Tuvalu consists of nine low-lying islands, which are at risk of flooding as sea levels rise

Alamy Stock Photo/model10

FIGURE 10.16 Storm damage in June 2016 at Collaroy on the Northern Beaches of Sydney

Ocean acidification

When CO_2 dissolves in sea water, the levels of a number of important chemicals fall. CO_2 first combines with water to form carbonic acid. This lowers the ocean water's pH. Carbonic acid is a weak acid but it gives up a hydrogen ion. This hydrogen ion reacts with carbonate ions in the sea water to form hydrogen carbonate. This reduces the amount of carbonate in the sea water. This in turn upsets the amount of calcium carbonate in the ocean. This is significant because many ocean organisms use calcium carbonate to build their shells and skeletons (calcareous organisms).

Ocean acidification refers to the increasing acidity of the ocean caused by the ocean's uptake of CO_2 from the atmosphere. One estimate of the rate of CO_2 absorption is 22 million tonnes per day. Since the start of the Industrial Revolution, the ocean has become more acidic and the pH of the ocean has decreased by 0.1 pH units. Because of the nature of the pH scale, this actually represents an increase in acidity of approximately 26%. It is expected under current conditions that pH will fall another 0.6–0.7 pH units by the end of this century. The current pH of the ocean is 8.1, which is slightly alkaline. A neutral pH is 7.0.

NOAA sea level trends page

What is the trend shown for sea level rises in areas around Australia and in the Pacific Ocean?

Some ocean organisms may benefit from ocean acidification, but many, particularly animals, do not. Some algae benefit because they have more CO_2 available for photosynthesis, but not all algae benefit. Because acidification reduces the availability of calcium carbonate to calcareous organisms, these organisms have difficulty building their shells and expend more energy doing so. This means they

FIGURE 10.17 A pteropod or sea butterfly. Organisms such as this provide food for animals ranging from krill to whales.

have less energy for other processes and their growth can be affected. Animals such as corals add calcium carbonate to their skeletons a little bit at a time in layers, as you saw in Chapter 9. This process is called **calcification**. As ocean acidification increases, calcification becomes more difficult. Examples of organisms that build calcium carbonate shells are calcareous plankton, shellfish such as oysters and mussels, sea urchins and corals.

As well as harming the development of calcareous organisms, ocean acidification can harm organisms that depend on calcareous organisms for food. An important food source for animals in the Pacific Ocean are pea-sized organisms called **pteropods** (Figure 10.17). Pteropods are molluscs and, like their relatives snails and oysters, they secrete a shell. Experiments have shown that in waters with a similar pH to the ocean today, their shells gradually dissolve. If this happens to similar organisms in the ocean, their size and numbers will decrease. Decreasing the amount of food near the bottom of food chains will successively affect other organisms higher up the food chains.

The solubility of CO_2 depends on the temperature of the ocean. In Figure 10.18, the annual oscillation of pH reflects changes in absorption and uptake by photosynthetic organisms. The cold deep ocean stores more than 20 times the CO_2 stored in the upper layers of the ocean. Some marine ecosystems are affected by ocean upwelling, which can bring cold acidic water to the surface. This affects calcification and, sometimes, the attachment of coral lavae to surfaces, reducing their survival. General increases in ocean acidification are predicted to reduce the ability of corals to recover from temperature bleaching events.

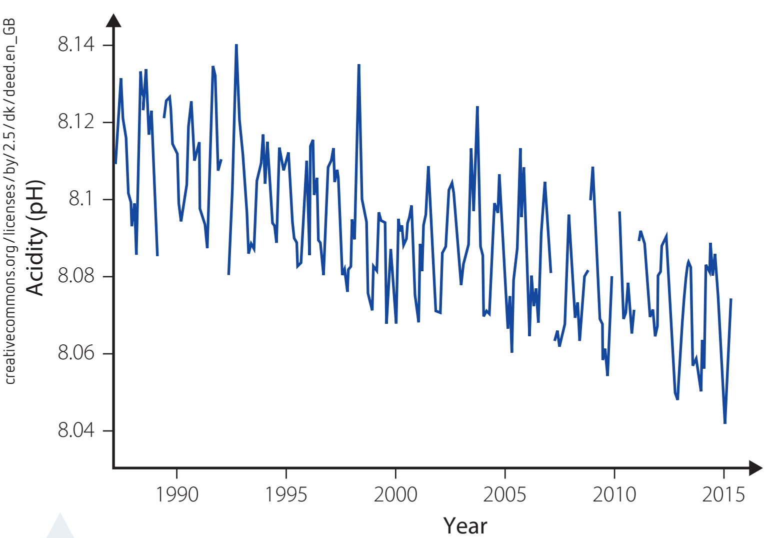

FIGURE 10.18 The decrease in pH, or the increase in acidity, from 1990 to 2015 at the Aloha station on Hawaii

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Changes to the cryosphere

The **cryosphere** includes snowfall, lake and sea ice, glaciers, ice sheets, and frozen ground. More than two-thirds of the fresh water on Earth is in the cryosphere.

Changes to sea ice and ice shelves

The cryosphere is very sensitive to changes in the atmosphere. As the temperature of the atmosphere increases, the amount of ice forming or persisting is decreasing. In the Arctic, sea ice coverage has decreased since at least 1979. The extent of sea ice coverage at the poles is seasonal, shrinking in summer and growing in winter. However, since 1979, in the Arctic, the period over which melting occurs has increased by about 6 days per decade. The extent of the Arctic sea ice has decreased at 3.5–4% or half a million square kilometres every decade (Figure 10.19a). During winter, the ice thickness has declined by 1–2 metres and the persistence of ice from one year to the next has declined by approximately 11% per decade. In Antarctica, sea ice has increased slightly by 1.2–1.8% on average but some areas of ice have grown and others have disappeared. The total mass of ice in Antarctica and in Greenland (Figure 10.19b and c) has decreased.

In Antarctica, changing surface temperatures affect both ice cover and the life influenced by the cryosphere. Since 1955, upper ocean temperatures around Antarctica have warmed by a degree and the Antarctic Circumpolar Current has warmed more rapidly than the global ocean as a whole. This has led to sea ice loss in many areas and as sea ice conditions have changed, so has the distribution of penguin colonies. There has also been a long-term decline in the number of Antarctic krill, an 80% decline since the 1970s, which may be due to the changes in sea ice cover. **Krill** are small crustaceans (about 5 cm in length) (Figure 10.20, page 252) that feed on algae found under the base of floating sea ice. The loss of that ice has reduced the food sources for krill. On land, the melting of perennial ice cover has seen the colonisation of some areas by plants

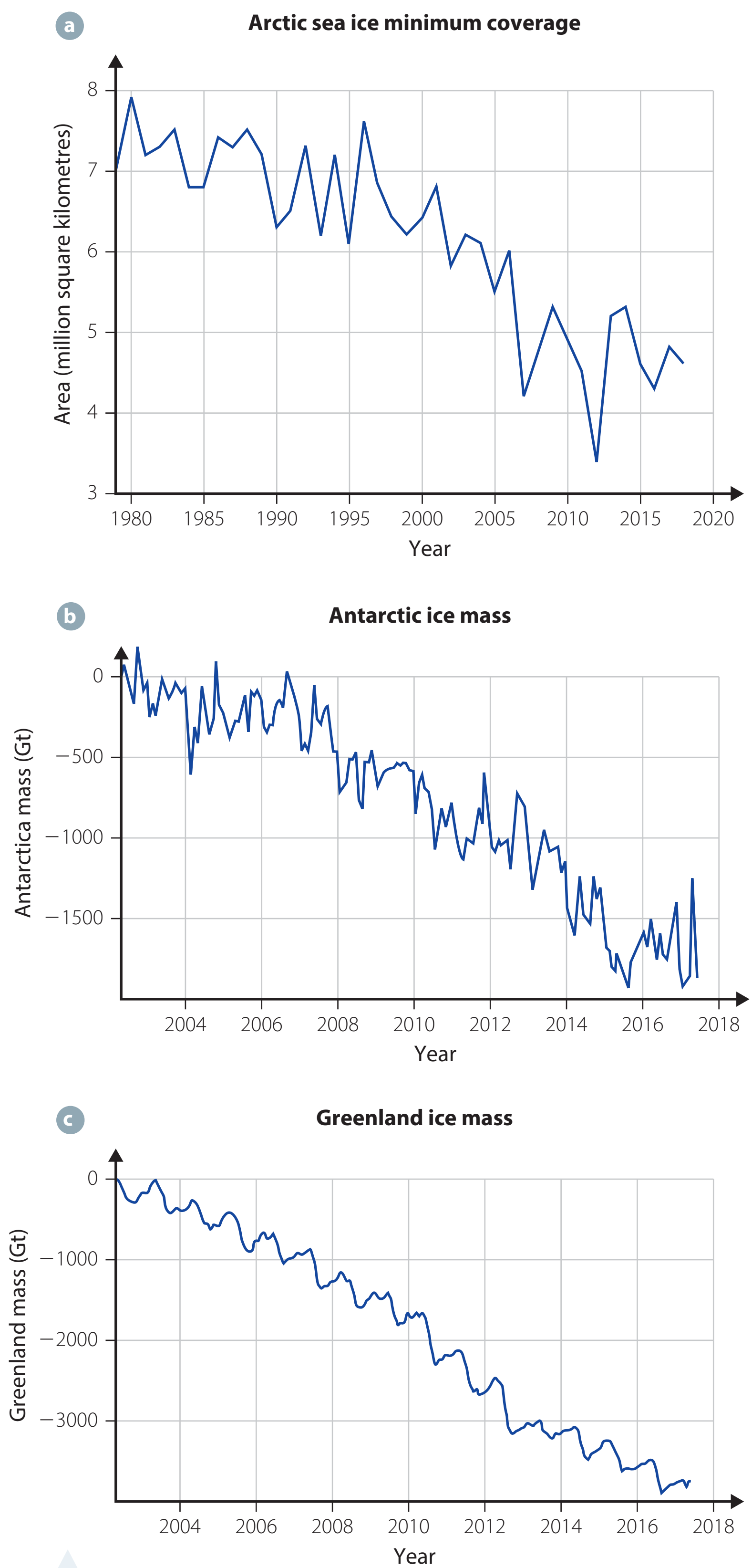

FIGURE 10.19 Changing coverage and mass for Earth's major ice stores (1 gigatonne (1 Gt) = 1×10^9 tonnes)

Alamy Stock Photo/Helmut Corneli

FIGURE 10.20 Krill numbers in Antarctica have declined drastically since the 1970s.

along the Antarctic peninsula and in ice-free areas created by hydrothermal activity.

The decline in Arctic sea ice has altered local environments and ecosystems (Figure 10.21). The loss of sea ice, as in Antarctica, removes the habitat of algae that live in the ice and phytoplankton that live in the water below the ice. This affects zooplankton that rely on the algae and phytoplankton for food. Together, the phytoplankton and zooplankton provide food for all the larger organisms in the Arctic ocean. The loss of ice restricts the places where seals and walrus can rest and breed. Walrus feed on seafloor molluscs and use the ice as a platform from which to reach the seafloor. As the sea ice decreases, feeding areas become restricted. Carnivores such as the arctic fox and the polar bear have a smaller area to hunt and fewer foraging days, which reduces their condition and ultimately their survival.

FIGURE 10.21 Changes to Arctic sea ice and permafrost coverage. The solid line shows the area in which permafrost exists today. The broken line shows where it will exist 70 years from now.

The loss of sea ice and the melting of ice shelves such as that on Greenland has important consequences for sea level rise and the rate of global warming. The loss of ice reduces Earth's albedo, so more visible light is absorbed and reradiated in to the atmosphere rather than being reflected into space. This increases the rate of permafrost thawing in the Arctic. The extent to which the loss of albedo is adding to the greenhouse effect is not well understood. The loss of ice on land, such as the Greenland ice sheet, is better understood. It is expected that if the whole Greenland ice sheet, a massive 2.85×10^6 km^3 of ice, melts, the sea level of the ocean will rise by 7.2 metres. At the current rate of melting, this is expected to take more than 14 000 years. Modelling suggests that a quarter of the current sea level rise is due to melting in Antarctica. In some areas, the effect of ice melting on ocean salinity may also create issues for ocean processes and ecosystems.

Taking the pulse of Ngozumpa
Summarise the potential impact on communities in Nepal due to the increased rate of melting in the Ngozumpa glacier..

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FIGURE 10.22 The Ngozumpa glacier (on the left) in the Himalayas is one of many shrinking glaciers. This could have devastating effects on nearby villages.

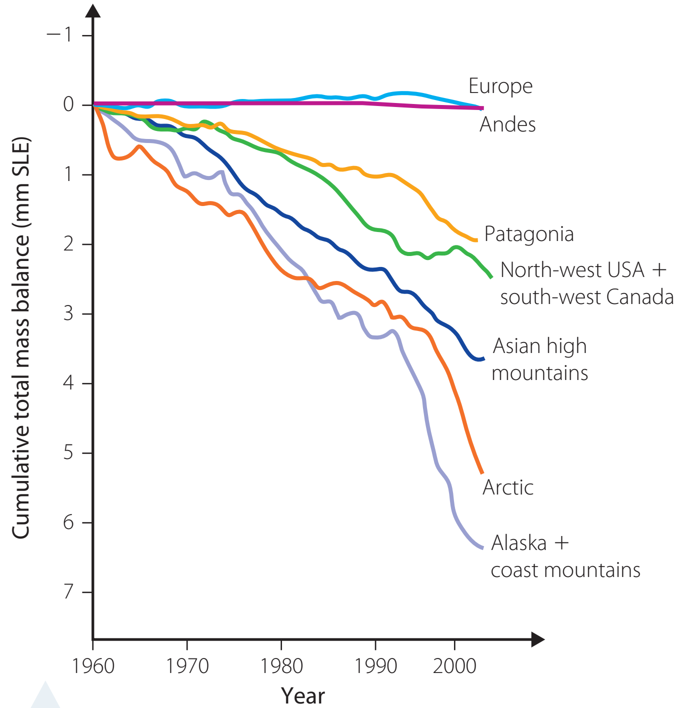

FIGURE 10.23 Changes in the mass balance for selected glaciers and ice caps. The units mmSLE stand for millimetres sea level equivalent – the potential effect on sea level if the ice were added to the ocean.

Decline in the mass of glaciers

The decline in glacial ice is also a consequence of the warming atmosphere. There are more than 168 000 glaciers around the world, which cover more than 726 000 km^2 (Figure 10.22). **Glacial mass balance** describes the gain or loss of ice from a glacier. Since the 1970s, the mass balance for most glaciers has been negative (Figure 10.23). The estimated global loss rate for the period 1971–2009 was approximately 2.26×10^{11} tonnes/year. There is a fairly large variation in estimates because of the various data sources used, but the loss appears to be real and increasing. In the 15 years to 2009, the rate appeared to increase to an average of 2.75×10^{11} tonnes/year. Some of the factors affecting **accumulation** and **ablation** of ice are shown in Table 10.2. A loss of ice is increased by changes to rates of melting and changes in snowfall. While most glaciers in the Himalayas show negative mass balances, a small number seem to have grown as regional wind patterns have changed and altered where snow falls.

TABLE 10.2 Processes affecting the accumulation and loss of ice from glaciers

PROCESSES	EFFECT OF INCREASING TEMPERATURE
ACCUMULATION (PROCESSES THAT ADD ICE)	
Precipitation of hail sleet and snow	Less ice but possibly increased precipitation as rain
Wind-blown snow	Decrease as snow fall decreases
Avalanches from adjacent mountains	Short term increase
Hoar-frost (ice crystals forming from damp freezing air)	Decrease
ABLATION PROCESSES (PROCESSES THAT REMOVE ICE)	
Surface melting and run-off	Increase
Wind-blown snow	Decrease as snow fall decreases
Avalanches from edges	Increase
Sublimation (ice changing to water vapour)	Increase
Melting within the glacier and at the glacier base	Increase
Calving to form icebergs when glacier enters the ocean	Increase
Melting of the front and base as glacier enters the ocean	Unknown

The decline in the length and volume of glaciers has implications for many natural ecosystems and human communities. The 2015 Paris Climate Agreement sought to restrict global temperature increase to 1.5°C. However, researchers have used modelling to show that even if that target is met, about a third of the mass of ice in the high mountain glaciers of Asia will disappear by 2071–2100. Hundreds of millions of people around the world rely on the summer melt of glaciers for their freshwater supplies. The natural ecosystems on which they depend also rely on that water. Countries that depend on glacial water include China, India and large areas of central Asia, many places in South America and the western USA. Many of the great rivers of Asia start at the base of glaciers in the Himalayas. These include the Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Yellow, Mekong and Yangtze rivers. The agriculture, industry and natural ecosystems along these rivers will all be negatively affected by declining water flow from glaciers.

Thawing of frozen ground

The thawing of frozen ground releases greenhouse gases that contribute to the rate of atmospheric warming. **Permafrost** is ground that remains frozen from one year to the next. In the northern hemisphere, permafrost soils can be as deep as 80 metres. Due to the warming atmosphere, the upper surface of some areas of permafrost is melting during the northern summer and not fully refreezing in the following winter. Over time, the depth of thawed soil increases and microbes become more active, decomposing organic matter in the soil. This leads to the release of CO_2 and CH_4 into the atmosphere. As the climate warms, the extent of permafrost is expected to decline (Figure 10.21).

In Siberia and Alaska, melting permafrost has led to the formation of water bodies known as **thermokast lakes**, which hasten the rate of permafrost thawing (Figure 10.24). Thermokast lakes are bodies of fresh water found in depressions caused by ice melting in the permafrost. Liquid water has a smaller volume than ice, which means that soils become unstable and slump to form depressions. Some of the water in the lakes is from the thaw but rain and snow melt also add to the lake. The mass of the water and its thermal capacity means that thawing occurs much more rapidly. This is called abrupt thawing. It may mean that the rate of addition of CH_4 to the atmosphere through the formation of thermokast lakes is greater than current models using slow thawing predict.

Besides creating thermokast lakes and ponds, permafrost thawing causes land to become unstable. This leads to landslides, soil slumping, coastal erosion and increased flooding. Houses built on permafrost can be damaged as the permafrost melts and the ground loses its strength. In some cases, thermokast lakes and the wetlands around them can drain, disrupting the biological communities living there. Changed groundwater flows also leads to changes in stream chemistry and can disrupt food chains by interfering with aquatic life cycles.

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FIGURE 10.24 The collapse of a palsa (a permafrost-generated landform) has created this Alaskan thermokast lake.

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INVESTIGATION 10.2

CO_2 solubility and temperature

Critical and creative thinking

AIM

To determine the relationship between CO_2 solubility and water temperature and to use the relationship to make predictions about the ocean and climate change

MATERIALS

Per student or group of students:

- 1 × 250 mL beaker
- Plastic container large enough to hold the beaker
- Plastic drinking straw
- Dropper bottle containing universal indicator
- Universal indicator colour pH guide
- 10 ice cubes
- Thermometer or temperature probe
- Hot plate or warm water bath
- Digital camera (optional)

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Universal indicator can cause eye and skin irritations.	Wear safety glasses to protect your eyes. Wear a lab coat to protect your clothes. Be careful not to splash the universal indicator liquid. Dispose of the final solution as directed by your teacher.
Hot plates and water bath can cause burns and scalds.	Be aware that these pieces of apparatus may be hot. Do not heat your solution above 50°C.
Universal indicator solution is toxic if swallowed.	Be careful not to suck up the solution through the straw. Inform your teacher if you ingest any of the solution.

RISK ASSESSMENT

What other risks can you identify in this investigation? How will you manage them?

METHOD

1. Copy the table in the Results section.
2. Place the ice cubes in the bottom of the plastic container.
3. Fill the beaker with 150 mL of cold water.
4. Add 5 drops of universal indicator solution to your beaker. The water should turn green.
5. Place the beaker in the plastic container and let the temperature of the water fall for 5 minutes.
6. Carefully blow bubbles through the water in the beaker using the straw. Continue to do so for at least 3 minutes.
7. Remove the straw and measure the temperature of the water with the thermometer.
8. Note the colour change of the liquid and the temperature.
9. Place the beaker on the hot plate or in the warm water bath. Adjust your heating so that it is low and the solution warms slowly.
10. Every 1–2 minutes, record the temperature and colour of the solution in the beaker. Stop when the water temperature reaches 35°C.
11. Use the colour guide to record the pH of each colour you observed in the Results table.

»

»

RESULTS

Copy and complete this table.

STAGE	COLOUR OF SOLUTION	pH	TIME (min)
Before bubbling CO_2	Green	7	
After bubbling CO_2			
Heating readings			0
			2
			4
			6
			8

ANALYSIS OF RESULTS

1. Why does the colour of the solution change when your breath bubbles through it?
2. What does the colour change say about the change in acidity of the water?
3. Graph the change in pH against time. What trend is shown in the graph?

DISCUSSION

1. What is the relationship between CO_2 solubility and water temperature?
2. Which part of the ocean, the surface layer or the deep ocean, is capable of storing more CO_2? Why do you think so?
3. As the temperature of the ocean increases, how will the amount of CO_2 in the ocean change?
4. What will be the effect of this change on atmospheric CO_2 levels?
5. How might an increase in ocean acidity affect living things in the ocean?

CONCLUSION

1. Describe the relationship between water temperature and CO_2 solubility.
2. Outline two possible consequences of adding more CO_2 to the ocean and the warming of the ocean.

INVESTIGATION 10.3

Critical and creative thinking

Modelling sea level rise

AIM

To compare the effect on sea level of sea ice melting to the melting of ice sheets such as those on Greenland and Antarctica in a simple modelling exercise

HYPOTHESIS

Melting ice in water will cause the water level to rise less than the addition of an equivalent volume of water to the volume of water in the ice.

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MATERIALS

- 2 × 250 mL beakers
- 150 mL beaker
- 100 mL measuring cylinder
- Electronic balance
- Marking pen
- 30 cm ruler marked in millimetres
- Crushed ice

METHOD

1. Use the measuring cylinder to accurately add 150 mL of water to each of the 250 mL beakers.
2. Label one beaker 'Sea ice' and the other 'Ice shelf'.
3. Place the 150 mL beaker on the balance and add 10–12 g of ice to the beaker. Record the amount of ice.
4. Add the ice to the beaker labelled 'Sea ice'.
5. Use the pen to accurately mark the height of the water in each beaker.
6. Add water to the measuring cylinder until the number of millilitres in the cylinder equals the number of grams of ice you measured.
7. Add the water to the beaker labelled 'Ice shelf'.
8. When the ice has melted in the 'Sea ice' beaker, mark the height of the water in each beaker.
9. Use the ruler to measure the change in water level for each beaker.

ANALYSIS OF RESULTS

1. What assumption was made in using a millilitre of water for each gram of ice used?
2. Which beaker had the greater increase in water level?

DISCUSSION

1. Explain why the floating ice did not raise the water level as much as the equivalent amount of water added in the 'Ice shelf' beaker.
2. Compare the effect of similar amounts of sea ice and ice shelf being added to the ocean in terms of sea level rise.
3. How else does a warming climate cause sea level to rise?
4. Are there assumptions made in this model that may not be correct?
5. How might this model be improved or extended?

CONCLUSION

Which melting contributes more to sea level rise: sea ice melting, or an equivalent amount of land-based ice melting?

KEY CONCEPTS

- Heat transfer from the atmosphere to the ocean, together with ice sheet melting, is causing sea levels to rise.
- Sea level rise is causing flooding in low-lying areas, increasing coastal erosion and increasing the effects of extreme weather events such as cyclones.
- Ocean acidification is caused by more CO_2 dissolving in ocean waters.
- Ocean acidification reduces the ability of some organisms to create their shells, reduces food supplies to ocean ecosystems and affects the life cycles of important groups of organisms such as corals.
- The cryosphere is very sensitive to changes in the atmosphere and the ocean and its components have declined or shown changes due to a warmer atmosphere.
- Sea ice, ice sheets and glaciers are all declining and their loss is causing changes to natural processes and ecosystems.
- The loss of ice increases climate change through a change in albedo and the release of greenhouse gases.
- The loss of frozen ground releases greenhouse gases that increase the greenhouse effect, increases land instability and alters natural ecosystems.

CHECK YOUR UNDERSTANDING 10.2

1 Describe how ocean warming contributes to sea level rise.
2 Outline the effects of sea level rise on coastal regions and islands.
3 What is ocean acidification?
4 Describe the effects of ocean acidification on living things.
5 Describe how a warmer atmosphere leads to a loss of ice around the world.
6 Describe the impacts of glacier loss on natural environments and human communities.
7 How do changes in the cryosphere add to climate change?
8 Outline the effects of permafrost thawing.

10.3 Changes in weather patterns and ecosystems

Weather patterns

One of the flow-on effects of a warming climate is changing weather patterns. More heat energy in the atmosphere intensifies processes such as evaporation and convection. This leads to changes in the way air masses and climate systems operate, which affect land and ocean temperatures and rainfall patterns. In this section, you will learn about changing weather patterns in Australia but the processes acting in Australia are found in other countries too.

Climate change in Australia
Compare the projected changes for three Australian cities using this CSIRO report. What changes are common? What changes vary between the cities?

Temperature

While Australia's weather naturally changes from year to year due to influences such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), global warming has added to the energy in the climate system. Australia has warmed 1°C since 1910 but most of the warming has occurred since 1950. Figure 10.25 shows how average Australian temperature has changed relative to the average for the 30-year period 1961–1990. Different parts of Australia have warmed in different ways, North-western Australia appears to be warming more slowly than southern and eastern Australia. There are fewer cold days and nights than in the early 20th century. In a city such as Canberra, there is a chance of frost on average about 90 days per year but this is expected to decrease by 20–40 days in the next 70 years. In the same city, the number of days hotter than 35°C is expected to increase from fewer than 10 to close to 30.

You will explore regional climate changes in more detail in Investigation 10.4.

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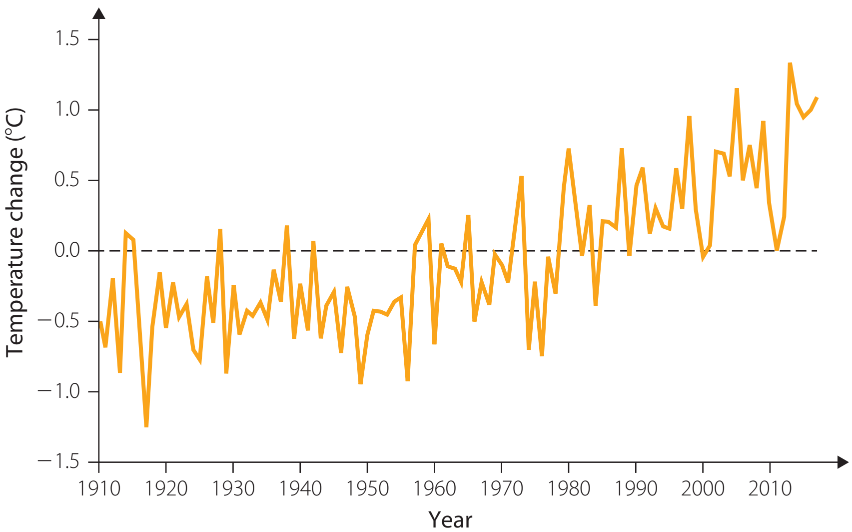

FIGURE 10.25 Australia's average temperature change since 1910

Since the start of the 20th century, there has been an increase in the frequency of extreme weather events such as heatwaves. From 1950, the number of heatwave days in Australia has increased. For example, high pressure systems in the Great Australian Bight block cooler air from reaching southern Australia and delay monsoon conditions, allowing heat to build up in central Australia. These two processes create heatwave conditions. Some climate change models predict that these conditions will occur more frequently.

MyClimate2050

Locate where you live, or a place close to your home, using the MyClimate2050 application. What proportion of days will exceed the 1960–1990 average in 2050 without action to slow climate change?

Rainfall and snowfall

During the 20th century, there have been changes in the amount and distribution of rainfall in Australia. In general, Australia can be thought of as having a northern part that receives summer rain largely due to the Australian monsoon and a southern part that receives rain as a consequence of the behaviour of cold fronts, the subtropical ridge and the **Southern Annular Mode**. While the interaction of these climate influences creates some of the variability in Australia's rainfall, there has been a change in the amount of rain Australia receives over the past 40 years (Figure 10.26).

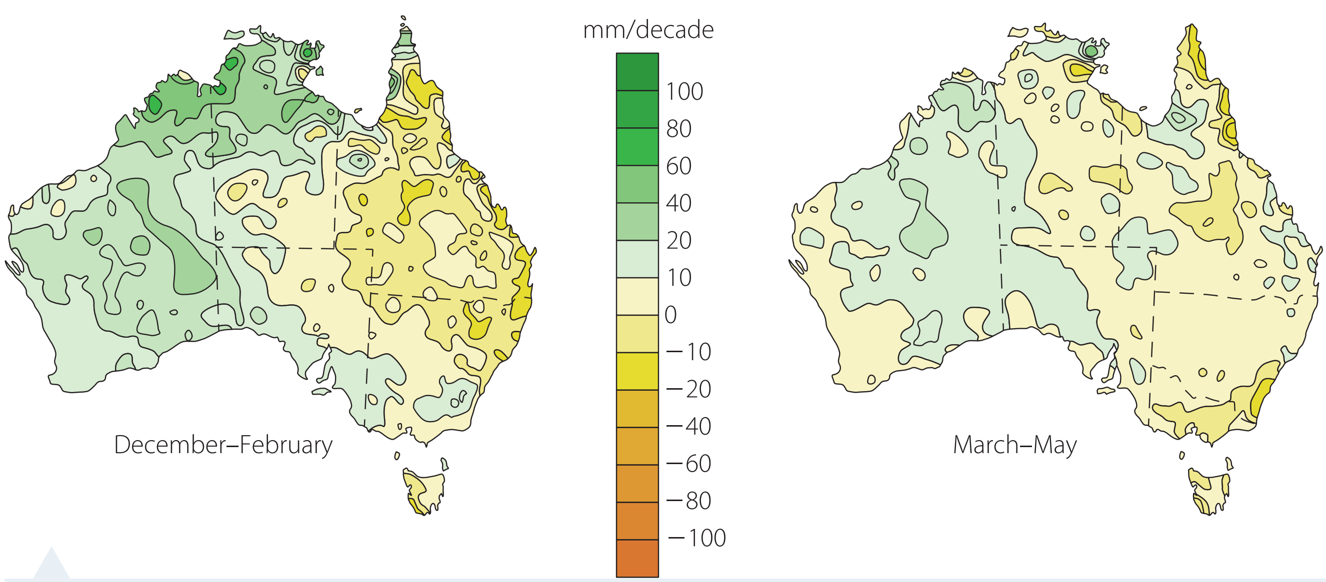

FIGURE 10.26 Australia's change in summer and autumn rainfall 1970–2018

During summer, north-western Australia has had more rainfall but much of southern Australia has had less rain during its normal wet season from April to November.

While Australia has a higher natural **variability** than some other places in the world, the frequency and severity of droughts seems to be increasing. In 2019, much of eastern Australia experienced a prolonged drought. It is thought that a stronger subtropical ridge coupled with more frequent positive Indian Ocean Dipole events contributed to the dry conditions. The behaviour of the subtropical ridge is consistent with climate models, taking into account anthropogenic greenhouse gases and their atmospheric warming. Exactly how much of our drought conditions can be attributed to climate warming remains uncertain.

When it does rain, the intensity of the rainfall appears to be increasing. Extreme rainfall events are projected to increase in both frequency and severity over time. Increased evaporation puts more water vapour into the atmosphere to fall as rain. While rain days may become less frequent, some will involve storms and intense downpours. Climate projections for cyclones are similar. Tropical cyclones form when the ocean surface temperature is above 26.5°C and are more common in La Niña years than in El Niño years. Climate models show that tropical cyclones will occur less often into the future but the frequency of intense and powerful cyclones will increase. Some modelling suggests that cyclones may move further south than they normally do. Rising sea levels mean that associated storm surges will affect areas of the Australian coast more strongly.

For the same reasons that rainfall is decreasing in some areas, the amount of snow in higher and southern parts of Australia is decreasing. Snow cover is declining in coverage, depth and the time for which it persists. Snow may fall less frequently in large amounts but high air temperatures and the effect of water falling on the snow as rain will mean that the snow disappears quickly. This is currently happening at the end of the eastern Australian snow season. A rising snowline, the height above which snow accumulates, and increasing rates of snow loss after August are also consequences of a warming atmosphere.

Changed fire conditions

A feature of the Australian environment is bushfires. The long history of fire in Australia is reflected in the adaptations of many Australian plants to cope with fire (Figure 10.27). However, the health of Australian forests and grasslands is affected by the frequency of bushfires. Many species do not persist in areas that are burned too often.

Alamy Stock Photo/Suzanne Long

FIGURE 10.27 Many Australian plant species, such as this *Banksia*, have adaptations to survive the effects of bushfires.

Bushfires depend on dry fuel and hot, dry, windy conditions to sustain the fire once it starts. A warmer climate leads to increased evaporation rates, which generate dry fuel. Evaporation, together with rainfall, temperature, humidity and wind speed are used to calculate the McArthur Forest Fire Danger Index (FFDI), which measures the degree of fire danger in Australia. The FFDI was developed in Canberra by CSIRO scientist Alan Grant McArthur and has been refined over many decades using data from fires such as the catastrophic 2009 Black Saturday bushfires in Victoria. The 2019–2020 fires will no doubt be used to refine the index further. Calculations involving more than 30 sites across Australia for the period 1973–2010 have shown a gradual increase in the index, particularly in south-eastern Australia. This indicates that the number of possible fire days is increasing. The variability in fire conditions is due to a range of factors but there is a trend over the last three decades in an increasing number of extreme fire days in spring. This has led a number of state governments to declare the start of the bushfire season earlier in recent years.

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Sea level rise and species distribution

Increasing sea levels will alter the distribution of many species. Sea level rises lead to land loss and increased rates of erosion on low-lying and intertidal habitats. As the high-water mark of tides is pushed inland by rising sea levels, ecosystems are altered or lost. In some cases, habitats do not migrate inland as the sea level rises due to natural barriers such as elevated landscapes or human infrastructure.

A wide range of habitats exist in shallow near-shore conditions. River estuaries, deltas, coral reefs, kelp beds, sea grass meadows and intertidal rocky habitats are examples of such habitats (Figure 10.28). The loss or alteration of these habitats has profound implications for the distribution of species found within them. The loss of mudflats and marshes removes the large numbers of invertebrates that live in the sediment and this reduces the food supplies for the birds, fish and mammals that also live in these habitats. Many fish and crustaceans feed in the intertidal zone of mudflats and these areas together with mangroves provide important habitats for young fish. The loss or reduction of these habitats affects the distribution and number of fish species, which also reduces the fisheries relied on by people around the world. The distribution of animals such as the dugong in northern Australia is tied to their food sources. Dugong feed exclusively on sea grass, and if rising sea levels reduce sea grass distribution, the dugong distribution will also shrink.

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FIGURE 10.28 Estuaries and mangroves like these north of Townsville, Queensland, are affected by rising sea levels.

Birds are an important group whose distribution is affected by sea level rise. In Australia, the orange-bellied parrot (*Neophema chrysogaster*) is already critically endangered and 40% of its breeding range is in low-lying coastal areas less than 10 metres above sea level. As the sea level rises, the breeding range will continue to contract, adding another pressure threatening the species survival.

There are many rare species in the Pacific Ocean that nest and live on low-lying islands. Loss of islands will reduce the distribution of those species. The effects of storm surges and sea level rise will affect eastern Australian shore-nesting birds such as hooded plovers, sooty oystercatchers and the beach stone-curlew (Figure 10.29). Some Australian shore birds migrate annually to Siberia and rely on mudflats in Asia for food on the way. Loss of these habitats will affect not only the distribution but the survival of these species.

Dreamstime.com/Artistrobd

FIGURE 10.29 The beach stone-curlew is one of Australia's, and the world's, largest shore birds. Storm surges and rising sea levels will affect its habitat.

Climate change and ocean species distribution

The range and distribution of organisms in the ocean is also affected by climate change. Most oceanic organisms rely on the temperature of the ocean for their cell processes to occur efficiently. In these organisms, cellular respiration, reproduction, nutrient uptake or photosynthesis are all sensitive to temperature change. As conditions warm, marine fish species and invertebrates shift their distributions to higher latitudes or into deeper, cooler water. Decreases in abundance and size also occur. Because many ocean organisms are dispersed by currents, changes in the timing and distance travelled by currents is affecting species distribution. Along the eastern Australian coast, a strengthening East Australian Current has moved temperate fish species as far south as Tasmania.

Warming and acidification reduce the **productivity** of phytoplankton in a number of ways. Productivity is a measure of how much life is produced in an area. Species that have adapted to cooler conditions disappear as water warms. Stratification of water reduces the upwelling of nutrients that the phytoplankton need. Modelling suggests that 2–20% of ocean primary production, the phytoplankton, will be lost from the ocean by 2100. This loss will have negative effects on all the organisms that rely on the phytoplankton for their energy needs.

Species that found new communities in disturbed environments, such as corals and oysters, are particularly sensitive to temperature, pH changes and the spread of pathogens. Coral and oysters do not compete successfully with algae to establish habitats suitable for other organisms. This is an issue on the Great Barrier Reef after bleaching or cyclone events. Corals do not repopulate the reefs as easily as algae and, while part of this problem is due to nutrient run-off from land, climate change will continue to influence it into the future. Disease also affects the ability of organisms to cope with changing conditions. As water warms, currents can transfer pathogens such as viruses and bacteria to new areas.

INVESTIGATION 10.4

Distribution of organisms in a changing climate

Sustainability

Critical and creative thinking

Information and communication technology capability

Ethical Understanding

The distribution of a species is determined by both abiotic and biotic factors. Most organisms have a preferred temperature range, particular rainfall and humidity requirements. The climate also affects a species' food sources, competitors and disease. As climate changes, a species will either cope with the change or, if it can, adjust its distribution to maintain the environmental factors.

AIM

To research the characteristics of some species that will potentially be, or are, affected by changing climate in order to better understand the threats such species face in a changing climate

METHOD

1 Select one of the following species, groups or vegetation communities:
- mountain pygmy possum
- green and gold bell frog
- *Melomys rubicola*
- marine turtle
- Adélie penguin
- chowchilla
- tooth-billed bowerbird
- Eurasian oystercatcher
- koala
- white-throated eared-nightjar
- heathland
- cool temperate rainforest
- alpine bogs and fen
- coastal freshwater lagoon
- coastal temperate fish fauna

Alternatively, select another suitable subject in consultation with your teacher. You might do some preliminary research on several subjects before picking the one you wish to research.

»

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» 2 For your species, locate the following information.
- Description of species
- Australian distribution
- Habitat or environmental characteristics
- Life cycle and timing of breeding or flowering
- Movement patterns (if applicable)
- Threats due to climate change
- Effect on species if it cannot adapt to the rapid rate of climate change
- Strategies humans can implement to reduce the possible changes you have identified

3 Use your research to prepare a report, article, or visual presentation, assessing:
- the impact of climate change on your subject
- the changes in distribution you expect as a result of environmental change
- reasons why we should value and maintain the species.

Remember, this is a science report and your predictions need to be supported by scientific reasoning and factual information.

KEY CONCEPTS

- As the climate warms, weather patterns change.
- In Australia, average temperatures have increased, cold days have decreased and extreme weather events have increased.
- In the last century, the amount and distribution of rain has changed with an apparent increase in rainfall intensity.
- Changes in rainfall, humidity and evaporation rates have increased the number of potential fire days each year and have led to an earlier start to the bushfire season in many parts of Australia.
- Sea level rises change the distribution of shallow near-shore habitats and the species that live and breed in them.
- Climate change also affects the distribution of life in the ocean, with some species distributions moving to higher latitudes as a response to temperature or changing ocean current patterns.
- Warming and ocean acidification affect ocean productivity and the ability of organisms to recolonise areas affected by extreme weather events.

WS
Terms and meanings review

CHECK YOUR UNDERSTANDING 10.3

1 Describe how temperatures in Australia have changed since 1950.
2 How have the frequencies of heatwaves and frosts changed during the last century?
3 Outline the effects of climate change that increase the frequency of potential fire days in eastern Australia.
4 How has the distribution of rainfall changed in Australia in the 20th and 21st centuries?
5 Outline how sea level rises will affect the Australian coast and shallow near-shore habitats.
6 Why do changes to habitats affect the distribution of species?
7 Outline factors affecting species distribution on land and in the ocean.

10 CHAPTER SUMMARY

- Global average temperature has increased since the 1950s with many observed climate changes being greater than any recorded during the last 1000 years.
- The anthropogenic greenhouse effect is changes to the greenhouse process caused by humans.
- Anthropogenic greenhouse gases are those that trap infrared radiation and that are generated by human activity.
- A range of instrumental records and climate proxies show that atmospheric CO_2 concentrations have rapidly increased since the start of the Industrial Revolution.
- Climate forcing refers to influences that change the climate system and cause it to warm or cool.
- Factors that create climate forcing include albedo changes and changes in atmospheric gases.
- It is highly likely that global warming is due in large part to anthropogenic greenhouse gases.
- Evidence that anthropogenic greenhouse gases have affected the climate includes isotope changes, climate models and accounting for the carbon created by burning fossil fuels.
- Heat transfer from the atmosphere to the ocean, together with ice sheet melting, is causing sea levels to rise.
- Sea level rise is causing flooding in low-lying areas, increasing coastal erosion and increasing the effects of extreme weather events such as cyclones.
- Ocean acidification is caused by more CO_2 dissolving in ocean waters.
- Ocean acidification reduces the ability of some organisms to create their shells, reduces food supplies to ocean ecosystems, and affects the life cycles of important groups of organisms, such as corals.
- The cryosphere is very sensitive to changes in the atmosphere and ocean and its components have declined or shown changes due to a warmer atmosphere.
- Sea ice, ice sheets and glaciers are all declining and their loss is causing changes to natural processes and ecosystems.
- The loss of ice increases climate change through a change in albedo and the release of greenhouse gases.
- The loss of frozen ground releases greenhouse gases that increase the greenhouse effect, increases land instability and alters natural ecosystems.
- As the climate warms, weather patterns change.
- In Australia, average temperatures have increased, cold days have decreased and extreme weather events have increased.
- In the last century, the amount and distribution of rain has changed with an apparent increase in rainfall intensity.
- Changes in rainfall, humidity and evaporation rates have increased the number of potential fire days each year and have led to an earlier start to the bushfire season in many parts of Australia.
- Sea level rises change the distribution of shallow near-shore habitats and the species that live and breed in them.
- Climate change also affects the distribution of life in the ocean, with some species distributions moving to higher latitudes as a response to temperature or changing ocean current patterns.
- Warming and ocean acidification are affecting ocean productivity and the ability of organisms to recolonise areas affected by extreme weather events.

10 CHAPTER REVIEW QUESTIONS

Review quiz

1 Sketch a graph to show how global surface temperature has changed since 1850.

2 Describe the anthropogenic greenhouse effect.

3 Describe the role of a warming climate on Australia's average temperature and rainfall patterns.

4 Identify three greenhouse gases that occur naturally and that are also generated by human activity.

5 Outline three ways in which anthropogenic greenhouse gases are affecting living organisms.

6 Summarise the ways in which Earth's climate has changed over the last 200 years.

7 a Outline the environmental factors that contribute to a high risk of bushfires.

  b Explain how two of these factors are affected by a warming climate.

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8 What role did the Industrial Revolution have in subsequent changes in global temperature and ocean acidification?

9 How is the anthropogenic greenhouse effect different from the natural greenhouse effect?

10 What is the evidence for human activity increasing the concentration of greenhouse gases in the atmosphere?

11 Explain the role of climate models in understanding past, present and future Earth climates.

12 The table below shows the changes in the loss of ice from a glacier over time.

YEAR	ICE LOSS – EQUIVALENT CHANGE IN SEA LEVEL CAUSED BY ADDING THE LOST ICE AS WATER (m)
1950	0
1960	4
1970	5.5
1980	6
1990	9.5
2000	13.5

a Graph the ice loss over time.
b Describe the trend in ice loss.
c Explain the trend you described.
d Assess the loss of glaciers as a contribution to sea level rise.

13 The map in Figure 10.30 shows the distribution of a plant species in eastern Australia during 1974 and 2014.

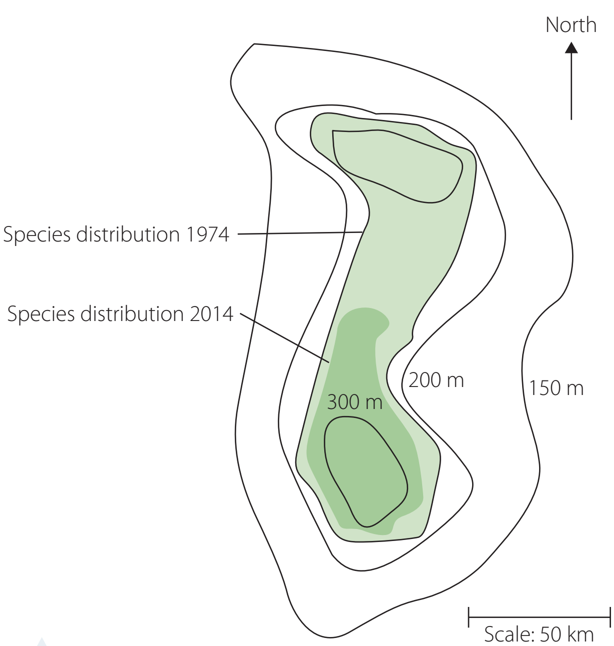

FIGURE 10.30 Distribution of a plant species in eastern Australia, 1974–2014

a Describe the ways in which the distribution of the plant species has changed over 40 years.
b Is the change in distribution consistent with distribution change due to a rising temperature?
c What additional information would you seek to identify the most probable cause of the distribution change?

14 Explain how albedo change acts as a climate forcing.

15 a Construct a flowchart to show how a warming atmosphere leads to sea level rise.
b Explain why sea level rise is expected to reduce the distribution of shore birds and birds that nest on low-lying islands.

16 Assess the effect of climate change on the frequency and effects of tropical cyclones.

17 Assess the role of climate change in altering the abundance and distribution of species on land and in the ocean.

18 Construct a table to summarise climate change in the atmosphere, hydrosphere and lithosphere and the effects of those changes on natural and human communities.

19 The table below shows information about three anthropogenic greenhouse gases.

GREENHOUSE GAS	GLOBAL WARMING POTENTIAL	AVERAGE TIME IN ATMOSPHERE (YEARS)	2016 CONCENTRATION (ppb)
Carbon dioxide	1	100	403 000
Methane	25	12	1842
Nitrous oxide	298	114	329

a Describe the anthropogenic sources of one of the gases in the table.
b Explain why CO_2 emissions receive more attention than methane or nitrous oxide.
c Assess the importance of reducing the concentration of these gases in the atmosphere.

11 Mitigation and adaptation strategies

OUTCOMES

In this chapter you will learn about:

- human-induced causes of the enhanced greenhouse effect ICT, AAEA
- scientific approaches to minimising human domestic contributions to the greenhouse effect CCT, ICT, S, CS
- the scientific basis of mitigation and adaptation strategies to respond to a warming atmosphere. S, AAEA, CCT, EU, ICT, L, ATSIHC

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The international scientific community accepts that human activity has contributed to global warming. Why then do people continue to add greenhouse gases to the atmosphere? If a changing climate will adversely affect people and natural systems, what can we do to reduce those effects? In this chapter, you will examine some of the causes of our greenhouse gas emissions and evaluate the usefulness of some strategies proposed to deal with the enhanced greenhouse effect.

11.1 Human-induced causes of the enhanced greenhouse effect

The two main causes of anthropogenic greenhouse gases are burning fossil fuels for energy and the changes society has made to land use. The emission contributions by different sectors of the Australian economy are shown in Figure 11.1 and Table 11.1. Emissions due to energy production occur in a number of forms. The largest single source of emissions is the generation of electricity. Coal, natural gas and oil are all used to generate electricity. Stationary energy emissions are gases generated in the production of heat, steam or pressure. Stationary energy generation occurs in many situations, including manufacturing, heating buildings, and some agricultural and forestry practices and electricity generation. The only sector in which greenhouse gases are removed from the atmosphere is in the land-use sector. Growing vegetation removes CO_2 through photosynthesis. This capture and long-term storage of carbon is called **sequestration**.

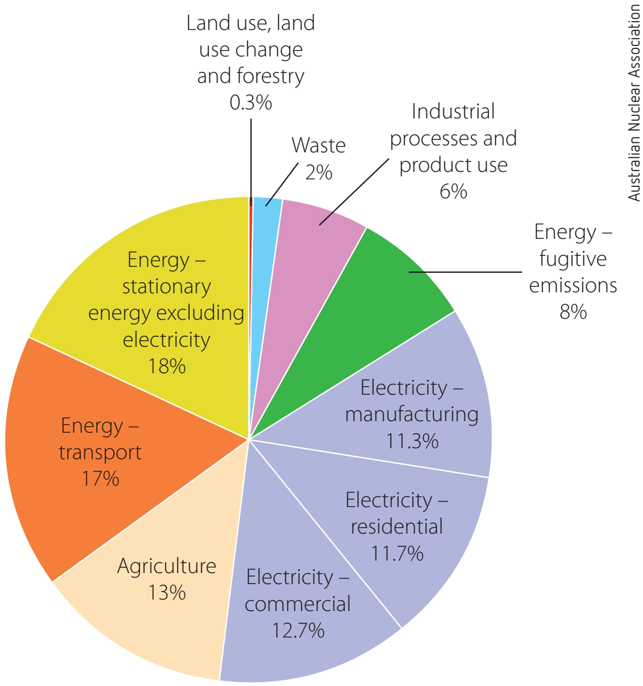

FIGURE 11.1 Greenhouse gas emissions by Australian sectors. The sectors are defined in Table 11.1.

TABLE 11.1 Sources of greenhouse gas emissions in Australia (March 2019)

SECTOR		NATURE OF SOURCE EMISSIONS	EMISSIONS IN MILLIONS OF TONNES OF CO_2 EQUIVALENT GAS (Mt CO_2-e)
Energy production	Electricity and heat production (stationary energy)	Combustion of fuels to generate electricity and direct combustion to generate steam, heat or pressure	282.3
Energy production	Transport	Combustion of fuels for transportation within Australia; includes cars, trucks, trains, aeroplanes, ships	101.2
Energy production	Fugitive emissions	Greenhouse gases released during the extraction, processing and delivery of fossil fuels	59.6
Industrial processes and product use		From non-energy-related industrial production and processes; includes hydrofluorocarbons (used in refrigerants and air conditioning)	34.6
Agriculture		From livestock, manure management and crop residues; also emissions from rice cultivation, nitrogen fertilisers, and burning agricultural residues	68.6
Waste		From the disposal of material to landfill and wastewater	12.1
Land use, land-use change and forestry		Emissions and sequestration from activities in forest and land converted to grasslands, croplands, wetlands and human settlements	−19.4

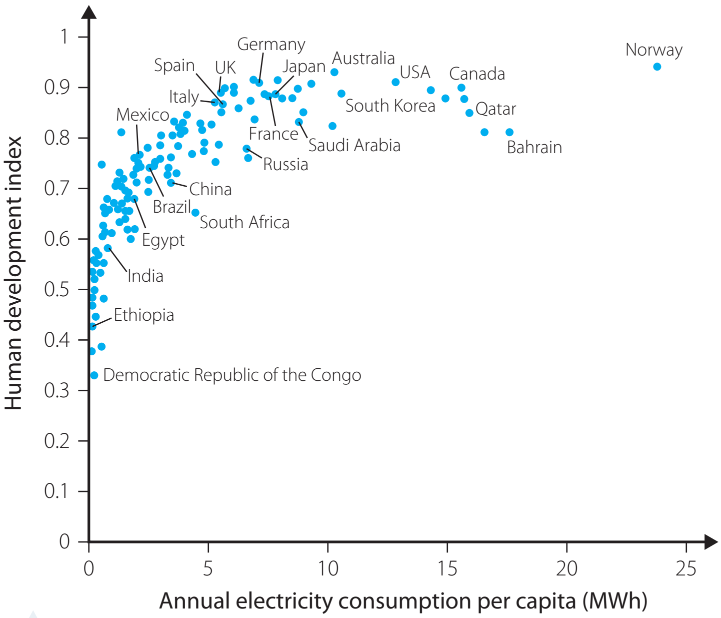

FIGURE 11.2 The relationship between the human development index (HDI) and electricity consumption per person for various countries in 2003–2004 (MWh = megawatt hours). HDI is a measure of life expectancy, education and income.

Burning fossil fuels and connection to standard of living

Human history has resulted in large populations, a growing complexity in how we produce goods and a high quality of life for many people. Each of these contributes to our dependence on fossil fuels and explains why humans have used an increasing amount of fossil fuels over time. For much of human history, humans relied on fuels such as wood, straw or peat for warmth and light. During the 19th century, humans learnt how to convert the heat from burning fuel into motion. That motion, in the form of steam engines, and later petroleum engines and gas **turbines**, increased our standard of living.

The real problem with burning fossil fuels is that it releases carbon that was locked away in Earth millions of years ago and in turn increases CO_2 in today's atmosphere to levels that have never been seen before.

The quantity of energy we use and how we use it can be linked to the standard of living of a society. **Standard of living** refers to the wealth, comfort and access to material goods and services that a person or society has. Figure 11.2 shows the relationship between a measure of a country's development, the human development index (HDI), and the average amount of electrical energy consumed per person in a year. The way in which HDI values are calculated is shown in Table 11.2, which also compares values for Australia and Chad. In 2018, Australia's HDI ranking (of 189 countries) was 6 and Chad's ranking was 187. Countries with higher standards of living (e.g. Australia) use much more energy than less well-off countries (e.g. Chad).

As the standard of living of poorer countries increases, they use more energy. A fourfold increase in global energy demand is predicted in the next century, and this has serious implications for greenhouse gas emissions from fossil fuels.

TABLE 11.2 Criteria for calculating the human development index (HDI)

DIMENSION	INDICATOR	MINIMUM	MAXIMUM	AUSTRALIA (2018)	CHAD (2018)
Health	Life expectancy (years)	20	85	83.3	54
Education	Expected years of schooling	0	18	22.1	7.5
	Average years of schooling	0	15	12.7	2.4
Standard of living	Gross national income per person (international dollars)	100	75 000	44 097	1716
Dimension index calculation	$\text{Dimension index } (I) = \dfrac{\text{actual value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$				
Aggregation of dimensions to calculate HDI	$\text{HDI} = \sqrt[3]{I_{\text{health}} \times I_{\text{education}} \times I_{\text{income}}}$			0.939	0.367
Energy consumption per person (kilowatt hours)				9324	14

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Population growth

Population growth and energy use are strongly interconnected. Twelve thousand years ago, it is estimated that there were only 4 million humans on Earth (Figure 11.3). Until the invention of steam engines, most of the energy for agriculture or industry came from human or animals. As machines began to provide energy during the Industrial Revolution, people began to live longer and could afford better lives. Longer lives helped increase populations. As the use of fossil fuels increased standards of living and scientists found cures for many diseases, populations grew and the demand for energy increased.

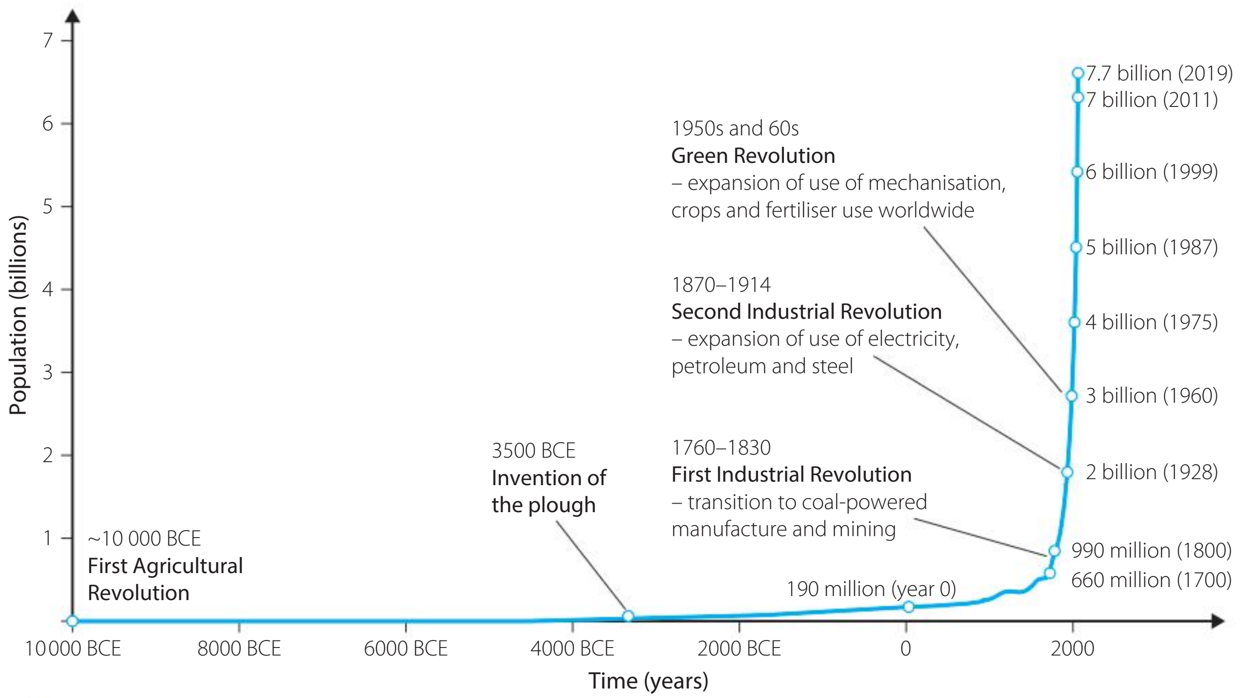

FIGURE 11.3 Growth in the human population over the last 12 000 years

The problem of efficiency

Efficiency describes the quantity of useful work a system does with the energy supplied to it. All energy transformations involve a loss of energy in the form of heat. During an energy transformation, some of the energy is transformed into heat, as described in the Sankey diagram (Figure 11.4).

Only some of the energy in fuel is transformed into a form of useful energy. Perhaps the most efficient way of turning fossil fuels into electricity is the combined-cycle gas turbine. In a power station, gas turbines convert about 60% of the energy in the fuel into electrical energy. Some energy is lost in electrical transmission to a home and then efficient lights generally convert only about 15% of the electrical energy

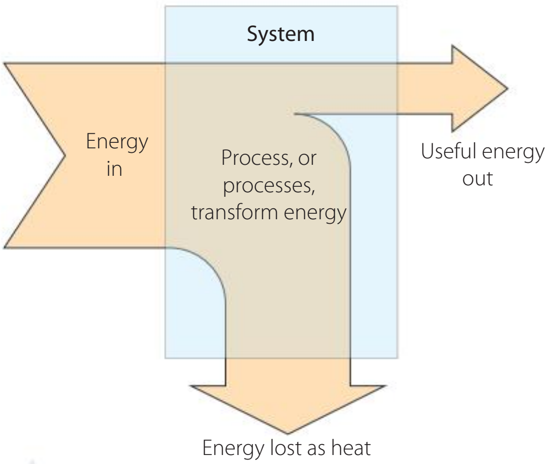

FIGURE 11.4 This Sankey diagram shows how all energy transformations involve some energy loss as heat.

OurWorldInData.org

Explore how human population has changed with this interactive graph. Use the interactive graph to compile a table of the human population at the start of each century from the year 0 to 2000.

Sankey diagrams

Use the information in the weblink to create a Sankey diagram for energy transformations from a power station to your household light.

into light. Less than 10% of the energy in the original natural gas used in the power station is converted into the useful light energy we use. Cars and appliances are also fairly inefficient (Figure 11.5). Improving efficiency in machines reduces greenhouse gas emissions.

Not all fossil fuels produce the same amount of energy and CO_2 emissions (Table 11.3). **Energy density** describes the quantity of energy contained in a certain volume of a material. The **specific energy** of a fuel is the quantity of energy per unit mass. Crude oil contains at least four times the energy per unit mass of very low energy density materials, such as air-dried wood, and releases only a sixth of the CO_2 for each megajoule of energy produced. Unfortunately, improvements in energy use efficiency have not compensated for the increasing demand for fossil fuels.

TABLE 11.3 Energy densities and CO_2 emissions of fuels

ENERGY DENSITY	EXAMPLES	CARBON (%)	ENERGY DENSITY ($MJ\,L^{-1}$)	SPECIFIC ENERGY ($MJ\,kg^{-1}$)	CO_2 EMISSION FACTOR $kgCO_2/GJ$
Very low	Grass, green wood, peat	17–50	2–11	5–10	381.6 (peat)
Low	Air-dried wood, dry dung, crop stubble or hay, lignite (brown coal)	60–70	9 (wood) 12 (lignite)	8–20	93.5 (brown coal)
Medium	Dry wood, bituminous coals	76–90	14–24	18–29	90
High	Anthracite, charcoal	90–95	36 (anthracite)	26–33	90
Very high	Crude oil	82–87	2–31	40–44	69.6
	Natural gas		0.0364	53.6	51.5

FIGURE 11.5
A highly sophisticated car is not necessarily energy efficient.

INVESTIGATION 11.1

Critical and creative thinking

Numeracy

Calculating energy provided by fuels and CO_2 emissions

AIM

To measure the heat delivered by burning two fuels, estimate the efficiency of the heating and calculate the relative quantities of greenhouse gas emissions generated by the burning of the fuels

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MATERIALS

- Metal container such as a can (You could also use a metal cup.)
- 100 mL measuring cylinder
- 250 mL beaker
- Stirring rod
- Alcohol thermometer or digital thermometer
- Disposable pipette
- 2 spirit burners, one containing ethanol, the other containing butanol (or similar fuel)
- Retort stand, boss head, heatproof mat and clamp

WHAT RISKS ARE THERE IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
The fuels are flammable.	Ensure that no fuel is spilt. Use one burner at a time.
The fuels will produce fumes during their combustion.	Ensure the room is well ventilated.
Thermometers are fragile and easily broken.	Take care when handling alcohol or mercury thermometers. Do not stir the water with the thermometer. If you break the thermometer, ask your teacher how to dispose of the fluid from the thermometer.
The metal can will get hot and could cause burns.	Handle the apparatus carefully or allow time for it to cool before it is moved.

RISK ASSESSMENT

What other risks can you identify in this investigation? How will you manage them?

METHOD

1 Copy the table in the Results section.
2 Half-fill the 250 mL beaker with water and use it to accurately measure 100 mL into the measuring cylinder.
3 Pour the water into the metal can.
4 Attach the boss head and clamp to the retort stand.
5 Place the metal can in the clamp. Tighten the clamp so it firmly holds the metal can.
6 Adjust the height of the can by loosening the boss head. Raise the base of the can so the wick of the spirit burner is 2–3 cm below the base of the can. Tighten the boss head.
7 Measure the temperature of the water in the can. Record the temperature in the table.
8 Increase the temperature of the water by 50°C. Calculate what the final temperature will be and record it in the table.
9 Measure the mass of the ethanol burner. Record the mass in the table as the initial mass.
10 Place the spirit burner under the can and light the spirit burner.
11 Stir the water in the metal can with the stirring rod. Measure the temperature regularly with the thermometer.
12 When the water reaches the final temperature that you calculated in step 8, snuff out the flame. Do not blow it out. Record the actual temperature of the water when the flame was snuffed out.
13 Measure the mass of the spirit burner again. Record the mass as the final mass in the table.
14 Let the metal can cool a little and then carefully remove it from the clamp.
15 Pour the warmed water into a sink. Wash and dry the metal can.
16 Repeat steps 2–15 using the other fuel burner.

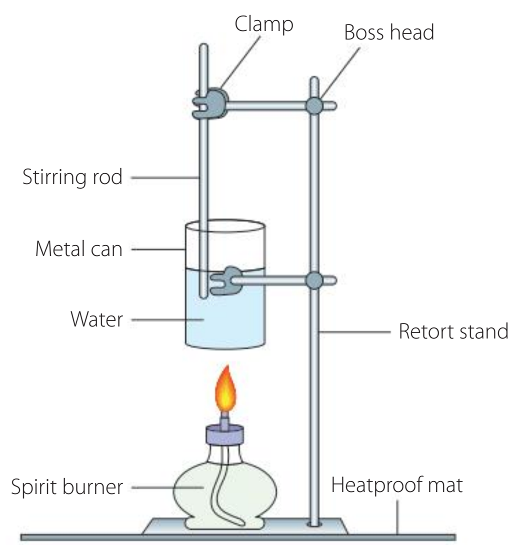

FIGURE 11.6 Experimental set-up

RESULTS

Copy and complete this table.

MEASUREMENT	FUEL	
	ETHANOL (CH_3CH_2OH)	BUTANOL ($CH_3(CH_2)_3OH$)
Water initial temperature (°C)		
Water calculated final temperature (°C)		
Water actual final temperature (°C)		
Actual change in water temperature (°C)		
Initial mass of the burner and fuel (g)		
Final mass of the burner and fuel (g)		
Amount of fuel burned (g)		
Fuel mass needed to change water temperature 1°C (g)		

ANALYSIS OF RESULTS

1 For each fuel, calculate the:

a actual change in temperature by subtracting the initial water temperature from the actual final temperature. Record the temperature change in the results table

b fuel burned by subtracting the final mass of the burner and fuel from the initial mass of the burner and fuel. Record the change in fuel mass in the results table

c fuel mass needed to change water temperature 1°C. To do this, divide the mass of fuel burned by the actual change in the temperature of the water.

2 Table 11.4 shows the equations for the combustion of three alcohols and the heat generated by burning a gram of fuel at 25°C.

TABLE 11.4 Data for heat generated by three fuels

FUEL	COMBUSTION EQUATION	HEAT OF COMBUSTION ($kJ\ g^{-1}$) (25°C)	MASS OF CO_2 PER GRAM OF FUEL BURNED (g)	MASS OF CO_2 PER KILOJOULE OF ENERGY (g)
Ethanol (CH_3CH_2OH)	$CH_3CH_2OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$	22.7	1.91	0.084
Propanol ($CH_3(CH_2)_2OH$)	$2CH_3(CH_2)_2OH(l) + 9O_2(g) \rightarrow 6CO_2(g) + 8H_2O(l)$	29.7	2.20	0.074
Butanol ($CH_3(CH_2)_3OH$)	$CH_3(CH_2)_3OH(l) + 6O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l)$	36.1	2.38	0.065

3 For each fuel, calculate the heat generated by the fuel burned. Use this equation:

Heat generated (kJ) = mass of fuel burned (g) × heat of combustion ($kJ\ g^{-1}$)

4 How many molecules of CO_2 are produced when each fuel is burned? If necessary, ask your teacher for help with the combustion equations in the table.

DISCUSSION

1 Which fuel produced the greatest quantity of heat when it burned? Why do you think so?

2 Much of the heat generated by the flames was not transferred to the water. Outline where this lost heat was transferred to.

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3 Copy the diagram of the apparatus used in the experiment (Figure 11.6). Add labels for how the apparatus might be improved to capture more of the heat from the burner.

4 Which fuel produced the lowest amount of CO_2 per gram of fuel used? Does this mean that low carbon-emitting fuels are the best fuels?

5 How could the experiment be improved to reduce heat loss from the water and the can?

6 Comment on the reliability and validity of the experiment.

CONCLUSION

Summarise the results of the experiment and your confidence in them.

KEY CONCEPTS

- Australians live in an energy-intensive society that relies on burning greenhouse gas producing fossil fuels for its energy.
- In Australia, greenhouse gases are predominantly generated in the production of electricity, the generation of steam and heat, and transport.
- Society's use of fossil fuels has increased throughout history as populations have grown, society has become more complex and our lifestyles have required greater amounts of energy.
- When fossil fuels are used, a lot of energy is lost because of the inefficiency of devices and transmission.

CHECK YOUR UNDERSTANDING 11.1A

1 Identify the two main causes of anthropogenic greenhouse gas emissions.

2 Outline how fossil fuel use contributes to the anthropogenic greenhouse effect.

3 Outline Australia's major sources of greenhouse gas emissions.

4 Describe reasons for the increasing use of fossil fuels through history.

5 Explain why energy is lost in the transformation and transmission of energy.

Land use and forestry

Internationally, agriculture and other land uses, including land clearing, are responsible for approximately a quarter of anthropogenic greenhouse gas emissions. The largest sources of such emissions are agriculture and land clearing. Of the land that is ice free, human societies utilise little more than 70% for agriculture and forestry (Figure 11.7, page 274).

Agriculture

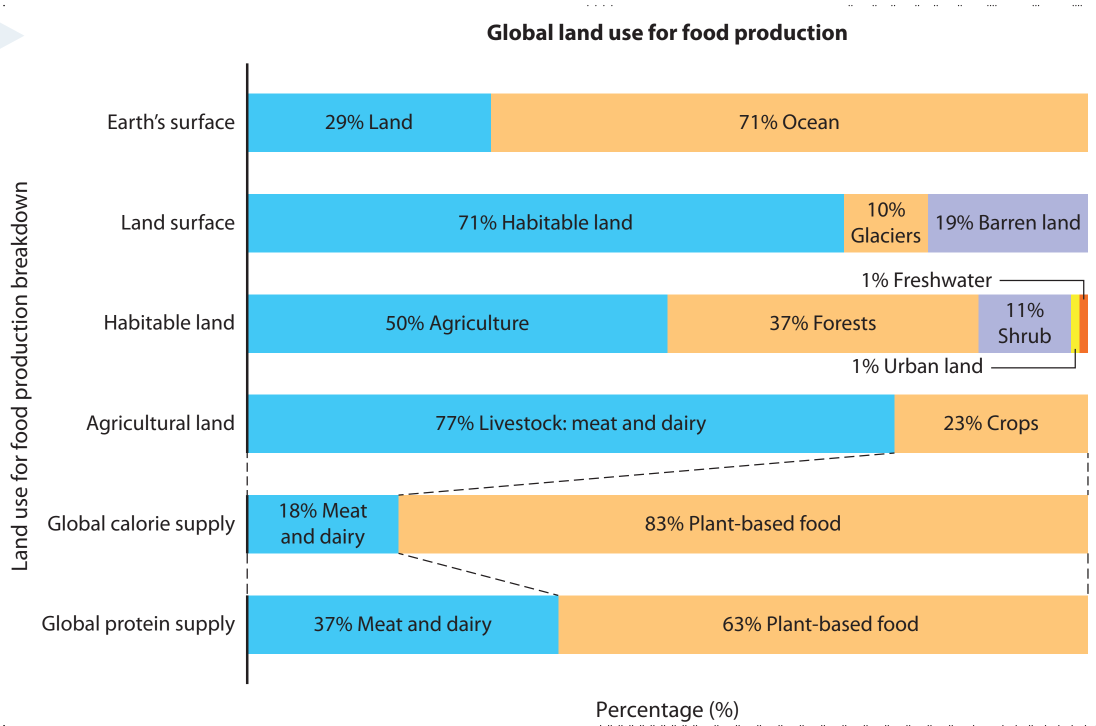
Agriculture produces greenhouse gases in a variety of ways. More than 10% of Australia's greenhouse gas emissions are generated by agriculture, with carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) being the major gases emitted. The use of fertilisers, manure management and the gases produced by animal digestion are all sources of greenhouse gases. Modern farming is energy intensive. Greenhouse gases are produced when planting, growing, harvesting, and in the processing and transport of crops. Building infrastructure to store or process the material produced also involves the expenditure of energy and production of greenhouse gases.

Animals are a source of greenhouse gas emissions in four ways: stomach fermentation, manure management, feed production and energy consumption. Ruminant animals have microbiological fermentation in their stomach, or rumen, as part of digestion. Ruminant animals include cows, sheep, goats and buffalo. Fermentation benefits these animals because it breaks large carbohydrate molecules into shorter, more easily absorbed molecules. A product of this process is CH_4. The volume of CH_4 depends on the quality of the feed the animals ingest. High-fibre feeds cause more CH_4 emissions than low-fibre feeds supplying the same amount of energy to the animals. Between 2 and 10% of the energy in the food is lost as energy in CH_4. About 10% of Australia's total greenhouse gas emissions come from these CH_4 emissions. This is approximately equivalent to 55 million tonnes of CO_2.

GLEAM model

Use the information to identify the sources of livestock emissions and the ways those emissions might be mitigated.

FIGURE 11.7 Global land use for food production by percentage



Manure is another source of greenhouse gas. When manure decomposes without oxygen (anaerobic decomposition), CH_4, N_2O and ammonia (NH_3) are produced. NH_3 is not a greenhouse gas but it reacts with oxygen to form N_2O, which is a strong greenhouse gas. One kilogram of N_2O is equivalent to about 298 kg of CO_2 and it has an atmospheric lifetime of 110 years. The production of greenhouse gases is greatest when manure is stored in liquid form in tanks or deep lagoons. The decomposition of nitrogen-rich plant material and wastewater treatment also generate N_2O.

Livestock feed production, processing and transport generate CO_2 and N_2O gases. The clearing of natural habitats to make way for pastures and feed crops causes plant matter and soil carbon to **oxidise**, producing CO_2. Artificial fertilisers also contribute to greenhouse gas emissions. Emissions are created in the production of the fertilisers, their transport and application, and then breakdown in soil. Nitrogen-rich fertilisers such as urea or processed manure give rise to nitrous oxides. Globally, 3.3 Gt of greenhouse gases are produced annually in the production of feed for livestock.

Nitrous oxide – another powerful greenhouse gas

Use the article to describe the link between N_2O gas emissions and agricultural practices.

Land clearing

Land clearing refers to the removal of native vegetation and regrowth. Land clearing is a major source of greenhouse gas emissions in Australia and worldwide. In 2017–18, in New South Wales, 58 000 ha were cleared. High-resolution SPOT5 satellite images can accurately identify land cover changes to crop, pasture, thinning (removal of branches, roots and buds), forestry, infrastructure, and bushfire damage and regrowth (Figure 11.8 and Table 11.5).

TABLE 11.5 New South Wales woody vegetation loss 2017–18 (1 km^2 = 100 ha)

LAND USE	LOSS (ha/year)	PERCENTAGE (%)
Crop, pasture, thinning of trees	27100	46.72
Forestry	21 700	37.4
Infrastructure	9200	15.9
Fire	7000	12.1

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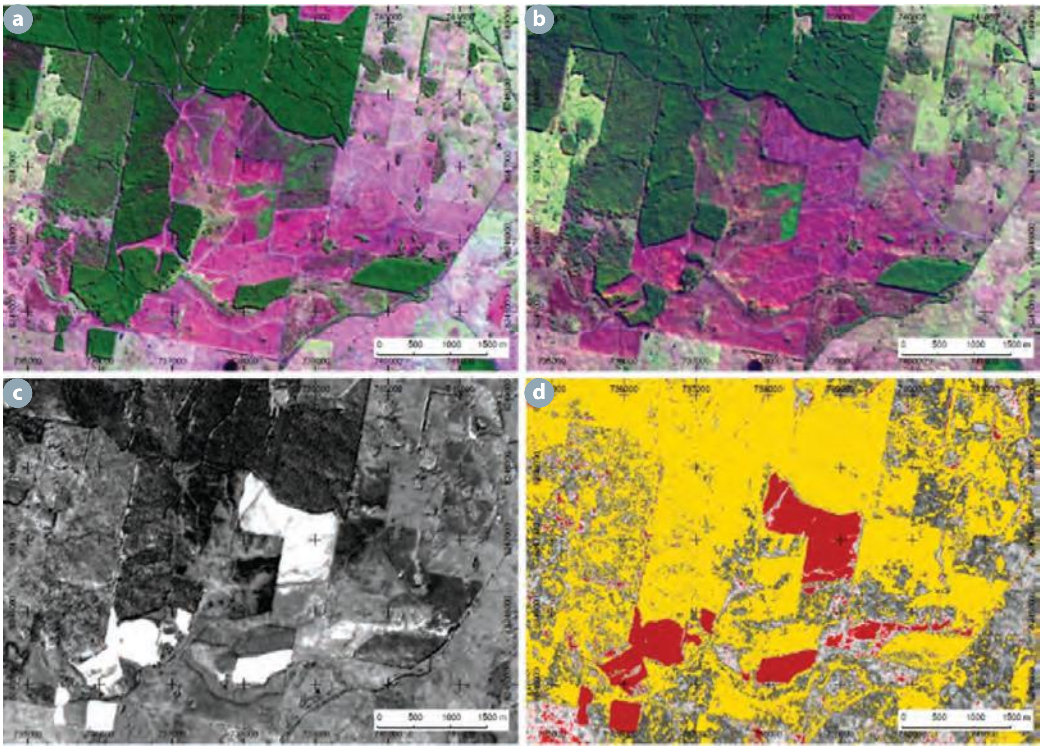

FIGURE 11.8
a Before and **b** after clearing has occurred. In **c** and **d** white areas are likely clearing, red areas are most likely clearing, grey areas are less likely clearing and yellow areas are not clearing. (Photos c and d produced from SPOT5 satellite images)

Clearing native vegetation contributes to anthropogenic greenhouse gas emissions in several ways. Removal of living native vegetation reduces the removal of CO_2 by photosynthesis. This is a particular issue for young actively growing plants, which absorb CO_2 from the air. Carbon stored in dead trees and cleared vegetation is often burned, releasing CO_2 into the atmosphere. Vegetation that is ploughed into the ground decays as microbial action generates CO_2. Finally, CO_2 is released as carbon in the soil is oxidised. Tilling, or ploughing, the soil can speed up this process because oxygen is better able to oxidise soil carbon. Land clearing increases light absorption and changes evaporation and atmospheric circulation. In areas such as the Amazon, land clearing is thought to have had an impact on rainfall patterns.

About 90% of the native vegetation in the eastern temperate part of Australia has been cleared since European settlement for agriculture, industry, infrastructure or habitation. Fifty per cent of rainforests have been cleared and eastern Australian forests have been reduced by more than a third of what they once were.

National Map

Use the National Map page to assess the amount of vegetation where you live. Use the Add Data button and search for the LAN29 Vegetation assets. How much of New South Wales appears to have been modified, transformed or replaced?

KEY CONCEPTS

- Agriculture generates greenhouse gases through the growth of ruminant animals, the application of fertilisers, the management of agricultural wastes and the processing of agricultural products.
- Land clearing generates greenhouse gas emissions through the burning and decay of cleared vegetation, changes to stored soil carbon and changes to surface conditions.

CHECK YOUR UNDERSTANDING 11.1B

1 Identify four ways in which agriculture contributes to greenhouse gas emissions.
2 Describe how ruminant animals generate the greenhouse gas CH_4.
3 Identify the greenhouse gases generated by the decomposition of animal manures.
4 Describe two ways by which land clearing leads to greenhouse gas emissions.
5 Outline how oxidation of carbon in soil generates CO_2.

11.2 Minimising greenhouse gas production in our daily lives

Households are directly and indirectly responsible for greenhouse gas emissions. In 2019, Australia's greenhouse gas emissions were a little less than 22 tonnes of CO_2 equivalent gases per person. You have already learnt that electricity generation accounts for a significant amount of greenhouse gas emissions (Figure 11.1). In households, electricity is used for a range of purposes (Figure 11.9), accounting for 61% of greenhouse gas emissions. The biggest single source of greenhouse gases is transport, which accounts for more than a third of a typical home's emissions.

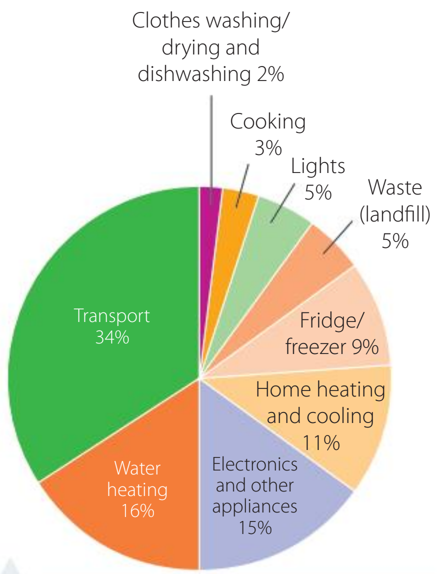

FIGURE 11.9 Household sources of CO_2 emissions

Transport emissions can be reduced by using a car less often and walking, cycling or catching public transport more. Choosing an electric car or a fuel-efficient vehicle reduces emissions and replacing a car less often saves emissions arising from the car's manufacture.

Heating or cooling homes combined with how water is heated accounts for more than a quarter of a typical family's greenhouse gas emissions. Attention to simple things can reduce energy and fuel costs as well as reduce greenhouse gas emissions. Slightly lowering the temperature when heating the house or raising the temperature on the air conditioner by 1–2°C results in less energy being used and therefore generates less greenhouse gases. Insulation in the roof and walls lets less heat in during summer and less heat out during winter. How we power our water heating can also reduce our emissions. Using solar power or solar hot water heating (Figure 11.10) does not create greenhouse gases, whereas using electricity from coal or gas to heat water does produce greenhouse gases.

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FIGURE 11.10 Solar-evacuated glass tube collectors generate hot water without producing greenhouse gases.

Evacuated tube collectors

Read how solar-evacuated glass tubes work and identify the pros and cons of this technology in providing hot water.

Energy rating labels

How do energy rating labels allow consumers to reduce greenhouse gas emissions and energy costs?

Plastic warms the planet twice as much as aviation

Create a mind map showing the sources of greenhouse gas emissions in plastic manufacture and use.

Electrical appliances and lighting account for a substantial proportion of a household's greenhouse gas emissions. Emissions can be reduced by providing power only when using the appliances and by buying energy-efficient appliances. In Australia, energy rating labels allow consumers to choose more energy-efficient appliances and reduce greenhouse gas emissions. It is important to remember that manufactured goods all have an energy cost in their production and an associated cost in greenhouse gas emissions.

A quarter of the world's greenhouse gas emissions arise from the production and consumption of food. More than half of this comes from animal products, particularly beef and dairy production (for reasons examined earlier in the chapter). In Australia, the meat and livestock industry is working to reduce its emissions, and between 2005 and 2016 the industry reduced emissions by approximately 58%.

Wastes also generate greenhouse gas emissions. Organic material in landfill generates CH_4 as it decays. The production of plastic packaging generates greenhouse gases and the plastic is an ecological hazard. Glass and paper have low energy densities compared with plastics or metals. This means that less fossil fuel is used in their production. Refusing unnecessary or inappropriate packaging helps to reduce greenhouse gas emissions.

Ultimately, our choices help to reduce greenhouse gas generation in our daily lives. We need to be conscious of where emissions come from and work to reduce our role in their production. Advocating for change, or supporting such advocacy, to all levels of government is important too.

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INVESTIGATION 11.2

Modifying your family's greenhouse gas emissions

What can individual families do to reduce the amount of greenhouse gases they contribute to the atmosphere?

Critical and creative thinking

Numeracy

Sustainability

Civics and citizenship

AIM

To estimate your household's greenhouse gas emissions and explore some ways to reduce them

HYPOTHESIS

Do you think that your household generates a similar volume of greenhouse gases to the average Australian family? Write your answer to this question as a hypothesis to test in this investigation.

MATERIALS

You will require access to one of the sites in the weblinks.

Greenhouse gas calculator
Integrated Sustainability Analysis research team at the University of Sydney

Australian Greenhouse Calculator

METHOD

1 Copy the table in the Results section.
2 Use a greenhouse calculator to estimate your household greenhouse gas emissions. Record your CO_2 emissions for each category and how they compare with an average household.
3 Add the volumes of CO_2 emissions for the categories and record the total for your household.
4 Use the total to calculate the percentage of emissions for each category.

RESULTS

Copy and complete this table.

SOURCE	AMOUNT OF CO_2 PRODUCED	HOW DOES THIS COMPARE WITH A TYPICAL HOUSEHOLD? (HIGHER/SIMILAR/LOWER)	PERCENTAGE OF TOTAL GREENHOUSE GASES
Transport			
Air travel			
House heating and cooling			
Hot water			
Clothes dryer			
Lighting			
Refrigerator			
Cooking			
Other appliances			
Food and shopping			
Total			

ANALYSIS OF RESULTS

1 Which source of greenhouse gases was the largest for your household?
2 How does your household compare overall with a typical household?

»

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3 Calculate the mass of CO_2 generated per person in your household by dividing total emissions by the number of people in your home.
4 If the average greenhouse gas emission for an average world citizen is about 7 tonnes per year, how much would your household have to reduce emissions to meet the global average?
5 Which sources of emissions would be the easiest to reduce? Why do you think this? How would you reduce the emissions?

DISCUSSION

1 Which sources provide the greatest amount of greenhouse gases in your household?
2 Could your household reduce annual greenhouse gas emissions by 10%? How could this be done?
3 Is it easier to improve energy efficiency or to reduce other sources of greenhouse gases in your home?

CONCLUSION

Outline how your family could minimise their contribution to the greenhouse effect.

KEY CONCEPTS

- Australian households generate large amounts of greenhouse gases through heating and cooling, transport, using electrical appliances and waste.
- Transport emissions can be reduced by more efficient cars, low-emission vehicles and using transport other than cars.
- Heating and cooling can be addressed through more efficient insulation, lower heating temperatures or higher cooling temperatures, and the use of renewable energy.
- Turning appliances off, buying appliances with high energy ratings and reducing their number reduces greenhouse gas emissions.
- Reducing household wastes, particularly plastics, and reducing organic material directed to landfill is a mitigation strategy that will reduce CO_2 emissions.

CHECK YOUR UNDERSTANDING 11.2

1 List the main sources of greenhouse gases in homes.
2 Describe how emissions due to transport can be minimised.
3 How can greenhouse gas emissions from heating and cooling our homes be reduced?
4 Why is reducing food waste going to landfill a way of reducing greenhouse gas emissions?
5 Describe three ways that your family can reduce their contributions to the greenhouse effect.

11.3 Assessment of mitigation and adaptation strategies

Australians can use a range of strategies to reduce greenhouse gas emissions and adapt to the effects of climate change. Strategies intended to prevent or reduce greenhouse gas emissions are called **mitigation strategies**. Strategies intended to reduce the impact of climate change due to greenhouse gas emissions are called **adaptation strategies**. For example, reducing electricity production by coal-fired power stations is a mitigation strategy, and changing planning rules to anticipate sea level change is an adaptation strategy.

Urban design

Urban design involves the arrangement, function and design of buildings, public spaces, transport systems, services and other amenities in towns, suburbs and cities. Cities account for about 70% of greenhouse gas emissions worldwide (Figure 11.11) and good urban design provides both mitigation and adaptation

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strategies for dealing with changing climate and greenhouse gas emissions. Mitigation strategies can include simple things such as the use of high-efficiency LED lights for street lighting or planning suburbs so that car use is reduced. This might be by placing workplaces closer to where people live or by providing convenient public transport. Four important issues that urban design can help us adapt to are changing rainfall patterns, increased bushfire risk, heat waves and the effects of rising sea levels.

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FIGURE 11.11 Night peak hour in Sydney. Lights and transport all increase our greenhouse gas emissions.

Changing rainfall patterns present problems for Australian towns and cities in two important ways. One is a reduction in rainfall and the other is how urban areas deal with intense rainfall events and possible flooding. Designing urban areas that reduce water use and store rainwater more effectively helps communities adapt to potential droughts. The design and planting of vegetated areas in suburbs reduces the area of hard surfaces and absorbs water, which reduces flash flooding. It is important to consider drainage in urban designs to reduce the risk of flooding. Incorporating wetlands in urban designs helps with this, improves the quality of stormwater and supports biodiversity within urban areas.

Getty Images/Purple Images

FIGURE 11.12 This building in Sydney is covered with plants. How might the plants modify the environment of the building?

Natural hazard events such as fires, heat waves and the consequences of rising sea levels can be accommodated to some degree by urban design. Designing suburbs to account for their location relative to potential fire corridors or areas of coastal flooding better adapts urban areas to extreme weather events. Planning so that emergency services can access areas and residents can leave areas is an adaptive strategy. Heat waves can be accommodated by planting trees to provide moisture and shade in built-up areas. This reduces the **urban heat island effect** created when concrete or metal surfaces absorb and re-emit the Sun's energy, increasing daytime and night-time temperatures in cities. Plants provide shade and absorb light so that it is not reradiated as heat (Figure 11.12).

Energy use in our homes can be reduced by energy-efficient architecture or passive design. Homes are major consumers of energy but attention to house orientation and insulation can significantly reduce the energy used to keep our homes comfortable. Orienting a house so that it faces north provides maximum exposure to the Sun during winter and allows for appropriate shading design in summer. Insulation of roofs and walls, together with reducing air leakages, reduces heating and cooling costs. What we build with is also an important source of both mitigation and adaptation strategies. Concrete slabs, water tanks and brick walls all have high **thermal masses**. This means that during winter they absorb heat during the day and emit it at night, moderating the temperature of a room or house. The thoughtful use of these materials is a mitigation strategy because it reduces energy use and the carbon emissions used to generate that energy. The use of thermal masses for passive heating and cooling is also an adaptation strategy because it helps us deal better with increasing temperatures. However, the materials themselves may have a greenhouse gas cost in their manufacture. Wood is a **carbon sink** because it stores carbon in its carbohydrate products such as cellulose and lignin, but concrete involves the production of CO_2 in its manufacture. Recycled steel has the same strength as newly created metal products but requires less energy for its manufacture than producing steel from iron ore. What we choose to build with has implications for greenhouse gas emissions.

Passive design – YourHome

Summarise five ways in which passive house design can reduce energy use and greenhouse gas emissions.

World Food Programme

Use the World Food Programme website to summarise the potential impacts of climate change on food security.

KEY CONCEPTS

- Mitigation strategies reduce or prevent the emission of greenhouse gases. Adaptation strategies prevent or reduce the effects of greenhouse gas emissions.
- Insulation, aspect, thermal mass and the use of low-energy materials produce houses and buildings that are energy efficient and generate less greenhouse gases.
- Urban design provides mitigation and adaptation strategies, addressing changing rainfall patterns, increased bushfire risk, heat waves and the effects of sea level rise.
- The design of urban areas to facilitate better public transport reduces greenhouse gas emissions, and attention to drainage mitigates against flooding from more intense rainfall events.

CHECK YOUR UNDERSTANDING 11.3A

1 What is the difference between a mitigation strategy and an adaptation strategy?
2 Identify three effects of global warming that urban design can help us adapt to.
3 Outline some of the ways in which better urban design can help us adapt to more intense rainfall events and sea level rise.
4 Explain why moving workplaces closer to where people have their homes is a greenhouse gas emission mitigation strategy.

Geo-engineering strategies

WS Worksheets Geo-engineering and climate change

Geo-engineering or climate engineering is the use of engineered interventions in a natural Earth system process to directly combat climate change. Geo-engineering technologies aim to reduce the amount of light reaching Earth's surface or reduce the amount of CO_2 in the atmosphere. Reducing the amount of light reaching the surface would reduce the amount of heat radiated into the atmosphere and limit atmospheric warming. Removing CO_2 will also reduce temperature increase because less CO_2 results in a smaller enhanced greenhouse effect.

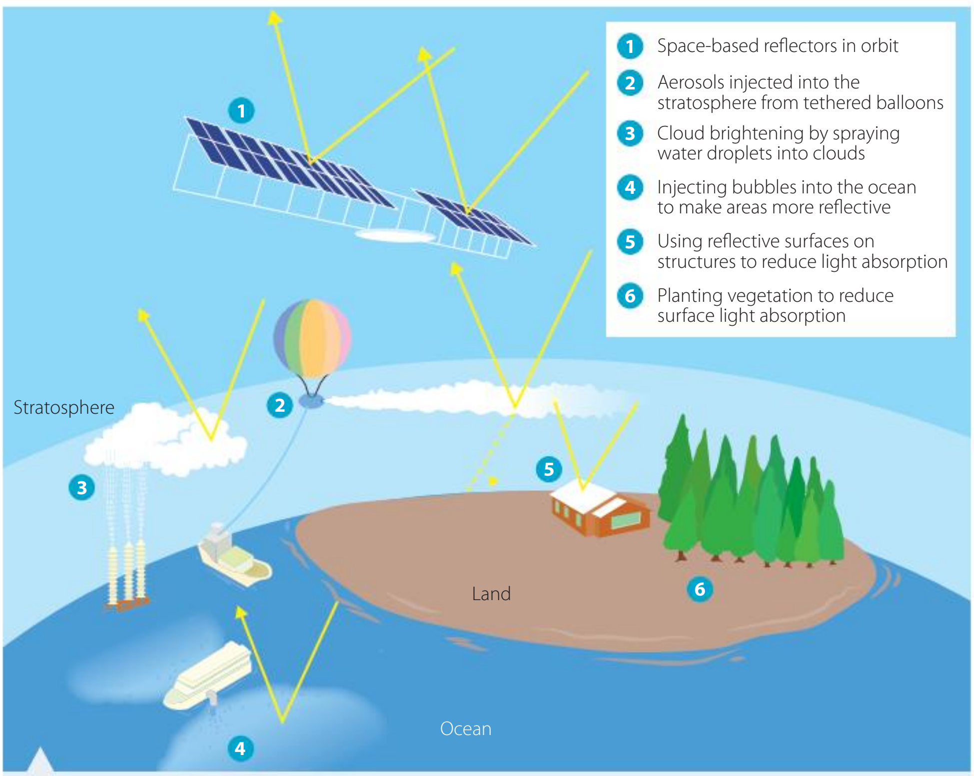

FIGURE 11.13 Six ways of potentially managing solar radiation by geo-engineering

Geo-engineering technologies are potential solutions for limiting the rate of atmospheric warming but no single method provides a complete solution. Uncertainties exist about their environmental impacts, how quickly they can be implemented, and the costs involved. None of the geo-engineering methods described in this section has been proven to work on a large scale and there are legal issues with their deployment because these technologies act on large areas across international boundaries.

Solar radiation management aims to reduce the amount of light entering Earth's atmosphere (Figure 11.13). One method involves injecting large numbers of reflective aerosol particles into the upper atmosphere. The mechanism

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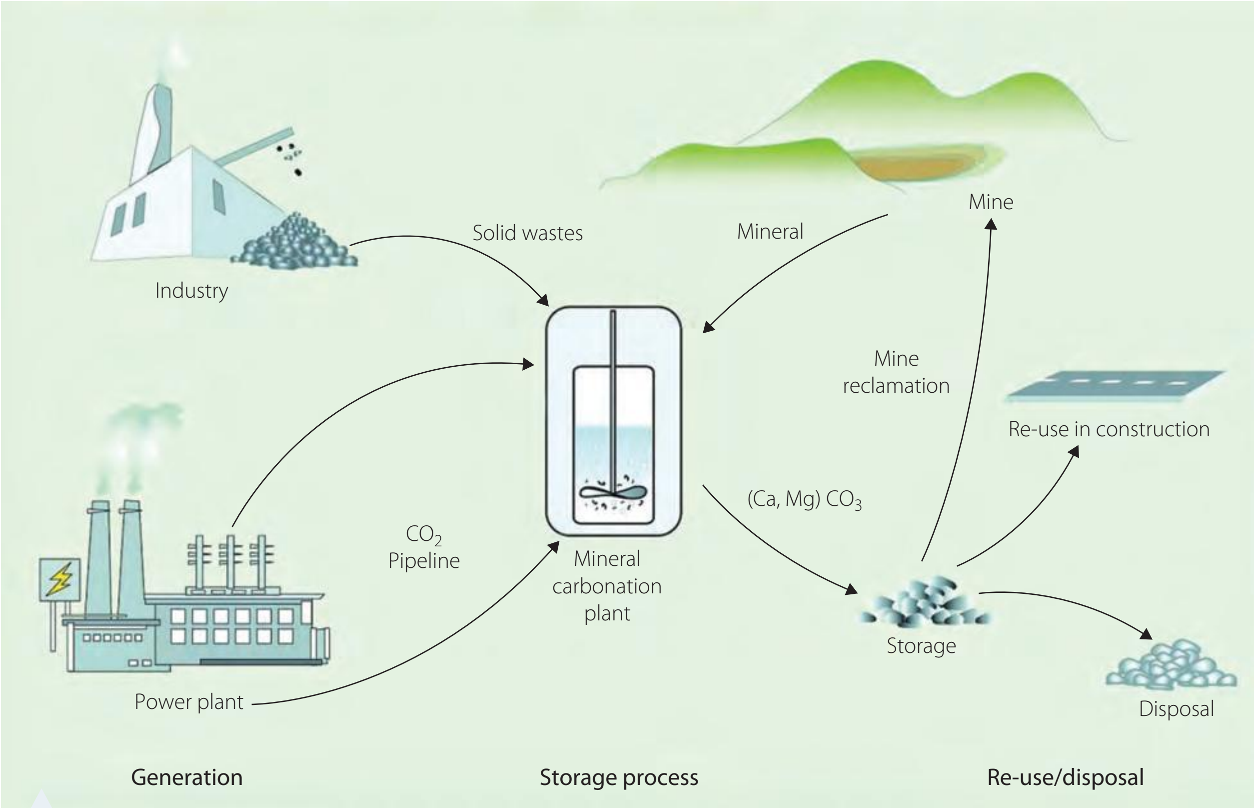

FIGURE 11.14 The mineral carbonation process using serpentinite

Figure TS-10 from IPCC 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

is the same as that observed in the global cooling caused by massive volcanic eruptions such as the 1815 Tambora eruption. Sulfate aerosols enter the upper atmosphere and reflect sunlight, causing surface cooling.

While solar radiation management would reduce the amount of light reaching Earth's surface, there are disadvantages in using the technology. Natural aerosols are usually removed from the upper atmosphere in 2–3 years so the introduction of aerosols would have to be periodically repeated. This would add to the expense of the intervention. There is also some scientific debate on the effect of light reduction on the productivity of important crops such as rice and wheat. Some scientists are also concerned that the reduction in light could alter rainfall patterns, the aerosols might damage the ozone layer and the effects on phytoplankton might change ocean ecosystems.

Removing CO_2 from the atmosphere and storing it in Earth is called **carbon sequestration**. This can be relatively simple, such as planting more trees to absorb CO_2, or more technologically sophisticated such as **mineral carbonation** (Figure 11.14), which mimics the long-term weathering of rocks. Each method has its advantages and disadvantages. For example, tree planting requires large areas of land and there are uncertainties in how much CO_2 different tree species store at different ages and in different climates. However, tree planting is relatively cheap, benefits biodiversity and produces a valuable building resource.

You will study methods of carbon sequestration in more detail in Investigation 11.3.

Mineral carbonation

Read the document on mineral carbonation to outline how the process of mineral carbonation works. Discuss the advantages and disadvantages of mineral carbonation.

INVESTIGATION 11.3

Critical and creative thinking

Ethical understanding

Sustainability

Evaluating methods of capturing and storing carbon

AIM

To evaluate methods of removing CO_2 from the atmosphere and storing it

PROCEDURE

1 Read the article by science writer Mary Hoff at the weblink *Carbon sequestration*.
2 Identify three methods you wish to study further.
3 Create a table to record how much carbon the method might remove per year, strengths, weaknesses, uncertainties and how well the method would work where you live.
4 Complete the table using the article.
5 Verify the information by conducting an Internet search on each of your three methods. Add any information you think relevant from your additional sources.

Carbon sequestration
Read Mary Hoff's *Ensia* article on carbon capture and storage methods.

DISCUSSION

1 Some of the methods are energy intensive. How does this affect the amount of CO_2 in the air?
2 Do all the methods have the potential to work where you live? Give reasons for your answer.
3 Write an evaluation of the methods you have researched. Remember to make a value judgement after comparing the strengths and weaknesses of each method as immediate and effective answers to climate change.
4 How reliable is the information you have studied? Use the Currency, Relevance, Authority, Accuracy and Purpose (CRAAP) test as a scaffold for your answer. Further information on this test is provided in the weblink *CRAAP test*.

CRAAP test
Use the questions to help you analyse the reliability of information.

CONCLUSION

Is carbon capture and storage the best answer to reducing global climate change?

KEY CONCEPTS

- Geo-engineering describes large-scale projects that seek to modify Earth's natural systems
- Geo-engineering may remove CO_2 from the atmosphere or aim to limit the amount of sunlight reaching Earth's surface.
- Solar radiation management and carbon sequestration are examples of geo-engineering technologies and each has advantages and risks.

CHECK YOUR UNDERSTANDING 11.3B

1 What is meant by geo-engineering solutions for climate change?
2 Identify two geo-engineering strategies for reducing rising global temperatures.
3 Describe two methods of solar radiation management.
4 Explain how carbon sequestration reduces CO_2 levels in the atmosphere.
5 Create a flowchart to show how a method of carbon sequestration works.

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Alternative energy sources

Alternative energy sources are those other than fossil fuels. Some alternative energy sources, such as uranium, are **non-renewable** resources. Non-renewable resources take a long time to form or are concentrated under conditions that are now rare. As a result, they are consumed faster than they are replaced and so their availability decreases over time. Many alternative energy sources are **renewable** – they are replaced rapidly and are not likely to be exhausted.

Worksheets
Alternative energy sources

Most alternative energy sources, except **bioenergy** sources, do not produce greenhouse gases in generating useful energy (Table 11.6), but they generate greenhouse gases in their production. Some photovoltaic cell manufacturers estimate that approximately 190 tonnes of CO_2 greenhouse gas emissions are produced for every megawatt of solar panels they produce. Building a hydroelectric facility or a wind turbine generates greenhouse gases during mining, manufacture and construction. Many alternative energy plants cannot generate energy on the scale of fossil fuel power stations but they can be built close to where energy is needed and large amounts can be added to the electricity grid.

Currently in Australia, bioenergy generates the largest share of renewable energy but solar radiation, wind and hydroelectricity account for more than 30% of the energy consumed. During 2016–2017, these alternative energy sources showed the greatest rate of growth. Some alternative energy sources, such

TABLE 11.6 Some alternative energy sources

TYPE	ULTIMATE SOURCE OF THE ENERGY	GREENHOUSE GAS GENERATED IN ENERGY PRODUCTION	CURRENT USE IN AUSTRALIA	AUSTRALIAN PROPORTION OF RENEWABLE ENERGY CONSUMPTION 2016–2017 (%)	RENEWABLE
Solar heat	Radiation from the Sun	No	Yes	4.2	Yes
Solar electricity	Radiation from the Sun	No	Yes	7.7	Yes
Wind power	Radiation from the Sun	No	Yes	12.0	Yes
Wave power	Radiation from the Sun	No	No	0	Yes
Tidal power	Gravitational energy from the moon and the Sun	No	No	0	Yes
Hydroelectricity	Gravitational potential energy in stored water	No	Yes	15.5	Yes
Geothermal power	Heat energy stored within Earth	No	No	0	Yes
Nuclear fusion	Conversion of mass into energy when two atomic nuclei are fused	No	No	0	Yes
Nuclear fission	Conversion of mass into energy when an atomic nucleus splits apart	No	No	0	No
Hydrogen gas	Chemical potential energy	No	No	0	Yes
Biomass	Chemical potential energy	Yes	Yes	54.2	Yes
Biogas	Chemical potential energy	Yes	Yes	15.0	Yes
Biofuels	Chemical potential energy	Yes	Yes	7.1	Yes

Capacity is the maximum energy a power source can generate at some point in time and is measured in megawatts (MW). Energy generated is measured in kilowatt hours (kWh) or megawatt hours (MWh).

as tidal, wave and geothermal power, are not currently used in Australia although there is a great deal of potential for their use. Alternative energy technologies do not generate as much energy as a coal-fired power station but having a large number of distributed and varied alternative energy technologies may provide the energy we require.

Solar technologies

Solar technology produces no greenhouse gases during operation. Australia receives vast amounts of solar radiation each day but not all areas are equally good for generating electricity or heat. A photovoltaic cell generates electricity in proportion to the intensity of light that falls on the cell. Light intensity is greater when the Sun is high in the sky than when it is lower in the sky. Latitude affects the angle at which sunlight falls on a panel and the angle also changes with the seasons and the time of day. Areas that have more cloudy days produce less electricity than similar but less cloudy sites.

Getty Images/Fabian Fortmann/EyeEm

FIGURE 11.15 The PS10 and PS20 solar power plants at Seville, Spain, use heliostats – movable mirrors.

Shutterstock.com/John Carnemolla

FIGURE 11.16 Solar farms are best located in areas where sunshine is intense and regular, such as this one in Toowoomba, Queensland.

Three generation technologies currently use solar radiation. **Thermal solar power** involves converting solar radiation into heat. This technology is used to supply hot water in some homes. Large-scale solar thermal power systems use mirrors to concentrate solar radiation and generate heat. Steam is produced to drive turbines and generators, producing electricity. Figure 11.15 shows two solar power plants near Seville in Spain. The many large movable mirrors called **heliostats** focus the light on the towers and generate 71.4 GWh of energy per year. The Bayswater coal-fired power station in the Hunter Valley by comparison produces 17 000 GWh of energy per year but consumes 8 million tonnes of black coal to do so.

Photovoltaic cells convert light into electricity using two thin layers of silica crystal with different properties in close contact with each other. Light causes electrons to move away from the junction of the two layers and creates a voltage between the top and bottom layers. Large currents require large surface areas; **solar farms**, consisting of hundreds of panels, provide commercially important amounts of electricity to the electricity grid. The solar farm shown in Figure 11.16, located near Toowoomba in Queensland, is the first stage of an 80 MW farm. Large solar farms in New South Wales include one near Nyngan with a **capacity** of 102 MW and another near Coleambally with a capacity of 150 MW. In 2017, New South Wales generated 4314 GWh of electrical energy using solar technologies.

NSW Renewable Energy

Examine the map from the New South Wales Government Department of Planning and Environment to identify the range and distribution of alternative energy sources in the state. Where are wind and solar farms concentrated in the state?

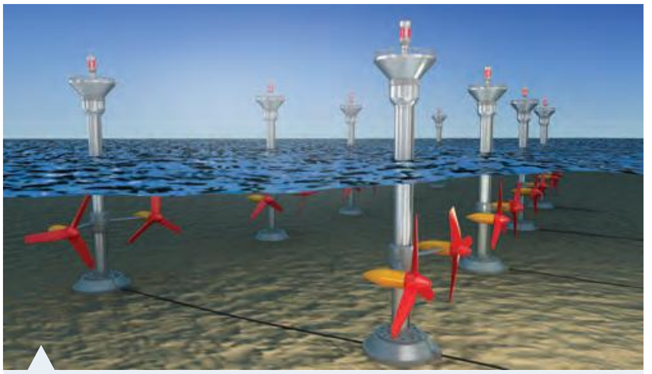
Wind power

Wind turbines transform the kinetic energy of moving air into electricity. There are different types of wind turbine, some suitable for individual homes and others suitable for generating commercial-scale electricity. Not all areas have suitable wind conditions. In New South Wales, the most consistent winds occur near the top and on the western side of the Great Dividing Range. Ocean-based turbines along the east coast have great potential due to wind consistency. Electricity from a wind turbine network could be linked into the electricity grid existing along the coast. At present, wind generation is land based. In 2017, wind generation supplied more than 1900 GWh of energy.

Wave and tidal energy

The moving water in waves and tides contains a lot of energy. Wave energy generally increases with distance from the coast, and tide heights vary around Australia. The southern coast of Australia has strong wave action and tides at areas such as the North West Shelf rise more than 8 metres.

Wave power systems can be fixed or float in deep water. Floating systems are most common worldwide. The disadvantages of floating systems are the difficulties in transmitting the energy they generate to the grid and issues with servicing the generators. Also, tethered wave generators can be damaged by extreme weather events.



Shutterstock.com/Alex Mit

FIGURE 11.17 A tidal stream system

There are several types of tide generators. **Tidal stream systems** resemble wind generators situated on the ocean floor (Figure 11.17). As water flows over the propellers, generators transform the kinetic energy into electricity. This technology can also operate in ocean currents. A **tidal barrage** is a dam-like structure with a turbine at the base. As water rises against the barrage, panels called sluice gates are raised and water flows through pipes to turbines that drive electricity generators. When the tide recedes, the mechanism can operate in reverse.

Nuclear power

Australia has the largest reserves of uranium in the world and is the third biggest producer of uranium in the world. Nuclear power generates electricity by using heat. In **nuclear fission**, atoms break apart, releasing energy as some of their mass is converted into energy (Figure 11.18a). In **nuclear fusion** the nuclei of hydrogen atoms are combined under immense pressures, converting mass into energy (Figure 11.18b). In both cases, heat derived from the energy released is used to generate electricity using turbines.

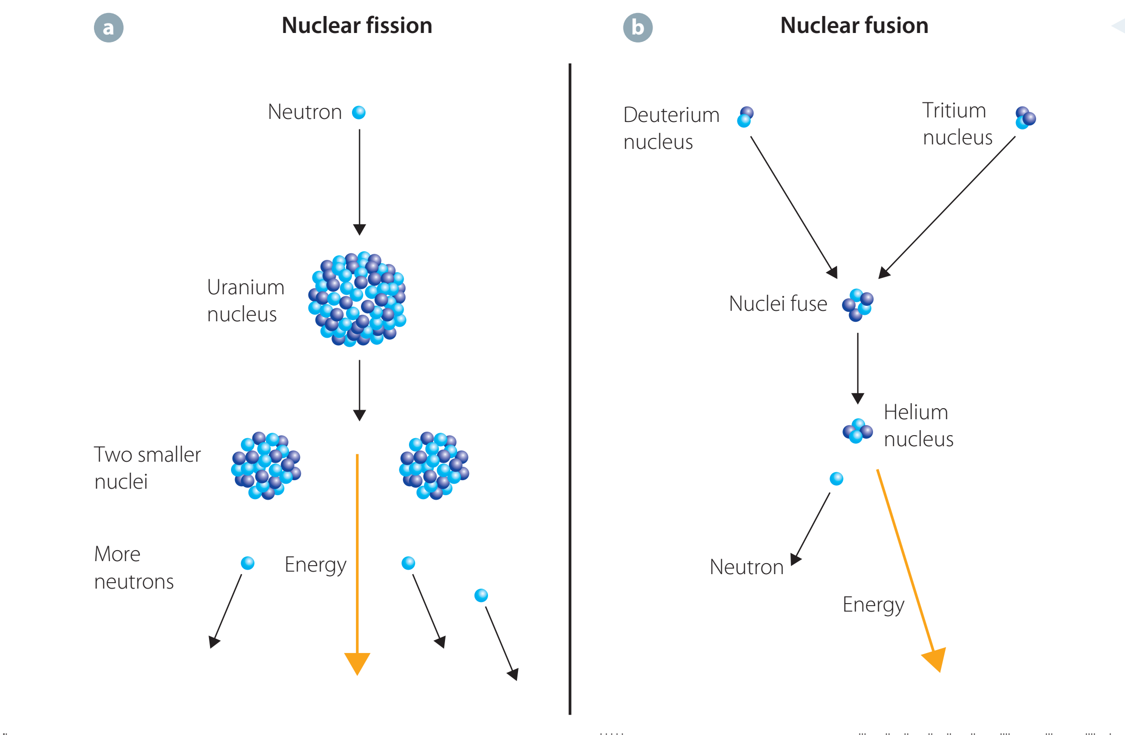


FIGURE 11.18 **a** A fast-moving neutron strikes a uranium nucleus and produces two smaller nuclei, neutrons and energy. **b** Deuterium and tritium nuclei fuse to produce a helium nucleus, a neutron and energy.

Nuclear power plants using fission produce approximately 11% of the world's electricity. Building nuclear power plants generates greenhouse gases but their operation does not. Most operating reactors have electricity capacities between 1 and 8 GW. Nuclear power is expensive to produce and other alternative energy sources can provide electricity more cheaply. There are also issues with nuclear waste. Spent fuel and materials in reactors are radioactive and need to be stored safely for very long periods. Radioactive contamination causes cancer and radiation sickness. Soils can become infertile and many organisms suffer mutations when exposed to radioactive materials.

Hydroelectric power

Hydroelectric power involves the generation of electricity using flowing water that has been stored in dams. The water drives turbines and electricity generators in hydroelectric power stations. The Snowy Mountains Scheme is Australia's largest hydroelectric power system and was built between 1949 and 1974. It has a capacity of 3.77 MW. To provide the water for the power stations, the scheme uses 16 dams that store water from the Snowy River system. About 2100 GL of water are released westward each year to support agricultural irrigation.

Pumped hydroelectric storage is a method of storing energy by pumping water from a lower elevation dam to a higher elevation one. During times of high demand for electricity, the water is released through pipes down to turbines in hydroelectric power stations to generate energy (Figure 11.19).

Changing rainfall patterns due to climate change could affect the volume of water available for hydroelectricity production. There are also environmental issues arising from building dams. Changed flow affects downstream river systems and can restrict water to natural ecosystems without suitable management.

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FIGURE 11.19 These water pipes deliver water down to a hydroelectric power station at Tarraleah in Tasmania.

Alamy Stock Photo/imageBROKER

FIGURE 11.20 These egg-shaped digestion towers in Hamburg, Germany, generate 90 000 tonnes of CH_4 each day, which generates 268 GW of electricity and heat.

Bioenergy

Bioenergy is the energy derived from the combustion of organic material to generate heat or electricity. **Biomass** is biological material used as fuel. In Australia, burning **bagasse**, the remains of sugarcane processing, accounts for approximately 60% of Australia's bioenergy. The type of biomass used depends on location. In and around Sydney, waste is used to produce bioenergy. **Biogas** is gaseous fuel, such as CH_4, produced by the fermentation of organic material. Such gas can be generated as a by-product of wastewater treatment (Figure 11.20). At Lucas Heights in Sydney, three bioenergy power stations use CH_4 gas from landfill to produce a capacity of 21.5 MW. **Biofuel**, fuel derived from organic material, includes substances such as ethanol and biodiesel. Used cooking and vegetable oil is reacted with methanol to produce biodiesel, and the fermentation of sugar or starch generates ethanol.

Bioenergy use reduces the rate of greenhouse gas emissions. Bioenergy uses organic material produced when photosynthesis removes CO_2 from the air. Generating bioenergy returns that CO_2 to the atmosphere. When a fossil fuel is burned, we add additional CO_2 to the atmosphere: a one-way transfer. Land clearing to grow bioenergy fuels contributes to greenhouse gas emissions.

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KEY CONCEPTS

- Alternative energy sources may reduce the amount of greenhouse gas emissions due to fossil fuel burning and create greater efficiency in the use of energy produced.
- Alternative energy sources include hydroelectric, nuclear, wind, wave, photoelectric and geothermal power.
- All alternative energy sources have advantages and disadvantages in relation to their impacts on the environment.

CHECK YOUR UNDERSTANDING 11.3C

1 Define 'alternative energy source'.
2 Describe three alternative energy sources that do not produce greenhouse gases in their operation.
3 Outline how pumped hydroelectricity is a method of storing energy from alternative energy sources such as wind or photovoltaic cells.
4 Outline the advantages and disadvantages of nuclear materials and wind as sources of alternative energy.

Agricultural practice changes

Changing agricultural practice can mitigate greenhouse gas emissions. While globally about a third of greenhouse gases are generated by the systems that produce our food, land-based ecosystems absorb about a fifth of those emissions. The careful management of land can reduce emissions and perhaps boost the amount of greenhouse gases that pastures and forests absorb. Earlier in the chapter, you learnt that agriculture generates more than 10% of Australian emissions and is energy intensive. Eating less red meat and wasting less food mitigate agricultural greenhouse emissions. Reducing the energy-intensive nature of modern farming and land clearing will help mitigate greenhouse gas production in agriculture.

We also need to anticipate and adapt to key impacts that climate change will have on agriculture. Rising temperatures will increase heat stress for animals and plants on farms and lead to changes in the suitability of regions for certain types of agriculture or crops. The predictability of seasons and rainfall will decrease over time. Extreme weather events such as fires and floods may increase crop and stock losses. The distribution of disease outbreaks may change and their severity may be increased by the effects of higher temperatures on livestock and crops.

iStock.com/hypedesk

FIGURE 11.21 How will outback grazing be affected by a warming climate?

Agricultural practices that maintain or improve soil quality and use less water are important adaptation strategies. Planting legume crops, recycling crop wastes and manure into soils, **no-till farming**, and the use of **biochar** are all methods of holding carbon in the soil and improving soil fertility without the use of fertilisers that generate greenhouse gases. Increasing the biodiversity of a farm also maintains nutrients in the soil. As rainfall becomes less frequent, the selection of crops, the maintenance of wetlands and avoiding evaporation will be important conservation methods.

Dealing with the effects of higher temperatures will be critical for maintaining agricultural productivity. Our standard of living is sustained by agricultural exports, which help to feed Earth's growing population. A drop in agricultural productivity will affect both these things. The development of heat-adapted crops and the relocation of crops to more suitable cooler climates are adaptation strategies. Some winemakers have already transferred vineyards to cooler Tasmania. In New South Wales, drier inland cropping areas are experiencing lower productivity due to climate change and there is some evidence that the zone suitable for crops, the **cropping belt**, is moving south. Productivity losses in the livestock industry due to heat stress may be worth billions of dollars. Heat stress on animals causes them to eat less and their breeding rates can decrease (Figure 11.21). Scientific research on increased pasture productivity, genetics for livestock that deal better with heat and feed supplements is trying to address this issue.

INVESTIGATION 11.4

Aboriginal and Torres Strait Islander histories and cultures

Critical and creative thinking

Intercultural understanding

Sustainability

Seasonal calendars and Indigenous agriculture

In northern Australia, many Aboriginal peoples have developed an understanding of seasonal change and ecology that allows them to manage their country in a sustainable and efficient way. In this investigation, you will examine an example of this seasonal ecological knowledge to understand how the knowledge contributes to sustainable land management practices.

METHOD

1. Copy the table in the Results section.
2. Access the weblink *About the Indigenous seasons calendars* and select one of the seasonal calendars.
3. List the calendar seasons of your Indigenous calendar.
4. Next to each season, write the months (January, February etc.) of the season.
5. Identify and summarise the weather changes that characterise the season.
6. Record the features of the vegetation for each season, including when it is burned.
7. Record the animals available for food during this season.
8. Use your information to identify the key foods targeted during the season.

About the Indigenous seasons calendars

RESULTS

Copy and complete this table. You will need as many rows as there are seasons. Make your columns wide enough to write as much information as you can.

»

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ABORIGINAL OWNERS OF THE KNOWLEDGE					
LOCATION					
MONTHS	CALENDAR SEASON	WEATHER PATTERNS	CONDITIONS FOR VEGETATION	CONDITIONS FOR ANIMALS	PRINCIPAL SOURCES OF FOOD

ANALYSIS OF RESULTS

1 Identify the weather conditions during which fires are started to burn the vegetation.

2 Describe the weather conditions when the fires are made and the conditions in the following season.

3 Describe two relationships between weather conditions and the behaviour of animals used as food.

4 How would knowledge of food availability influence the movement of Indigenous people over their country?

5 Assess the diversity of food eaten by the Indigenous people.

6 How does targeting different species in different seasons help to make food sustainable?

7 Based on the information you have gathered, do Indigenous people only hunt and gather food or do they actively manage their country? Justify your answer.

8 Explain why an Indigenous seasonal calendar in northern Australia would not be the same as one in southern New South Wales.

DISCUSSION

1 Are Indigenous seasonal understandings valuable tools for sustainably managing the areas where they have developed?

2 What might modern agricultural scientists learn about fire management from Indigenous seasonal calendars?

3 Assess Indigenous seasonal calendars as a guide to modern land management practices.

To develop successful mitigation and adaptation strategies for increasing temperatures, we might need to adopt the practices of some cultural groups and modify the practices of others. A cultural group is a group that shares a common identity based on social and cultural practices passed from one generation to another. If we are to understand how changing sea levels might affect agriculture and aquaculture, we might benefit from tribes in Bangladesh who have learnt to cope with these issues over thousands of years. Similarly, in the Middle East, methods for accessing irrigation water through building underground channels called quanats have existed for more than 2000 years. Might this technology change how Australian farmers think about water security for their farms? Australian farmers are also a cultural group. Earlier in this chapter, you examined the importance of making agriculture more sustainable through modifying fertiliser and energy use. Many farmers are already making progress towards sustainable farms and improved carbon sequestration.

Aboriginal plant use

Use this page from the Australian National Botanic Gardens to summarise information on some of the plants used sustainably by Aboriginal people across Australia.

Australia's Indigenous people have acquired a deep understanding of living in the variable Australian climate over many tens of thousands of years. They have developed a deep knowledge of their environment and sophisticated and sustainable agricultural systems suited to where they lived. Indigenous people use **mosaic burning** to maintain food stocks and systematically sowed and stored food. Mosiac burning is the burning of small areas at the correct time of day. The Indigenous people widely cultivated the yam daisy (*Microseris lanceolata*) called murnong or nyamin, in Victoria and the south coast of New South Wales. Many native grass species, including *Themeda triandra*, *Panicum laevinode*, *Trigonella suavissima*, *Themeda arborea* and *Sorghum leiocladum* were cultivated by Aboriginal people in Australia for tens of thousands of years. Some of these native grasses survive well in arid conditions, and their adoption by modern agriculture may help cropping adapt to changing rainfall and temperatures.

Aboriginal and Torres Strait Islander peoples have a long history in maintaining sustainable fisheries. The Gunditjmara people, of what is now south-west Victoria, created ponds, wetlands and weirs to create a sustainable aquaculture system that supported large numbers of people. One of the eel traps near Lake Condah has been carbon dated as being more than 6500 years old. Managing wetlands and technologies such as stick weirs in the Macquarie Marshes and stone weirs at Brewarrina were also used by Aboriginal people to harvest fish. The use of seasonal knowledge allowed Aboriginal people to harvest fish and other species at appropriate times. This meant that resources were not depleted and had time to recover as the people changed their focus on what they hunted or gathered. Torres Strait Islander people have a deep understanding of the biology and ecology of the animals they harvest. This understanding determines when they catch food and the types of food they target. The seasonal selection of food also created diverse and healthy diets as well as sustainable food reserves.

Getty Images/ Jason Edwards

FIGURE 11.22 Controlled burns such as this in Kakadu National Park, Northern Territory, reduce fire risk and have positive effects on the native vegetation.

Mosaic burning creates outcomes that sustainable agriculture practices also seek to achieve. Burning small areas maintains biodiversity, maintains soil cover and reduces the chances of large damaging fires that rob carbon from the soil (Figure 11.22). Indigenous people in arid areas also work to maintain water supplies for themselves and for wildlife. All of these practices can teach us about ways of maintaining food productivity in a hotter and drier world.

KEY CONCEPTS

- Changing agricultural practices and our diets can reduce greenhouse gas emissions.
- Agricultural practices that maintain or improve soil quality and use less water are important adaptation strategies.
- Development of heat-adapted crops and relocation of cropping areas to cooler climates may help Australian farmers to maintain our food supply and food quality.
- Indigenous Australians have important knowledge about living in a variable climate, which is derived from their intimate knowledge of the country they live in.
- Cultural groups globally and within Australia have knowledge that may contribute to better agricultural practices in a warmer world.
- The land management practices of Indigenous Australians maintained forests and allowed access to seasonal food sources, enabled water conservation and encouraged carbon sequestration.

CHECK YOUR UNDERSTANDING 11.3D

1. Describe two ways that increasing temperatures will affect agriculture.
2. Outline two agricultural practices that are adaptation strategies to climate change.
3. Describe three Aboriginal land management practices that may help agriculture adapt to or mitigate climate change.

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11 CHAPTER SUMMARY

- Australians live in an energy-intensive society that relies on burning greenhouse gas producing fossil fuels for its energy.
- In Australia, greenhouse gases are predominantly generated in the production of electricity, the generation of steam and heat, and transport.
- Society's use of fossil fuels has increased throughout history as populations have grown, society has become more complex, and our lifestyles have required greater amounts of energy.
- When fossil fuels are used, a lot of energy is lost because of the inefficiency of devices and transmission.
- Agriculture generates greenhouse gases through the growth of ruminant animals, the application of fertilisers, the management of agricultural wastes, and the processing of agricultural products.
- Land clearing generates greenhouse emissions through the burning and decay of cleared vegetation, changes to stored soil carbon and changes related to changed surface conditions.
- Australian households generate large amounts of greenhouse gases through heating and cooling, transport, using electrical appliances, and wastes.
- Transport emissions can be reduced by more efficient cars, low-emission vehicles and by using transport other than cars.
- Heating and cooling can be addressed through more efficient insulation, lower heating temperatures or higher cooling temperatures, and the use of renewable energy.
- Turning appliances off, buying appliances with high energy ratings and reducing their number reduces greenhouse emissions.
- Reducing household wastes, particularly plastics, and reducing organic material directed to landfill is a mitigation strategy that will reduce our CO_2 emissions.
- Mitigation strategies reduce or prevent the emission of greenhouse gases. Adaptation strategies prevent or reduce the effects of greenhouse gas emissions.
- Insulation, aspect, thermal mass and the use of low-energy produced materials produce houses and buildings that are energy efficient and generate less greenhouse gases.
- Urban design provides mitigation and adaptation strategies, addressing changing rainfall patterns, increased bushfire risk, heat waves and the effects of sea level rise.
- The design of urban areas to facilitate better public transport reduces greenhouse gas emissions and attention to drainage mitigates against flooding from more intense rainfall events.
- Geo-engineering describes large-scale projects that seek to modify Earth's natural systems.
- Geo-engineering may remove CO_2 from the atmosphere or aim to limit the amount of sunlight reaching Earth's surface.
- Solar radiation management and carbon sequestration are examples of geo-engineering technologies and each has advantages and risks.
- Alternative energy sources may reduce the amount of greenhouse emissions due to fossil fuel burning and create greater efficiency in the use of energy produced.
- Alternative energy sources include hydroelectric, nuclear, wind, wave, photoelectric and geothermal power.
- All alternative energy sources have advantages and disadvantages in relation to their impacts on the environment.
- Changing agricultural practices and our diets can reduce greenhouse gas emissions.
- Agricultural practices that maintain or improve soil quality and use less water are important adaptation strategies.
- Development of heat-adapted crops and relocation of cropping areas to cooler climates may help Australian farmers to maintain our food supply and food quality.
- Indigenous Australians have important knowledge about living in a variable climate, which is derived from their intimate knowledge of the country they live in.
- Cultural groups globally and within Australia have knowledge that may contribute to better agricultural practices in a warmer world.
- The land management practices of Indigenous Australians maintained forests and allowed access to seasonal food sources, enabled water conservation, and encouraged carbon sequestration.

11 CHAPTER REVIEW QUESTIONS

Review quiz

1 Describe how land clearing contributes to the enhanced greenhouse effect.

2 Explain how burning fossil fuels for energy has contributed to the enhanced greenhouse effect.

3 Why is planting forests a form of carbon sequestration?

4 **a** How has growth in the world population contributed to human use of fossil fuels?

b Explain two ways in which your lifestyle depends on the use of energy produced by burning fossil fuels.

5 Summarise four ways in which cars contribute to the anthropogenic greenhouse effect.

6 **a** Why do gas turbines in coal-fired power stations only convert about 40% of energy in coal to electricity?

b Assess the value of research into increasing the efficiency of devices in reducing greenhouse gas emissions.

7 Compare wood and crude oil in terms of their energy and CO_2 emissions.

8 Create a table to identify and describe the ways in which agricultural practices generate greenhouse gases.

9 Assess the removal of ruminant animals as a way of reducing greenhouse gas emissions.

10 How can changes to a home's structure reduce greenhouse gas emissions?

11 Organic material in landfill gives rise to greenhouse gases. Outline methods of mitigating these emissions.

12 How might the design of a suburb adapt the area to sea level rise or stormwater flooding?

13 Compare carbon sequestration with long-term weathering of rocks as a method of removing CO_2 from the atmosphere.

14 Outline possible benefits and risks in using geo-engineering to reduce the amount of light falling on Earth's surface.

15 Compare hydroelectricity generation and solar farms as ways of mitigating greenhouse gas emissions.

16 Explain the importance of improving soil quality and minimising water use as adaptations to a warming environment.

17 Indigenous Australians have used fire to manage the environment for thousands of years. Explain this practice as an adaptation to increased bushfire risk and soil management.

18 You have been asked to speak about ways that students in your school can reduce CO_2 emissions at home.

a Describe the three most important methods you would use in your talk.

b Assess the importance of your methods in reducing greenhouse gas emissions.

19 Evaluate methods of geo-engineering and urban design as ways of mitigating greenhouse gas emissions.

20 Analyse the reasons we burn so much fossil fuel and outline ways by which we can obtain the energy we need while reducing greenhouse gas emissions.

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Answer the following questions.

1 **a** Draw a diagram to show how solar radiation and greenhouse gases contribute to warming the Earth's lower atmosphere.

b The greenhouse effect model adapts rapidly to changes in parts of the model, but in the past climate has changed slowly over thousands or millions of years. Explain why rapid adjustments in the greenhouse model can lead to slow rates of climate temperature change.

2 Over the last 300 000 years, CO_2 levels and global temperature have varied in similar ways, but over the past 450 million years, global average temperature has not changed in the same way as CO_2 levels.

a Identify a factor other than CO_2 that can affect global climate temperature.

b Assess the role of a cause of natural climate variation, other than CO_2, that operates over long periods of time.

3 Plate tectonic supercycle changes climate on a timescale measured in hundreds of millions of years.

a Explain why supercontinent formation and break-up leads to climate change.

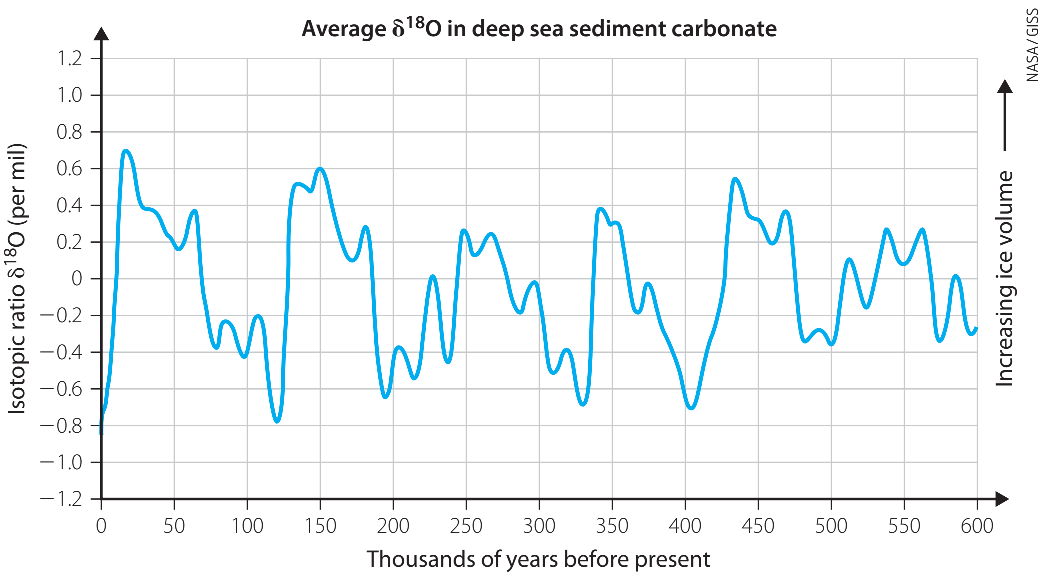
b Contrast the timescale of climate change by the plate tectonic supercycle with the timescale of changes caused by massive volcanic eruptions and changes in the Earth's orbital behaviour.

4 The graph below shows variations in $\delta^{18}O$ (the ratio of oxygen-18 to oxygen-16 isotopes) in deep ocean sediments over the last 600 000 years.

a Why do high $\delta^{18}O$ values indicate warm conditions?

b Suggest a reason for the periodic rise and fall in the $\delta^{18}O$ values.

c Describe two other sources of oxygen isotopes that have been used to describe ancient and recent climate variation.



5 Copy and complete the following table.

TYPE OF EVIDENCE	NATURE OF EVIDENCE	RECENT EVIDENCE OF CLIMATE CHANGE
Dendrochronology		
Aboriginal art sites		
Human instrumental records		
Isotopes from cave deposits and corals		

6 Evaluate the role of oxygen isotopes and gas bubbles from ice cores as scientific evidence of anthropogenic greenhouse effects since the industrial revolution.

7 **a** Explain the difference between the natural and anthropogenic greenhouse effects.

b Name and describe the sources of three greenhouse gases produced by human activity.

8 The table below summarises ocean CO_2 concentrations and pH measurements for an area in the central Pacific Ocean.

YEAR	2004	2006	2008	2010	2012
CO_2 CONCENTRATION (ppm)	345	356	360	363	370
pH	8.10	8.09	8.07	8.08	8.07

a Use the data in the table to draw a graph. Draw a line of best fit for the CO_2 data and for the pH data.

b Explain why a change in CO_2 concentration causes a change in the pH of the ocean.

c Describe the effects of ocean acidification on the ocean environment.

9 Increasing global temperatures produce important flow-on effects. Describe the nature and consequences for society and the environment of changes in ice distribution and changing weather patterns.

10 Each year around the world, an area larger than Tasmania is cleared of forests. Much of the land clearing is for agriculture.

a Describe two ways in which land clearing contributes to the enhanced greenhouse effect.

b Evaluate agriculture as a cause of the enhanced greenhouse effect.

11 Assess three ways in which Australians can minimise their contribution to the greenhouse effect in their daily lives.

12 Discuss the scientific evidence for mitigation and adaptation strategies for responding to increased global temperatures.

13 Burning fossil fuels for energy is a major source of greenhouse gases. Describe the sources of these greenhouse gases and ways by which society can reduce greenhouse emissions related to fossil fuel use.

DEPTH STUDY SUGGESTIONS

- → Investigate the timing of large igneous province eruptions and their possible effects on past climate.
- → Analyse the changing arrangement of continents as Pangaea broke up and the possible changes to ocean circulation and heat distribution.
- → Extract microfossils from sand samples and classify them into groups. Use Scientific Sketching techniques to draw and label them; make notes, question and record what you observe.
- → Compare the uses of fossils and microfossils in understanding past climates.
- → Investigate whether sediment cores from recent lakes and dams hold a record of past climate.
- → Model the greenhouse effect to measure the effect of changing albedo on the rate of atmospheric heating.
- → Create a spreadsheet or computer program to model the natural greenhouse effect.
- → Explore how CO_2 solubility and water pH changes with water temperature and salinity.
- → Determine how urban and building design might reduce our generation of greenhouse gases or adapt where we live to deal better with a warming world.
- → Investigate the effects of climate change on marine species distribution.
- → Plan a mitigation strategy based on an investigation of waste generation or energy use in your school.
- → Build a model of a mechanism for generating energy without also generating greenhouse gases.
- → Analyse the effects of Indigenous fire-management practices on ecosystem health and prevention of large bushfires.

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» MODULE EIGHT

RESOURCE MANAGEMENT

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12 Natural resources

OUTCOMES

In this chapter you will learn about:

- natural resources in Australia ICT, L, N
- the environmental impacts of mining and remediation methods ATSIHC, AAEA, S, EU, ICT
- the involvement of traditional owners in mining ATSIHC, S, CCT, EU
- important Australian resources. CCT, EU, ICT, L, N, DD

iStock.com / Dazman

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The Australian national anthem says 'Our land abounds in nature's gifts'. Australia's large land area, unique flora and fauna, variety of environments, and rich mineral deposits are 'gifts' that have been valued by Australians for more than 60 000 years. Aboriginal and Torres Strait Islander peoples used hundreds of species for food, medicine and goods. They mined, quarried, hunted, farmed and built houses using local resources and items obtained by trade from other regions.

Natural resources are vital to the modern global economy. Eight of Australia's top 10 exports in 2017–18 were natural resources. Iron ore and coal were the biggest earners, each worth more than $60 billion to the economy. Our future as a nation is inextricably tied to the resources available from the land.

12.1 Renewable resources in Australia

Renewable resources are those that can be replaced naturally in human timeframes. Geological resources replenished through tectonic processes are renewed over millions of years. Thus, there is a limit to the amount of mined resources, such as gold, that we can extract (Figure 12.1). Water, wind, sunlight, plants and animals are all renewable and can be used continually with proper management.

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FIGURE 12.1 Gold is a natural resource that is mined in the Fimiston Open Pit, better known as the Kalgoorlie Super Pit, in Western Australia.

Agricultural resources

Agriculture makes up approximately 3% of Australia's gross domestic product, with a value of $59 billion in 2017–18. Most of Australia's agricultural products are exported, with beef being the largest export earner (Figure 12.2). According to the National Farmers' Federation, on average, each Australian farmer produces enough food to feed 600 people – 150 at home and 450 overseas.

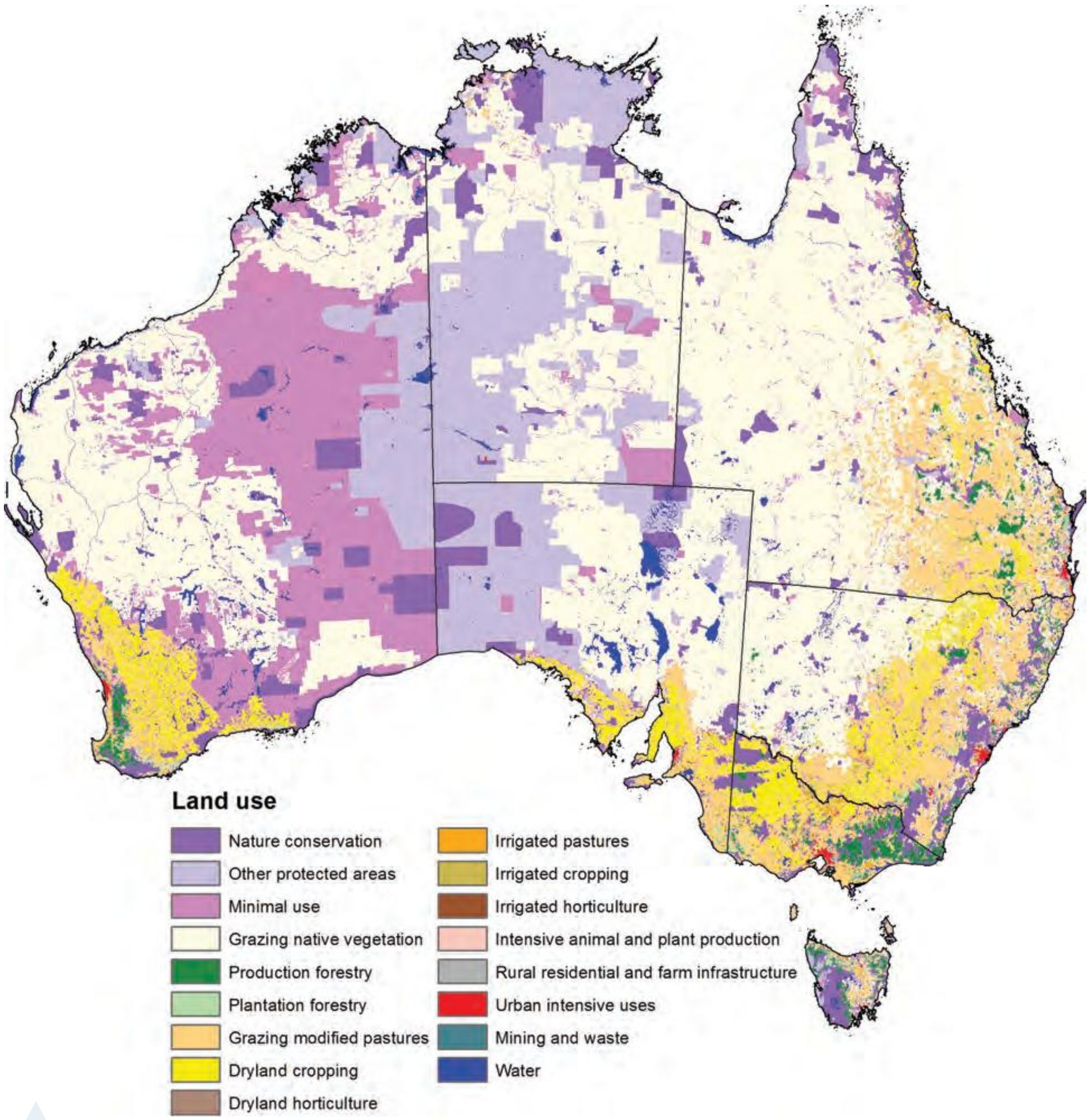
Shutterstock.com/Robyn Mackenzie

FIGURE 12.2 Beef is one of Australia's top exports. Beef is a renewable resource.

Land-based agriculture

Grazing is Australia's most common agricultural land use. More than 320 million hectares are used as pasture for sheep and cattle. Crops are grown on 31 million hectares. Major broadacre crops are wheat, barley, canola, sorghum, oats and cotton. The most productive fruit and vegetable crops (by mass) are grapes, potatoes, tomatoes, oranges, bananas, onions and apples. Plantation forestry occupies 730 000 hectares. An overview of Australian land use is shown in Figure 12.3.

The most profitable land-based agriculture in New South Wales is beef production, with a value of more than $2 billion



Land use of Australia 2010–11 sourced from the Commonwealth of Australia (Australian Bureau of Agricultural and Resource Economics and Sciences) at CC BY 3.0.

FIGURE 12.3 Types of land use in Australia

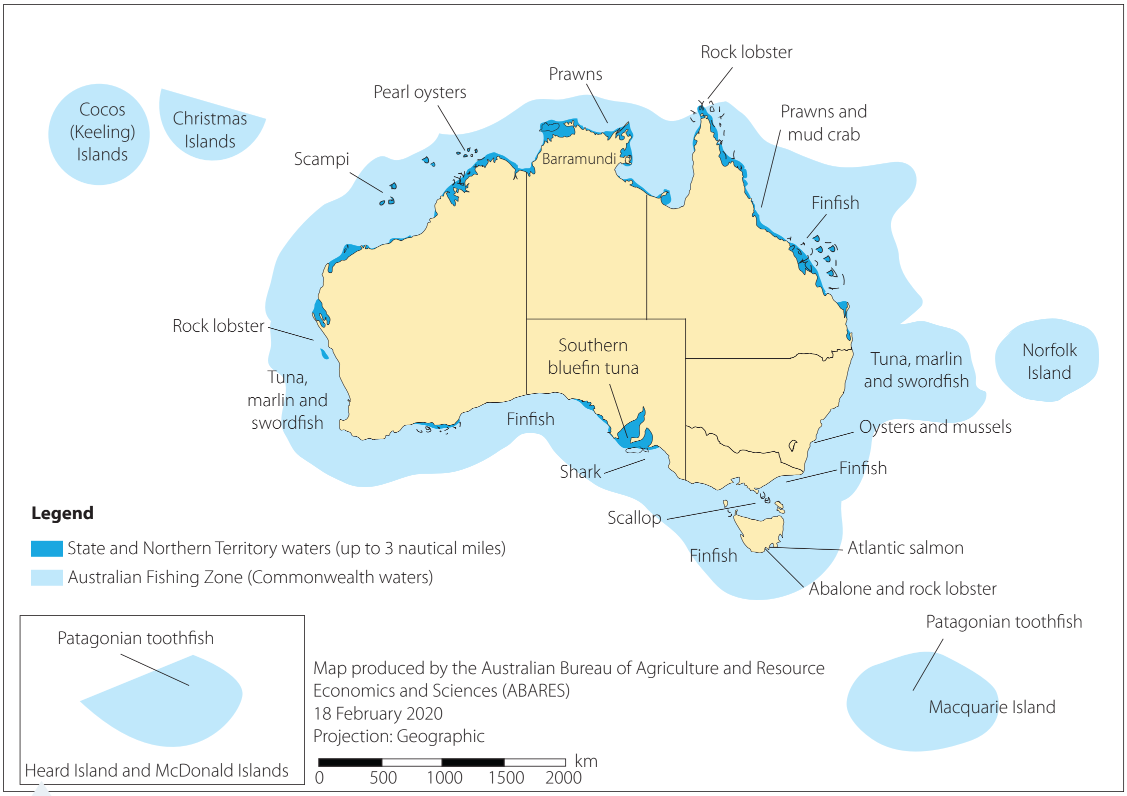


FIGURE 12.4 Australian major fisheries resources

each year, followed by cotton ($1.6 billion) and wheat ($1.4 billion). Beef is the major product for more than a quarter of farms in New South Wales. The next most common type of agricultural enterprise is grain or grain plus grazing.

Aquaculture and fisheries

Aquaculture and fisheries are worth $3 billion per year. More than $1.4 billion of that comes from exports. Salmon and rock lobster make up most of the domestic value, and rock lobsters are the most profitable export. Salmon, prawns, oysters and barramundi are commonly farmed, while rock lobster and southern bluefin tuna are wild caught. Australia's major fishing zones are shown in Figure 12.4. Tasmanian salmon farming has been steadily increasing, reflecting increasing demand for salmon and decreasing availability of wild stocks (Figure 12.5).

You will learn more about the sustainable harvest of tuna in Chapter 14.

The primary sources of aquatic products in New South Wales are wild-caught prawns and rock lobsters, plus farmed oysters. The value of New South Wales' fisheries and aquaculture has remained steady over recent years at approximately $150 million per year.

FIGURE 12.5 Salmon is farmed in aquatic pens.

Water resources

Fresh water is a scarce resource and Australia uses 50–70% of its fresh water for agriculture, with most of this going to irrigation. The Murray–Darling River Basin is home to roughly two-thirds of irrigation farming and covers most of New South Wales (Figure 12.6). From year to year, the amount of water used by agriculture varies more than for any other industry because water-intensive crops such as rice and cotton might not be planted in drought years.

FIGURE 12.6 The Murray–Darling Basin extends across four states and covers most of New South Wales.

In 2017–18, more than 76 000 gigalitres (1 GL = 1×10^9 litres) of fresh water were extracted from the environment to support the economy. Most of this (almost 60 000 GL) was used for hydro-electricity and discharged without consumption. Of the consumed water, more than 60% was used by agriculture, 16% was used by industry and 11% was used by households.

Most of the water used in New South Wales is surface water, the availability of which varies with rainfall. However, 17% of Australia's available water is groundwater. Our understanding, regulation and management of groundwater is poor compared with that of surface water. The use of groundwater for agriculture is becoming more important because of drought and climate change – groundwater use doubled during the drought in 2019. However, the infrastructure used to monitor groundwater levels is deteriorating. Many experts worry that groundwater levels could become critically low before dependent communities realise the problem. Water-sharing plans cover most of New South Wales, but we have a poor understanding of groundwater-dependent ecosystems and how they are affected by current levels of extraction.

Renewable energy resources

WS Renewable electric energy

In 2018, for the first time, more than 20% of Australia's electricity was generated from renewable energy sources. Australia's energy mix is gradually moving to renewable sources as fossil fuels are depleted and we work to minimise carbon emissions.

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The Snowy Mountains Hydro-electric Scheme was completed in 1974 and is Australia's oldest major renewable energy and water storage project. The nine major power stations in the scheme generate an average of 4500 gigawatt-hours of electricity every year. This is used to meet peak demand in cities from Adelaide to Brisbane. Water storage in the system is used to counteract droughts and supports irrigated farming worth around $3 billion annually. The Snowy 2.0 expansion will act as a giant battery to store excess electricity by pumping it to upper reservoirs and releasing the water for electricity generation at peak times.

Getty Images/Mark Kolbe

FIGURE 12.7 Wind farms like this one on a cattle property in Taralga, New South Wales, are a major source of renewable energy in Australia.

In Australia, wind power is the next major provider of renewable energy after hydro and is the fastest growing renewable source. In 2018, wind provided a third of all renewable energy and approximately 7% of Australia's total energy. Wind power stations are concentrated in southern Australia where strong prevailing winds provide ideal conditions for electricity generation (Figure 12.7).

Solar power is the largest energy generator in Western Australia. Small-scale solar systems are the third largest renewable energy source in Australia. They are steadily growing in use as individuals invest in household photovoltaic systems. Households are also investing in battery storage systems to protect against power outages and maximise the benefit of solar systems. Solar energy can be used to make electricity directly in photovoltaic cells, to heat water or to produce steam to drive a turbine in a massive thermal array. Solar energy farms are a growing contributor to the Australian energy mix with more projects being announced every year. In 2019, there were more than 60 solar farm projects under construction across Australia.

Geothermal energy stored in large granite bodies may be used for power, but most of the appropriate granite masses are far from population centres. Hot water in sedimentary aquifers may be used for direct heating or for electricity production.

Efforts to harness energy from tides, waves or ocean currents are mostly small in scale. Other renewable energy sources include methane from landfill or anaerobic digestors, and bagasse from sugar-cane waste. These products are burned to produce steam to drive turbines.

INVESTIGATION 12.1

Renewable energy in New South Wales

The distribution of renewable energy depends upon the land and geographic locations. Renewable energy sources may not be distributed near cities where energy demand is highest.

Information and communication technology capability

Literacy

Numeracy

AIM

To investigate the distribution of renewable energy resources in New South Wales

MATERIALS

- NSW renewable energy resources map (see weblink)
- 5 plastic transparency sheets or plastic sleeves
- Marking pens
- Two-hole punch

NSW renewable energy resources map

»

Interactive viewer

METHOD

1 Lay a plastic sheet over the map or computer screen showing solar resources.
2 Trace the outline of New South Wales. Label this sheet 'Solar'.
3 Trace the outline of each colour representing the average solar exposure and note the intensity near the edge of the outline.
4 Mark the locations of power generation and note the total generating capacity underneath the map title.
5 Repeat steps 1–4 for wind, hydro and wave, and bioenergy. Ensure that the map is the same size if using the computer screen for tracing.
6 Trace a further outline of New South Wales, marking the location of major cities and your school.

RESULTS

1 Stack the sheets with the cities at the base and others on top.
2 Use the two-hole punch to make holes in the aligned maps. Store these in a binder or connect them with string.

DISCUSSION

1 Identify the power generation sites that align with resource availability and those that do not align with availability.
2 Discuss reasons why the distribution of power generation may not match greatest availability.
3 Bioenergy is not often used for power generation. Use information from the maps about sources of bioenergy and your knowledge of greenhouse gases from Module 7 to discuss the advantages and disadvantages of bioenergy.

CONCLUSION

Summarise the current renewable energy production in New South Wales and identify major untapped resources.

EXTENSION

Use the interactive map to examine geothermal energy reserves and determine which areas are most suitable for new power generation.

KEY CONCEPTS

- Renewable resources are replenished naturally and can be used repeatedly.
- Australia produces enough food to feed four times the current population.
- The most common agricultural land use is grazing, followed by crops.
- Major aquaculture products include tuna, salmon and rock lobster.
- Agriculture is the greatest consumer of water.
- The Murray–Darling Basin supplies two-thirds of Australia's irrigated croplands.
- Hydro and wind currently produce the greatest amount of renewable energy.
- Energy from the Sun can be used directly to heat water or to produce electricity in photovoltaic cells.
- Other renewable energy sources include geothermal, marine, landfill gas and bagasse.

CHECK YOUR UNDERSTANDING 12.1

1 List six renewable resources available in Australia.
2 What is the most common agricultural land use?
3 Why is salmon farming becoming more profitable?
4 Explain why agricultural water use varies from year to year.
5 Outline the two purposes of the Snowy Mountains Hydro-electric Scheme.
6 Which renewable energy source is commonly used by households?

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12.2 Environmental impacts of mining and remediation methods

Australia's mining history dates back at least 40 000 years. Aboriginal mines had a small impact on the environment. European settlement brought demand for new resources and mechanised mining. Coal was discovered in the late 1700s and lead mining began at Glen Osmond, South Australia, in 1841. The discovery of a rich alluvial gold deposit near Bathurst in 1851 and subsequent discoveries in Victoria led to a gold rush that accelerated immigration and development in Australia. During the 1850s, Australia produced approximately 40% of the world's gold, and gold remains an important economic resource.

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Alamy Stock Photo/ Trevor Smithers ARPS

FIGURE 12.8 **a** Panning was used to extract gold from alluvial deposits during the 1850s. **b** Open pit mining for copper, gold and silver at Mount Morgan in Queensland from 1882 to 1990 has left a legacy of acid mine drainage.

You learnt about different methods of mining and the resources extracted in *Earth and Environmental Science in Focus Year 11*, Chapter 5. In this chapter, you will focus on the environmental effects and rehabilitation of mine sites.

A 2017 study by the Australia Institute estimated that there are more than 60 000 abandoned mines in Australia that have not been rehabilitated. Only a handful of mines had been fully rehabilitated. The job of making abandoned mines safe and restoring the environment is the responsibility of state government offices, which can be poorly funded.

Mining processes have changed dramatically over time. Current mining approvals require environmental impact assessments, negotiations with traditional owners, rehabilitation plans and a security deposit to cover environmental restoration if works are not carried out. Rehabilitation is tailored to the type of mine, but the aim is to restore ecosystems and prevent ongoing problems. The integrated rehabilitation and mining process is summarised in Figure 12.9.

Graphic produced by the Minerals Council of Australia

FIGURE 12.9 Modern mines consider rehabilitation from initial planning, throughout the production phase, until handover.

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Effect of mining on Aboriginal cultural sites

Early mining by European settlers in Australia did not consider environmental or cultural impacts. Today, mining companies that damage cultural sites are subject to legal action and penalties. For example, in 2011, MCG Quarries in Queensland was fined $80 000 plus legal costs for damage to a culturally significant Aboriginal quarry. In 2013, OM Manganese was convicted of desecration of a sacred site and fined $150 000. The company knew about the Two Women Sitting Down site near Bootu Creek mine near Tennant Creek, but carried out blasting nearby, causing significant damage. This was the first contested case of desecration.

Aboriginal cultural heritage sites are protected by the *National Parks and Wildlife Act 1974*. Industry and corporate codes of conduct guide best practice when dealing with Aboriginal and Torres Strait Islander peoples to identify significant sites before mining. Most Australian mines are located near Indigenous communities, so it is vital that mining companies cooperate with the local Indigenous communities to protect cultural sites. You will explore ways that mines involve traditional owners in the next section.


iStock.com/mikulas1

FIGURE 12.10 Open pit mining requires extensive clearing for the mine itself, waste rock and ore processing.

Open pit mining

Open pit mining is the most common mining method in Australia. It is frequently used for the extraction of coal, iron ore, aluminium and gold. Sites must be cleared of vegetation for mining, tailings and processing (Figure 12.10). The affected areas range in size from square metres for a small quarry to square kilometres for a larger mine. The Fimiston Pit shown in Figure 12.1, has a surface area of 5.25 km^2. Large-scale land clearing leaves the mine and surrounding areas vulnerable to erosion and salinisation.

Tailings and waste rock left over from mining pose both physical and chemical hazards. Piles of waste are unstable and vulnerable to erosion. Waste may also be a source of chemical contamination. Sulfur-containing minerals such as pyrites react with oxygen and water to form sulfuric acid. Acid alters the pH of the surrounding soil and water, restricting plant roots' access to water and nutrients. In addition, sulfuric acid dissolves other elements such as arsenic, lead, zinc, cadmium, aluminium, iron, manganese, selenium and copper, which results in toxic **acid mine drainage**. Both the acid pH and the presence of dissolved elements have negative impacts on aquatic life and the surrounding soil.

Rehabilitation

For more information about passive neutralisation see *Earth and Environmental Science in Focus Year 11*, Chapter 12.

Rehabilitation of land after open pit mining varies according to the resource mined, chemical hazards posed by waste and characteristics of the surrounding area. The general principle is to create natural land contours and revegetate the site for recreational or pastoral use. Voids (holes) left after mining are allowed to fill with water and become lakes.

If the mine and waste are vulnerable to acid mine drainage, they must be covered with a low permeability cover that prevents oxygen and water from reaching the sulfides. An example is covering a tailings pile with compacted clay. The clay is then topped with soil and revegetated. Acidic run-off may be treated with passive neutralisation. Passive neutralisation involves directing acidic water through limestone beds to neutralise the acid before the water is released into the environment.

An example of modern rehabilitation is Glencore's Mangoola coal mine in the Hunter Valley (Figure 12.11). The company used natural landform contouring and plants that reflect surrounding ecological communities. Rehabilitation occurs in tandem with mining so that the time of ecosystem disturbance is minimised.

WS
Mine Rehabilitation

age fotostock/UIG/Environmental Images

age fotostock/UIG/Environmental Images

FIGURE 12.11 Natural landforms at the Mangoola coal mine in the Hunter Valley are being revegetated as mining continues in adjacent areas.

Underground mining

Underground mining requires land clearing for mine works, ore processing and waste dumps. The waste rock is put back in the cavern in cut-and-fill mining but is left at the surface in other methods. Mine shafts (vertical) and adits (horizontal) present hazards for people and animals.

The risk of surface subsidence varies with the type of mining. The room-and-pillar method involves reinforcing the roof of the mine, which preserves the surface above. In contrast, longwall coal mining uses temporary roof reinforcement; when it is removed, the roof collapses.

Alamy Stock Photo/Adwo

FIGURE 12.12 An open mine shaft at an abandoned underground mine presents a hazard to people and animals.

Rehabilitation

The management of surface waste from underground mining is the same as that for open cut mining. All potential entries to underground mines must be blocked to protect people and animals (Figure 12.12). Sometimes, bat-friendly fencing is installed because abandoned mines provide valuable roosting habitat for insectivorous bats.

Over time, old mine pillars and workings collapse and can affect properties. In the five years before 2014, mine subsidence claims cost New South Wales $8.7 million. Subsidence Advisory NSW oversees the purchase of properties affected by subsidence. Areas at risk for subsidence should be fenced off before mining starts for maximum safety.

Acid mine drainage from underground mines is a particularly difficult problem to address. If the source of oxygen or water incursion can be identified, it may be blocked or capped. However, in many cases the contaminated water must be treated where it emerges at the surface.

Drilling

Drilling has the smallest footprint of any mining method (Figure 12.13). The drill pad is a cleared area in which the drilling rig and associated equipment are positioned. Multiple holes may be drilled in one pad.

iStock.com/JamesReillyWilson

FIGURE 12.13 An onshore drilling site

The greatest potential damage of onshore drilling is to groundwater. In 2018, Linc Energy was fined a record $4.5 million for contaminating groundwater on the western Darling Downs, Queensland. Incomplete understanding and modelling of groundwater resources and flows can make it difficult to predict the impact of a leaking pipe. To prevent contamination and leakage into non-target rock layers, the drill holes are protected by one or two layers of steel casing held in place with cement. However, this may not prevent gases and chemicals escaping through unpredictable fractures in the rock.

Another risk from natural gas extraction is fugitive emissions of methane, a powerful greenhouse gas. Methane may leak to the surface through soil or abandoned drill holes. In 2014, the CSIRO estimated that fugitive emissions from gas production accounted for about 2.5% of Australia's greenhouse gas emissions.

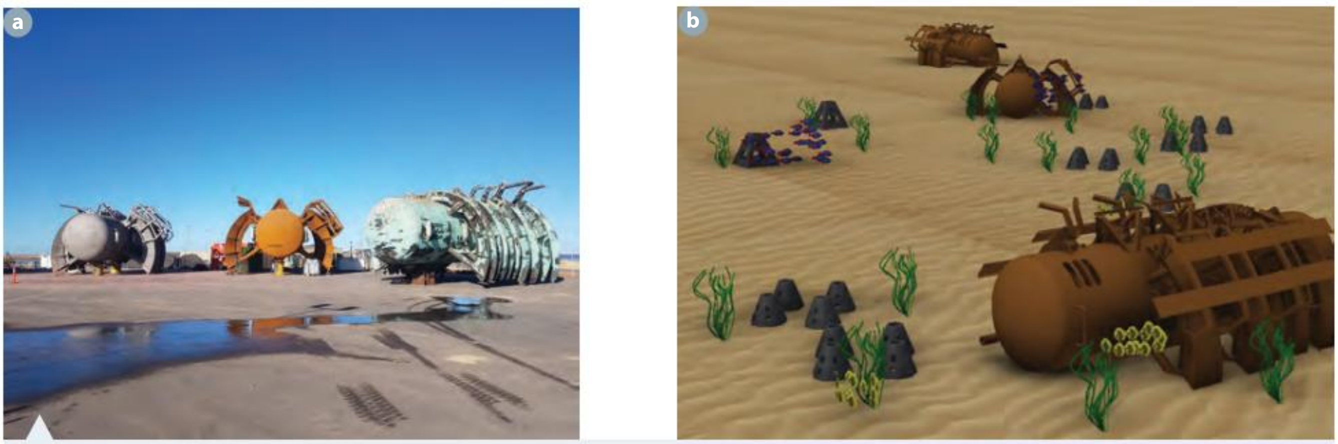
Offshore drilling may affect marine species through noise, hydrocarbon spills, waste discharge and seabed changes. Oil spills such as that from the oil tanker *Exxon Valdez* (Alaska, USA, 1989) and the oil rig Deepwater Horizon (Gulf of Mexico 2012) have had lasting effects on environmental and human health. Although petroleum spills have devastating effects, stationary oil platforms may provide habitat for marine species, acting as artificial reefs.

Rehabilitation

When onshore operations cease, the drill hole collar is cut at least 40 cm below the surface and plugged with a permanent plug. Requirements for the plugging depend upon the location of aquifers. After plugging, the soil is backfilled, compacted and mounded over the hole.

The drill pads and benches are removed, and compacted soil is ripped along contours to loosen the soil. The area is re-contoured and stockpiled topsoil is respread over the site. Vegetation is reseeded to restore the local ecosystem.

Rehabilitation of offshore drilling involves plugging the drill hole and removing structures. The structural components may be re-purposed as artificial reefs. Rig-to-reef programs began in 1986 in the USA, but are relatively recent in Australia. The first rig-to-reef project in Australia is the $1 million King Reef in the Exmouth Gulf, Western Australia (Figure 12.14). The King Reef is one of the largest structures of its kind with 58 modules and is as large as 11 Olympic swimming pools. The project was a finalist for the 2019 Golden Gecko Award, which recognises innovation and environmental outcomes in the resources sector.



Subcon Blue Solutions

FIGURE 12.14 The King Reef near Exmouth, Western Australia, was the first rig-to-reef project in Australia. **a** Re-engineered steel modules from the former oil rig. **b** An artist's impression of the artificial reef habitat created by the steel modules.

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INVESTIGATION 12.2

Rehabilitating abandoned mines

The earliest recorded European mine in Australia was Nobbys Head coal mine in New South Wales, which was opened in 1790. After that, tens of thousands of sites were mined and abandoned before rehabilitation programs were introduced. It is estimated that there are nearly 600 sites in New South Wales and many more across Australia. Many of these pose public and environmental risks such as heavy metal contamination and acid mine drainage.

Aboriginal and Torres Strait Islander histories and cultures

Sustainability

Ethical understanding

Information and communication technology capability

iStock.com/ mastersky

FIGURE 12.15 Abandoned mines, such as the gold mine at Jupiter Diggings in Adelaide Hills, South Australia, can pose safety risks.

AIM

To propose a rehabilitation program for an abandoned Australian mine

METHOD

1 Search for information about abandoned mines (also called derelict mines) in news articles or on websites. Examples from New South Wales are Conrad, Ottery, Sunny Corner and Captains Flat Mines. These have had some rehabilitation work done, but still present environmental risks from acid mine drainage.
2 Prepare a rehabilitation proposal that includes:
   - the mine name
   - a map showing the location of the mine
   - the traditional owners of the land where the mine is located and a list of any Aboriginal sites nearby
   - the type of mining and product that was mined
   - a description of the hazards associated with the mine, including physical dangers (e.g. mine shafts, piles of loose tailings) and environmental contamination (e.g. asbestos, acid mine drainage)
   - a recommendation for a solution for each of the hazards you have identified.

DISCUSSION

1 Which of the hazards at your mine site is most dangerous for people and why?
2 Explain the scientific basis for your proposed rehabilitation strategies.
3 Describe possible uses of the rehabilitated mine site. Should people stay away, or will the area be safe for some activities?

CONCLUSION

Evaluate the benefits of rehabilitating this mine site.

KEY CONCEPTS

- Australia has thousands of potentially dangerous abandoned mines.
- Modern mining requires an integrated plan to protect the environment and cultural sites.
- Open pit mines may affect several square kilometres and require extensive earthworks for rehabilitation.
- Underground mines often lead to subsidence of overlying land.
- Sulfide-containing waste rock must be carefully managed to prevent acid mine drainage.
- Drilling has a small surface footprint but leaking gas or oil can damage aquifers and surface areas.
- Offshore drilling rigs may be converted to artificial reefs.

CHECK YOUR UNDERSTANDING 12.2

1 Name three substances mined during the early days of European settlement in Australia.
2 How do governments ensure that mine companies rehabilitate land after mining?
3 What happens to mines that damage cultural sites?
4 Outline the environmental effects of open pit mining.
5 Identify some of the hazards associated with underground mining.
6 In what way can offshore drilling benefit the environment?

12.3 Involving traditional owners in mining

The Gold Rush of the 1850s was a time of prosperity for many Australians, but not for Aboriginal Australians. First forced from their land by pastoralists, Aboriginal peoples were often displaced again and their sacred sites despoiled as mining took place with disregard for environmental and cultural consequences.

The *Aboriginal Land Rights (Northern Territory) Act 1976* and the *Native Title Act 1993* provided Aboriginal and Torres Strait Islander peoples with rights to own and control land. Mining companies then had to formally negotiate access to land. State and federal governments sometimes left mining companies to provide basic services such as health and education in remote areas, a situation that caused discomfort for both traditional owners and companies. Subsequent legislation and policies enacted by peak mining bodies since 2005 have improved relationships and clarified the roles of government, industry and traditional owners.

Companies must now consult with traditional owners when they plan, operate and rehabilitate mines. Aboriginal and Torres Strait Islander peoples are increasingly being represented in businesses that support and carry out mining. For example, in 2019, the Anindilyakwa people on Groote Eylandt, Northern Territory, set up a mining company with a view to opening a new manganese mine as the GEMCO manganese mine finishes operations. A variety of mine-related companies are Aboriginal owned and employ mostly Aboriginal staff. Some work in mine operations, while others offer cultural liaison services to help bridge communication gaps between companies and traditional owners.

Planning

As shown in Figure 12.9 (page 303), many studies and steps are undertaken before mining can begin. Once a possible mine site is identified, mining companies must survey the area to see what environmental and cultural sites require protection.

The Wik-Waya people of the Cape York Peninsula in Queensland are the traditional owners of the land where Rio Tinto proposed to build a new bauxite mine. The Wik-Waya worked with Rio Tinto to develop a Communities, Heritage and Environment Management Plan. This plan lays out the involvement of traditional owners in cultural activities and land management around the mine area. The mine and traditional owners worked together to minimise the environmental and social impacts of mining, while acknowledging that the area of the mine will be irrevocably changed.

Mining

Approximately 47% of traditional owners live in regional and remote areas near mines. Education and services in these areas are often poor, so residents rarely have the skills necessary for traditional mining employment. Royalties from mining are directed to local organisations that address areas of need such as early childhood education, school programs, health care and housing.

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Many mining companies have developed employment programs. In 2014, Mount Isa Mines began a $1.3 million program to provide training and mentoring for members of the local Aboriginal community. Indigenous mentors help trainees to gain necessary work skills and bridge the gap between Indigenous and mine cultures.

In September 2018, the Australian Aboriginal Mining Corporation entered an agreement with Fortescue to create the first Aboriginal-owned and operated iron ore mine in Australia. This was a major step for traditional owners taking literal and figurative ownership of the mining process. The corporation has also set up a mining academy in the Pilbara (Figure 12.16).

Newspix/Ian Munro

FIGURE 12.16 Trainees at Purarrka Indigenous Mining Academy in the Pilbara, Western Australia, are being prepared for mining work.

Rehabilitation

Woodcutters Mine in Batchelor, Northern Territory, operated from 1986 to 1999. Newmont Goldcorp acquired the site in 2002 and took responsibility for rehabilitating the mine (Figure 12.17). The company worked with the Indigenous Consulting Group to develop a plan that incorporates the land use preferences of the traditional owners, the Kungarakan and Warai people. For example, when the mine needed to excavate soil from a borrow pit to cap the former tailing site, the borrow pit was turned into a wetland because the traditional owners preferred this option. The work was carried out by Rusca Bros Services, an Aboriginal-owned local contractor. Employment in the project was approximately 90% Aboriginal, and local trainees had the opportunity to gain a Certificate III in Civil Construction by working with Rusca's training program.

To help the local community understand how the land could be used after handover, Newmont Goldcorp, the Indigenous Consulting Group and traditional owners developed a map that showed what different areas can be used for, such as recreation or collecting bush tucker. Meetings between all parties are held at least twice a year so that traditional owners are informed about what is happening at the site and are satisfied with the rehabilitation before handover. Traditional owners have helped define the success criteria for mine closure and must sign off on this when the mine lease is relinquished.

a

Newmont Tanami Operations

b

Newmont Tanami Operations

FIGURE 12.17 **a** Rehabilitation is underway at Woodcutters Mine in the Northern Territory. **b** The new wetland area.

Case study: gold mining in the Granites, Northern Territory

The Granites and Dead Bullock Soak gold mines are located in the Tanami Desert on Warlpiri (Yapa) land 540 km north-west of Alice Springs. (Yapa is the Warlpiri word meaning person.) These underground gold mines are some of the most productive in the country and are located on Aboriginal freehold land. North Flinders Mines Ltd negotiated a Land Rights Agreement with the newly formed Central Land Council in 1983 and production began in 1986. Land clearing for the mine was approved by Warlpiri to ensure protection of sacred sites.

Southern Tanami Indigenous Protected Area Storybook Plan of Management

Listen to the Warlpiri tell the story of their land and how they care for it.

The mine was initially expected to last 10–20 years. In 2017, after 227 tonnes of gold production, Newmont Mining (owners since 2002) proposed a mine expansion. Newmont, the Central Land Council and Warlpiri developed the Granites-Kurra Ten Year Plan to make sure the mine meets several objectives and commitments. The plan has three main priorities:

- to support Yapa governance and self-determination, developing leadership capacity and succession planning (Yapa Voice)
- to increase employment in the mine and surrounding area, and support the development of Yapa business and social enterprises (Yapa Employment)
- to support education of children and youth in ways that respect and celebrate culture, strengthen employment training and increase opportunities for work experience in the region (Yapa Education).

Annual meetings are held to agree on priority actions and ensure that the Warlpiri are kept up to date with mining operations and plans. Royalties from mining support the Warlpiri Education and Training Trust that runs programs focused on early childhood development, school support and cultural support. Newmont Goldcorp supported the Central Land Council and Warlpiri to create a digital storybook that explains the management of Australia's largest Indigenous Protected Area, the Southern Tanami Indigenous Protected Area.

The mine workforce on site is approximately 12% Aboriginal. As a fly-in-fly-out mine, the facility is a self-contained community. Mine employees are given cultural awareness training. Also, local families have painted murals on structures and Warlpiri names are used on the site (Figure 12.19). This gives employees a sense of place and appreciation for the Country in which they work.

The Granites is still being actively mined, but rehabilitation planning is already underway in consultation with the Warlpiri and the Central Land Council.

Newmont Tanami Operations / Neil Cook

FIGURE 12.18 Murals on structures in the Granites mine facilities, Northern Territory, connect local Indigenous families to their culture.

INVESTIGATION 12.3

Aboriginal and Torres Strait Islander histories and cultures

Sustainability

Critical and creative thinking

Ethical understanding

Case study of the involvement of traditional owners in mining

A large iron mine may have a working life of 50 years, during which legislation and social expectations might change considerably. Modern mines consult with the local Indigenous communities throughout the mining process, but this has not always been the case. As traditional owners have become more involved, mining agreements and practices have adapted.

AIM

To prepare a case study of the involvement of traditional owners in planning, mining and restoration at a named Australian mine

»

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» METHOD

1 Search for information about an Australian mine operating in a remote area of Australia. Use books, news articles and websites to find information. Examples are the Ranger uranium mine, Argyle diamond mine, Yandicoogina iron mine, Century zinc mine and the GEMCO manganese mine.

2 Find at least three sources of information and summarise them in a table like that below.

SOURCE	AUTHOR	DATE	PURPOSE OR VIEWPOINT OF PUBLICATION	KEY FACTS

3 Summarise the involvement of traditional owners in the planning, mining and rehabilitation of the mine. Note whether there was little or no involvement and explain why.

DISCUSSION

1 Did you find sources that presented very different accounts of the mining process? Explain why there are often different viewpoints in available information.

2 Explain how the relationship between traditional owners and the mining company has changed over time. Were changes prompted by new legislation, a change of ownership or other factors?

3 Analyse the impact of mining upon the traditional owners. Note both positive and negative impacts.

4 What will the impact of mine closure be for traditional owners?

CONCLUSION

Assess the impact of mining upon remote communities of traditional owners.

KEY CONCEPTS

- Traditional owners have an increased voice in mining due to legislative changes.
- Before mining begins, companies work with traditional owners to identify important cultural sites and agree upon impacts.
- Mining companies are developing training programs to involve traditional owners in mining and related industries.
- Aboriginal and Torres Strait Islander peoples own contracting companies and mines.
- Traditional owners are consulted on rehabilitation plans and must agree that the work is sufficient before a mining lease is finished.

CHECK YOUR UNDERSTANDING 12.3

1 Name the laws that gave traditional owners the rights to control their land and negotiate mining agreements.

2 Outline the involvement of traditional owners in mine planning.

3 How are Aboriginal and Torres Strait Islander peoples involved in the mining process?

4 Give an example of where traditional owners are involved in mine rehabilitation.

12.4 Important Australian resources

Australia has a huge variety of renewable and non-renewable resources. Resources provide food, goods and income to residents, as well as a source of export income for Australia. So far in this chapter, you have learnt where important renewable resources are located and how the environment is affected when obtaining non-renewable resources.

The importance of different resources changes over time as we develop new technologies for extraction, management and use. For example, in 3000 BCE, glass was primarily a luxury item used for decorative purposes and drinking or storage (Figure 12.19a). By 1800, it was in great demand for windows, and today glass is used in a variety of applications ranging from optical communication fibres (Figure 12.19b) to food packaging.

Dreamstime.com/Neil Harrison

Shutterstock.com/Andrew Buckin

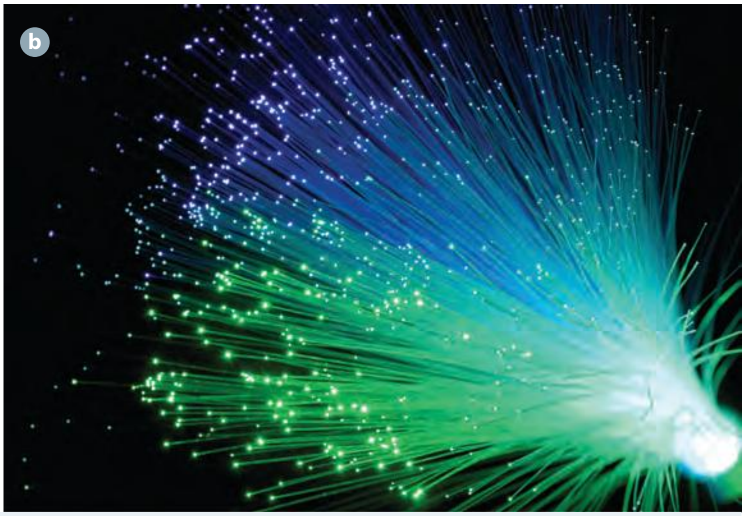

FIGURE 12.19 **a** Glass was used to make this ancient Roman vase. **b** Now, glass is used to make optical fibres.

The sustainable extraction and use of resources is a key consideration for the future. Natural agricultural enterprises such as forestry and fisheries must understand the life cycle of organisms to sustainably manage them. Managing soil and water is integral to the future of farming in Australia.

You will learn more about sustainability and management of resources in Chapter 15.

The changing use and importance of resources is demonstrated clearly by asbestos, a fibrous silicate mineral. As early as 4000 BCE, fireproof asbestos was used for wicks in lamps and candles. The ancient Greeks wrapped bodies in asbestos so that the ashes of the deceased would not mix with those of the fire. Although the substance was widely used in Greece and Rome, early historians noted that miners and asbestos workers became sick from inhaling the dust. Asbestos manufacturing became a thriving industry during Industrial Revolution, but by the early 1900s, there were more and more reports about the hazardous effect of asbestos on lungs.

As people became more aware of the health hazards of asbestos, its demand and use decreased. Asbestos mined in Australia was widely used in cement materials (Figure 12.20) and was exported worldwide from the 1940s to the 1980s. During the 1980s, asbestos use was phased out and from 31 December 2003, the use, transport, storage and sale of all forms of asbestos was banned in Australia. Despite the eventual ban on asbestos products, Australia has the second highest rate

Alamy Stock Photo/graham jepson

FIGURE 12.20 Fibro is the common name for thin cement sheets of flat wall board and corrugated roofing. In Australia, this was manufactured from asbestos from the 1940s to the 1980s.

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of mesothelioma (lung cancer caused by asbestos) in the world. The first successful lawsuits by asbestos-affected workers were in the 1990s. Compensation cases continue today as modern workers are exposed to asbestos while renovating older buildings.

Case study: obtaining aluminium

Aluminium is the third most abundant element in Earth's crust (8.2%). It is never found in a pure form but is extracted from bauxite ore (Figure 12.21). The most common aluminium minerals in bauxite are gibbsite, boehmite and diaspore. Australia is one of the world's largest producers of bauxite. Ore is extracted by open pit mining at major Australian mines in Gove (Northern Territory), Weipa (Queensland) and the Darling Range (Western Australia).

Bauxite is processed by the Bayer process, which was developed in 1888. Bauxite ore is treated with hot sodium hydroxide, purified and dried to yield white alumina (aluminium oxide). Smelting uses electrolysis of alumina to separate the aluminium and oxygen. This process uses a lot of electricity – more than 10% of Australia's total electricity production.

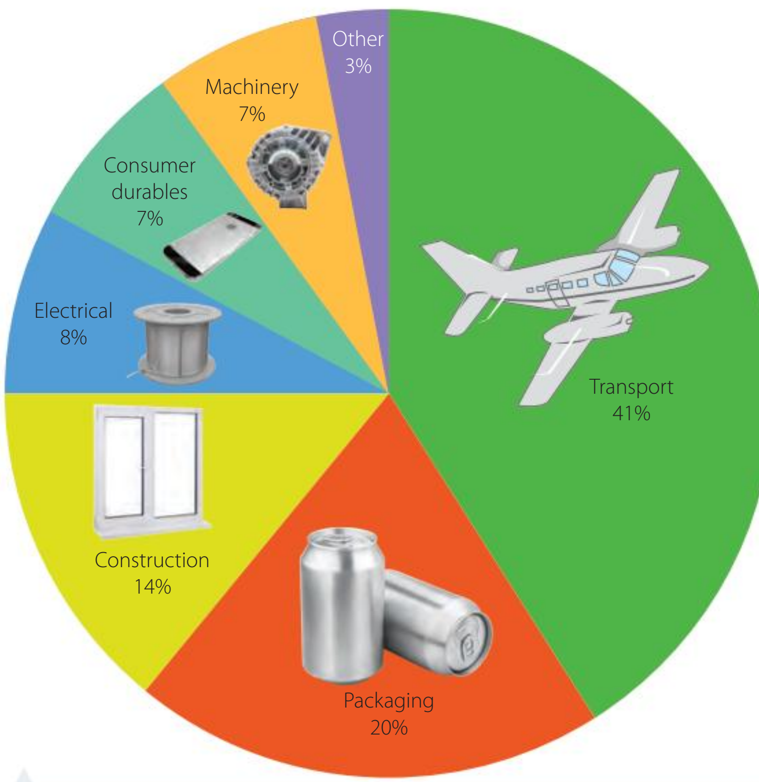
Dreamstime.com/Ekays
Shutterstock.com/Kanungnit
Shutterstock.com/Bjoern Wylezich

FIGURE 12.21 **a** Bauxite ore is refined to **b** alumina and then **c** smelted by electrolysis to produce pure aluminium metal.

Uses of aluminium

Aluminium is lightweight, easily shaped, non-toxic, highly conductive and resistant to corrosion. These properties make it an ideal metal for many applications. Aluminium is most commonly used in transport, packaging and construction (Figure 12.22). Modern aircraft are made largely from aluminium to reduce weight. The Empire State Building in New York was the first building to use aluminium widely in construction.

Aluminium is often alloyed with other metals to increase its strength. The metals are mixed when molten and then allowed to harden before being manufactured into products. Different alloys may be combined in one product. For example, aluminium drink cans are made with alloy 3004 for the body and alloy 5182 for the top. The numbers indicate the main alloy metal. Series 3000 are alloys of aluminium with manganese and are used for drink cans, heat exchangers and cooking utensils. Series 5000 are alloys of aluminium with magnesium and are used in the building and construction industries.



Shutterstock.com/Roman Samokhin; iStock.com/flyfloor; Alamy Stock Photo/David Sutherland
Shutterstock.com/Peter Sobolev, iStock.com/Bulgac, iStock.com/Janifest, iStock.com/Rawpixel

FIGURE 12.22 Aluminium can be made into a huge range of products.

Sustainability of aluminium

The production of aluminium involves open cut mining, concentrated solutions of sodium hydroxide and enormous amounts of electricity. As you learnt in section 12.2, open cut mining requires extensive land clearing and habitat loss. So much electrical energy is required to make aluminium that some people liken aluminium to 'solidified electricity'. The CSIRO calculates that 211 GJ of energy per tonne is required to make aluminium, as opposed to 22.7 GJ t^{-1} for steel. The light weight of aluminium means that over the lifetime of use it may save energy, especially if it replaces steel in transport. If hydroelectricity is used to power electrolysis, the environmental impact of production is also decreased.

Although the initial production of aluminium is very energy intensive, aluminium is infinitely recyclable. It is estimated that 75% of the aluminium metal ever produced is still in use today. Recycling aluminium uses only 5% of the energy required for extraction and does not affect the quality of the metal.

Use and importance over time

Aluminium was named by Humphry Davy in 1808, but it was not produced as a pure metal until 1845. In the 19th century, the complexity of refining aluminium made it rarer and more precious than gold or silver. French president Napoleon III (1808–73) was rumoured to have served state dinners on aluminium plates, while less exalted guests were served on gold or silver dishes. Aluminium was used for ornaments and luxury items because it was so expensive (Figure 12.23).

In the late 1800s, Paul Héroult and Charles Hall developed cost-effective techniques for extracting aluminium. The electrolysis process required large amounts of electricity for industrial manufacturing. Most smelters were built near hydroelectric power stations. With the advent of industrial production, the price of aluminium dropped greatly and its uses expanded.

Transport was an obvious use for this light metal.

- In 1891, Swedish chemist Alfred Nobel ordered a boat to be built with an aluminium hull.
- In 1894, US businessman J.P. Morgan started manufacturing railway cars with aluminium seats.
- In 1899, German engineer Karl Benz made the first sports car with an aluminium body.
- In1903, US aviators the Wright brothers achieved powered flight using an engine with aluminium parts.

Aluminium is now a vital metal for transport, aerospace, construction, electrical transmission, packaging and manufacturing. It is expected to replace steel in many building applications and new alloys are being developed to suit even more uses in the future.

AAP Photo/Universal History Archive

FIGURE 12.23 During the reign of Napoleon III, military and civilian medals were made of aluminium, which was regarded as a precious metal.

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INVESTIGATION 12.4

Case study of an important Australian resource

The use of resources is vital to our standard of living and national economy.

Critical and creative thinking
Ethical understanding
Information and communication technology capability
Literacy
Numeracy
Difference and diversity

AIM

To create an infographic about an important Australian resource

METHOD

1. Research your chosen resource to determine:
   - how we find, manage and obtain the resource
   - uses of the resource
   - the sustainability of resource extraction and/or use
   - the importance of the resource in the past, present and future.
2. Create an infographic about your resource.
3. Use an approved method to cite the sources of information and list these in a bibliography.

DISCUSSION

1. Describe any changes in the use of your resource over time.
2. Is your resource renewable? How must it be managed to ensure future supply?
3. What is the most sustainable method of obtaining your resource?

CONCLUSION

How will use of your resource change in the future?

KEY CONCEPTS

- Resources provide Australia with food, consumer goods and income.
- It is important to know about life cycles to manage agricultural resources.
- The relative importance of a resource may change over time.
- Improvements in production led to the development of new uses for glass and aluminium.
- The discovery of health hazards has halted the use and production of asbestos.

CHECK YOUR UNDERSTANDING 12.4

1. List the changing uses of glass over the past 5000 years.
2. What useful property of asbestos led to its widespread use?
3. Why is asbestos no longer used?
4. Explain why aluminium is widely used.
5. List reasons why aluminium was regarded as a luxury metal in the 1800s.
6. Outline two advances that made aluminium widely available.

12 CHAPTER SUMMARY

- Renewable resources are replenished naturally and can be used repeatedly.
- Australia produces enough food to feed four times as many people as the current population.
- The most common agricultural land use is grazing, followed by crops.
- Major aquaculture products include tuna, salmon and rock lobster.
- Agriculture is the greatest consumer of water.
- The Murray–Darling Basin supplies two-thirds of Australia's irrigated croplands.
- Hydro and wind currently produce the greatest amount of renewable energy.
- Energy from the Sun can be used directly to heat water or to produce electricity in photovoltaic cells.
- Other renewable energy sources include geothermal, marine, landfill gas and bagasse.
- Australia has thousands of potentially dangerous abandoned mines.
- Modern mining requires an integrated plan to protect the environment and cultural sites.
- Open pit mines may affect several square kilometres and require extensive earthworks for rehabilitation.
- Sulfide-containing waste rock must be carefully managed to prevent acid mine drainage.
- Drilling has a small surface footprint but leaking gas or oil can damage aquifers and surface areas.
- Offshore drilling rigs may be converted to artificial reefs.
- Traditional owners have an increased voice in mining due to legislative changes over time.
- Before mining begins, companies work with traditional owners to identify important cultural sites and agree upon impacts.
- Mining companies are developing training programs to involve traditional owners in mining and related industries.
- Aboriginal and Torres Strait Islander peoples own contracting companies and mines.
- Traditional owners are consulted on rehabilitation plans and must agree that the work is sufficient before a mining lease is finished.
- Resources provide Australia with food, consumer goods and income.
- The relative importance of a resource may change over time.
- It is important to know about life cycles to manage agricultural resources.
- Improvements in production led to the development of new uses for glass and aluminium.
- The discovery of health hazards has halted the use and production of asbestos.

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12 CHAPTER REVIEW QUESTIONS

1 a Label the location of two renewable resources on a map of Australian, such as the one in Figure 12.24.

FIGURE 12.24 Label the locations of two renewable resources.

b Describe the importance of these resources to the Australian population and economy.

2 a Identify one renewable energy source in Australia.

b How is this energy source used?

c Outline the future use of this energy source.

3 List two renewable energy sources that you believe are under-used and identify a possible reason for this.

4 Explain how mining may affect Aboriginal cultural sites.

5 Discuss the effects of open pit mining on soil by drawing upon information from this chapter and *Earth and Environmental Science in Focus Year 11*.

6 Create a table comparing the environmental impacts of open pit and underground mining.

7 Explain rehabilitation actions that are common to open pit and underground mines.

8 Describe how drilling can affect the geosphere, atmosphere and hydrosphere.

9 Contrast methods by which rehabilitation of offshore and onshore drilling can restore a local ecosystem.

10 Assess the effect of increasing the involvement of traditional owners in mining.

11 Outline some outcomes for the Warlpiri in engaging with the mining company in the Tanami region.

12 Analyse the role of advances in technology upon the use of Australian resources, using named examples.

13 You have been asked to prepare a case study of the involvement of traditional owners in mining using internet resources.

a Discuss the biases are you likely to encounter in your research.

b How will you determine whether a website is valid and reliable?

14 Minecrafters Mining discovers a deposit of redstone ore in remote Western Australia. Redstone can be smelted to produce a highly conductive metal with an attractive red colour that emits light at low voltages. Powdered redstone is highly flammable.

a The redstone deposit is near the surface and Minecrafters decides to undertake open pit mining. Outline a plan for rehabilitation of the site after mining.

b Describe ways in which Minecrafters should engage with the local Aboriginal community throughout the mining process.

c Propose some uses for this new resource (metal and powdered ore).

13 Managing waste

OUTCOMES

In this chapter you will learn about:

- conducting a waste audit ICT N
- management options for solid waste
- sustainability of waste management. S CCT L CC

Getty Images/Prapass Pulsub

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The original meaning of the word 'waste' referred to a ruined or neglected region. The ways we dispose of our waste can profoundly affect the health of the environment and humans in a region. Aboriginal middens provide evidence of the first Australians' approach to waste management (Figure 13.1). These neat piles of shells, bones and rocks not only show us what people ate and what animals were plentiful, but they also reflect the practice of confining rubbish to one place to keep the area clean.

Alamy Stock Photo / Andrew Bain

Alamy Stock Photo / Selfwood

FIGURE 13.1 **a** An Aboriginal shell midden in South Australia represents many years of waste; **b** this large pile of landfill was created in just days.

Modern Australians use an enormous quantity and variety of materials. As a consequence, we produce enormous quantities of waste – 67 million tonnes (Mt) in 2016–17. This equates to approximately 2200 kg per person. More than half of this waste was recycled, a small amount was incinerated to produce energy, but approximately 40% was buried in landfill. We still confine our rubbish to separate areas, but the amount of space required and the environmental impact of landfill are prompting people to rethink our approach to waste.

13.1 Conducting a waste audit

The first step towards reducing your waste is to discover exactly what materials are present in the waste. Australia's national waste stream is made up of municipal solid waste, commercial and industrial waste, construction and demolition waste, ash from power generation, mining waste and hazardous waste (mainly contaminated soil) (Figure 13.2). Some materials are highly recyclable, such as metals and masonry (building materials). Others present physical or chemical hazards, such as toxic soil. Approximately 20% of Australia's waste is municipal solid waste – the waste created in households, schools and local businesses.

A waste audit by the New South Wales Environment Protection Authority (NSW EPA) found that organic material made up more than half of household waste, with paper products and plastics being the next most common by mass (Figure 13.3). Waste from businesses varies according to the industry. For example, an office produces large quantities of paper waste, whereas a café or restaurant produces a large amount of food waste.

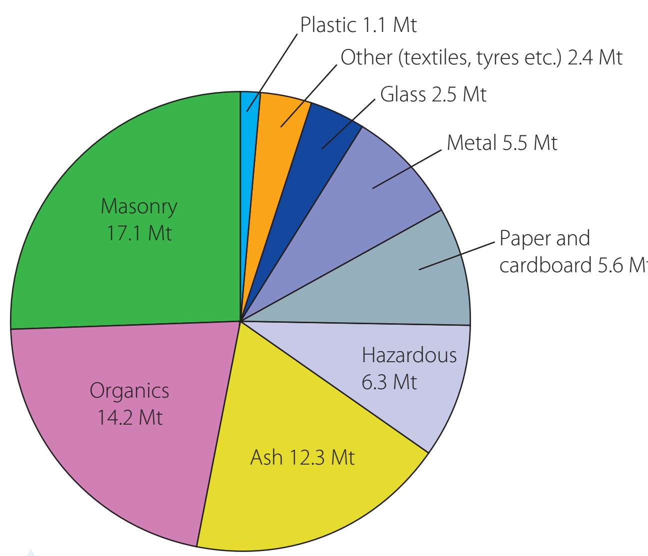

FIGURE 13.2 Australia's waste stream in 2016–17

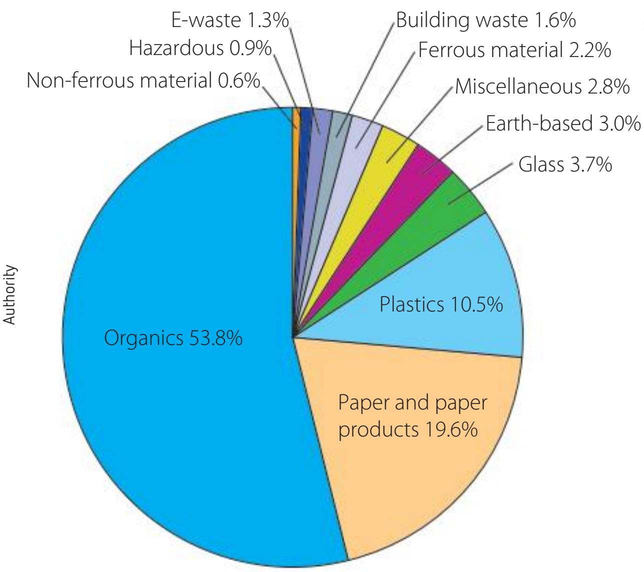

FIGURE 13.3 Composition of household waste in New South Wales in 2011

When you think of hazardous waste, you might think of chemical manufacturing and nuclear power plants. However, household waste also contains hazardous materials. People may dispose of hazardous chemicals such as paint, solvents or pesticides in household rubbish instead of taking them to a council depot. Sharp objects such as broken glass pose physical hazards. Spoiled foods, wound dressings and sanitary products are also potential health hazards.

INVESTIGATION 13.1

Information and communication technology capability

Numeracy

Waste audit

AIM

To conduct an audit of household or school waste

HYPOTHESIS

Write a suitable hypothesis for your investigation.

MATERIALS

Construct a materials list for your investigation. Include as much detail as possible for:

- source and amount of waste to be audited
- personal protective equipment, such as gloves
- scales
- receptacles for sorted waste
- equipment to record your audit results in a spreadsheet and with photographs.

Complete a risk assessment for your investigation.

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

»

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METHOD

1 Construct a method for your waste audit. Consider how much time you have and how much rubbish you can sort. A small household may produce only a small bag of rubbish every day, while a large school may have 100 bags each day. Decide whether you will sort an entire day or week of rubbish or survey a sample of the waste. Consider possible hazards from different types of rubbish and whether some should not be surveyed due to safety concerns.
2 Determine how to quantify the amount of rubbish. Choose a scale with appropriate accuracy and range of measurement – at least 10 kg capacity with 0.1 kg accuracy.
3 Select a suitable area and receptacles for sorting the waste. Decide upon categories before starting the project. Common municipal waste categories are organics, paper and cardboard, plastics, textiles, metals, glass, and other waste. You may wish to use categories based upon local recycling options.
4 Record your results. You may work in a team with one person recording masses and documenting the process with a camera during sorting. If working on your own, it may be easiest to sort everything first and then record the results.

RESULTS

Record the quantities of each category of rubbish in a spreadsheet. Use the data to create a pie graph of the rubbish composition. Create a final results table with the quantity and a representative photo of waste for each category.

DISCUSSION

1 Explain how you chose the amount and source of waste for the audit.
2 What was most surprising to you about the composition of the waste?
3 Compare your results to the composition of typical household waste in New South Wales, as shown in Figure 13.3. Explain any major differences in the composition.
4 Evaluate the validity, accuracy and reliability of your study.
5 If you wanted to lower the overall amount of waste produced, which type of waste could be most easily reduced and how? Justify your answer based on your observations from the audit.

CONCLUSION

Summarise the results of your waste audit.

EXTENSION

Many homes and businesses have separate bins for different types of recyclable products. The NSW EPA found that the average contamination rate in recycling bins was 7.3%. Carry out an audit of the recycling bins at your school or home to determine the contamination rate. Design a campaign to encourage people to sort their waste more accurately.

KEY CONCEPTS

- Australia generates 67 Mt of waste each year.
- Waste comes from households, businesses, industry, construction, power plants and mining.
- Waste can pose physical, chemical and biological hazards.
- The largest component of household waste is organic material.

CHECK YOUR UNDERSTANDING 13.1

1 Identify the two major destinations for waste.
2 What percentage of Australia's waste is municipal solid waste?
3 Contrast the expected composition of waste for two different types of businesses.
4 List the types of hazards you might encounter when doing a waste audit.

13.2 Managing solid waste

(NSW EPA)

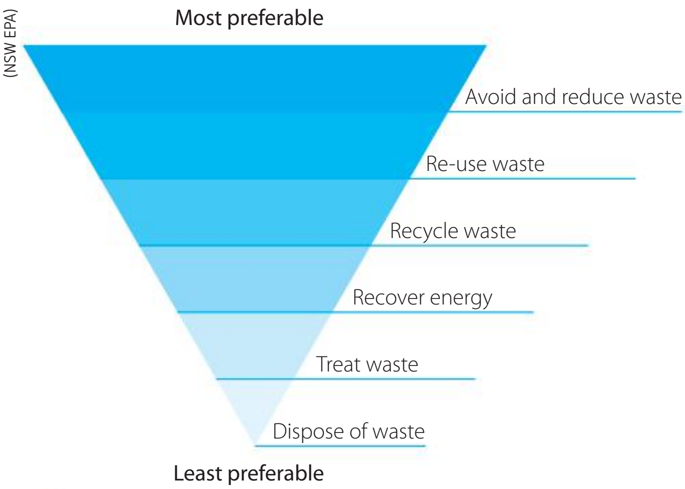

FIGURE 13.4 The waste hierarchy

iStock.com/fstop123

FIGURE 13.5 Garage sales are one method of re-using household items.

Naturalist Sir David Attenborough said that the one thing everyone can do to keep Earth healthy is to end waste. Reducing and avoiding waste is the first and most important step in any waste management hierarchy (Figure 13.4). Once waste has been produced, it should be regarded as a resource that can be re-used, recycled or recovered rather than a nuisance to be disposed of.

Re-use

Re-use is a suitable option for many types of waste. It requires no treatment or reprocessing, so is the most energy-efficient waste management option. Re-use takes place on all different scales from an individual household to an entire industry. Some examples are:

- washing a food container and using it to store leftovers
- holding a garage sale to rehome unwanted goods (Figure 13.5)
- donating unwanted clothing and household goods to opportunity shops for resale
- using sawdust from a timberyard for animal bedding and then using the soiled bedding as garden mulch
- using coal ash to replace some of the cement in the manufacturing of concrete.

INVESTIGATION 13.2

Sustainability

Information and communication technology capability

Re-use shopping map

Opportunity shops, swap meets and recycling centres sell re-usable goods direct to consumers. However, many of these shops have very little money to spend on advertising to let consumers know about their goods. A local shopping map can help consumers find these goods and reduce their waste footprint.

AIM

To create a map of local re-use shops

»

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METHOD

1 Use the Internet and local sources to discover the locations of local re-use shops and markets where second-hand goods are sold. Search for metal and building goods, as well as books. Do not include car yards.
2 Create a table with the name, address, type of goods and opening hours for each shop or market. Decide if you will arrange the table by name of shop, type of goods or location.
3 Use appropriate software to create a printed map or an interactive online map. Include the information in your table so that users can search for a particular type of goods.

DISCUSSION

1 What types of re-use shops are in your local area?
2 Do you think there would be demand for another type of re-use shop in your area?
3 Did you decide to list events that are only held occasionally, such as school fetes and garage sales? Explain the reasons your choice.
4 How will local residents benefit from using your map?

EXTENSION

Work with your local council or chamber of commerce to refine your map and distribute it in the community.

Recycling

Recycling requires energy input to remanufacture a resource and create new products. Activities such as composting organic waste and upcycling old goods are forms of recycling. Recycling generally uses much less energy than was required to produce goods from raw materials.

Many local councils hold e-waste and chemical collection days to encourage recycling. Community recycling centres take items that are not managed well in the recycling bin service, such as gas bottles, fluorescent globes, batteries, printer cartridges, soft plastics and e-waste. Some retailers will collect items such as soft plastics, used toner cartridges or old mobile phones for recycling.

WS Worksheets
Is there enough recycled PET in Australia

Metal

Metal items are easily recycled by melting and re-manufacturing. Australia recycles 90% of metal waste (Figure 13.6). As you learned in Chapter 12, recycling aluminium uses only 5% of the energy required to extract the metal from bauxite. The energy savings from recycling are 90% for nickel, 84% for copper, 75% for zinc, 65% for lead and 60% for steel. It is estimated that steel recycling alone offers enough energy savings each year to power 18 million homes.


Alamy Stock Photo/Prisma Archivo

FIGURE 13.6 Scrap iron is separated from other waste by large electromagnets and then recycled.

Masonry

Australia generated 17.1 Mt of masonry waste in 2016–17, of which 72% was recycled. Masonry materials include asphalt, bricks, concrete, plasterboard and cement sheeting. Concrete and rubble are crushed and used in pavement for roads and driveways. Crushed plasterboard can be used to improve soil during mine site rehabilitation. Other clean rubble may be used as fill in landscaping.

Dreamstime.com/Thomas Gowanlock

FIGURE 13.7 This recycled glass carafe may eventually be further recycled into a variety of other products.

Alamy Stock Photo/frederic reglain

FIGURE 13.8 These rows of shredded garden waste are being composted at a green waste recycling facility.

Alamy Stock Photo/FLPA

FIGURE 13.9 Soft plastics can be recycled to make durable outdoor furniture.

Glass

Glass bottles and jars are infinitely recyclable. Glass recycling uses 75% less energy than manufacturing new glass. The glass is sorted by colour, and then melted and remanufactured (Figure 13.7). Windowpanes, ovenproof glass, drinking glasses and ceramics have a higher melting point and cannot be re-melted. However, they can be ground up and used as a substitute for sand in construction applications such as road base. Fifty-seven per cent of Australia's 1.1 Mt of glass waste gets recycled.

Paper and cardboard

Each Australian generates approximately 230 kg of paper and cardboard waste every year, with about 60% of this being recycled. Paper recycling uses much less water and energy than making new paper. Every tonne of paper that is diverted from landfill saves 2.9 tonnes of carbon emissions.

Office paper is pulped, de-inked and transformed into high-quality recycled paper. Carboard and brown paper are recycled into packaging and boards.

Organics

Major sources of organic waste are livestock manure (33%), bagasse (sugar cane waste) (20%), food waste (14%) and garden organics (12%). Almost all organics can be recycled by composting (Figure 13.8). Compost is a valuable resource that improves soil productivity and health. Australia's National Food Waste Strategy aims to halve food waste by 2030 through waste avoidance and composting.

Plastic

In 2016–17, Australia generated 2.5 Mt of plastic waste, equating to 103 kg per person. Only 12% of this was recycled, often overseas. Unlike glass and metal, plastic can only be recycled two or three times and new material must always be added. On 10 May 2019, more than 180 countries agreed to manage the import and export of plastic waste in a transparent and traceable way. This is the first step towards addressing the overwhelming problem of plastic pollution that was estimated at 8 million tonnes per year in 2015 and forecast to increase 20 times by 2025 if no action is taken worldwide.

The advent of the Return and Earn scheme has improved recycling rates in New South Wales, with the milestone of 3 billion recycled containers reached in January 2020.. Rigid plastic drink containers are primarily PET (polyethylene terephthalate), which is the most commonly recycled type of plastic. Recycled PET can be made into polyester carpet fibre, clothing, shoes, luggage, industrial packaging and new containers. Soft plastics such as shopping bags, bubble wrap and bread bags are frequently excluded from kerbside recycling programs. Most supermarkets have a soft plastic collection bin and the recycled plastics are used to make building supplies and durable furniture (Figure 13.9).

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The agriculture industry has a low plastic recycling rate of only 5.2%. This waste consists of a variety of products such as silage and cotton wrap, tarps, grain tubes, chemical drums and fertiliser bags. Programs to recycle agricultural plastics are becoming more common. The longest running scheme is AgSafe's national drumMUSTER program, which has been operating for 20 years. AgSafe has collected more than 33.5 million chemical drums, which are recycled into products such as fence posts. Farm Waste Recovery picks up 80% of fertiliser bags from Queensland cane farms and is working towards increased recycling of agricultural plastics.

The Recyculator

Calculate the benefit of recycling the waste from your school by using this online tool developed for NSW businesses and councils.

E-waste

The number of electronic appliances in use is increasing rapidly. Mobile phones, computers and televisions belong to the general category of e-waste, and this portion of the waste stream is growing three times faster than any other category. Victoria banned the disposal of e-waste in general waste in July 2019. E-waste contains a wide variety of materials ranging from plastic to platinum. E-waste items are disassembled, shredded and sorted and then the raw materials are melted to manufacture new batteries, electronics and homewares (Figure 13.10).

Shutterstock.com/Evgeniya Mokeeva

FIGURE 13.10 E-waste includes a wide variety of items ranging from batteries to light globes.

INVESTIGATION 13.3

Rating recycling

Sustainability

Critical and creative thinking

Numeracy

Information and communication technology capability

Recycling is a vital step towards a circular economy and zero waste. Local and state governments must decide which municipal recycling technologies to prioritise and fund. All recycling technologies have an environmental impact that can be compared with the impact of landfill or new materials. This is called life cycle analysis and takes into account all of the resources required to make a product. A summary of the net benefits of recycling by material category is shown in Figure 13.11 and Table 13.1.

The net benefit of recycling depends on both the savings associated with each material and the quantity of material used. For example, there is great benefit in recycling metals, but they are a minor component of the waste stream compared with paper. Concrete, brick and asphalt have little benefit in terms of greenhouse gases, energy and water, but a great benefit in terms of avoiding landfill for many tonnes of product.

AIM

To calculate the net benefit of recycling different materials in household waste, taking into account the quantities of waste involved, and to decide which recycling program would have the greatest environmental benefit

METHOD

1 Decide whether you will use a calculator or spreadsheet program to calculate the efficiencies.

2 Extract data from Figure 13.3 about the composition of household waste in New South Wales. To simplify the calculations, assume that all ferrous metal is steel, non-ferrous metal is aluminium and plastics are PET.

»

» 3 Determine the population of your local area from local council information.
4 Complete Table 13.2 to summarise the waste produced in your local area.
5 Complete Table 13.3 by combining data from Tables 13.1 and 13.2 to calculate the net benefit of recycling each material in your local council area.
6 Prepare summary graphs like those in Figure 13.11 to display your final results.

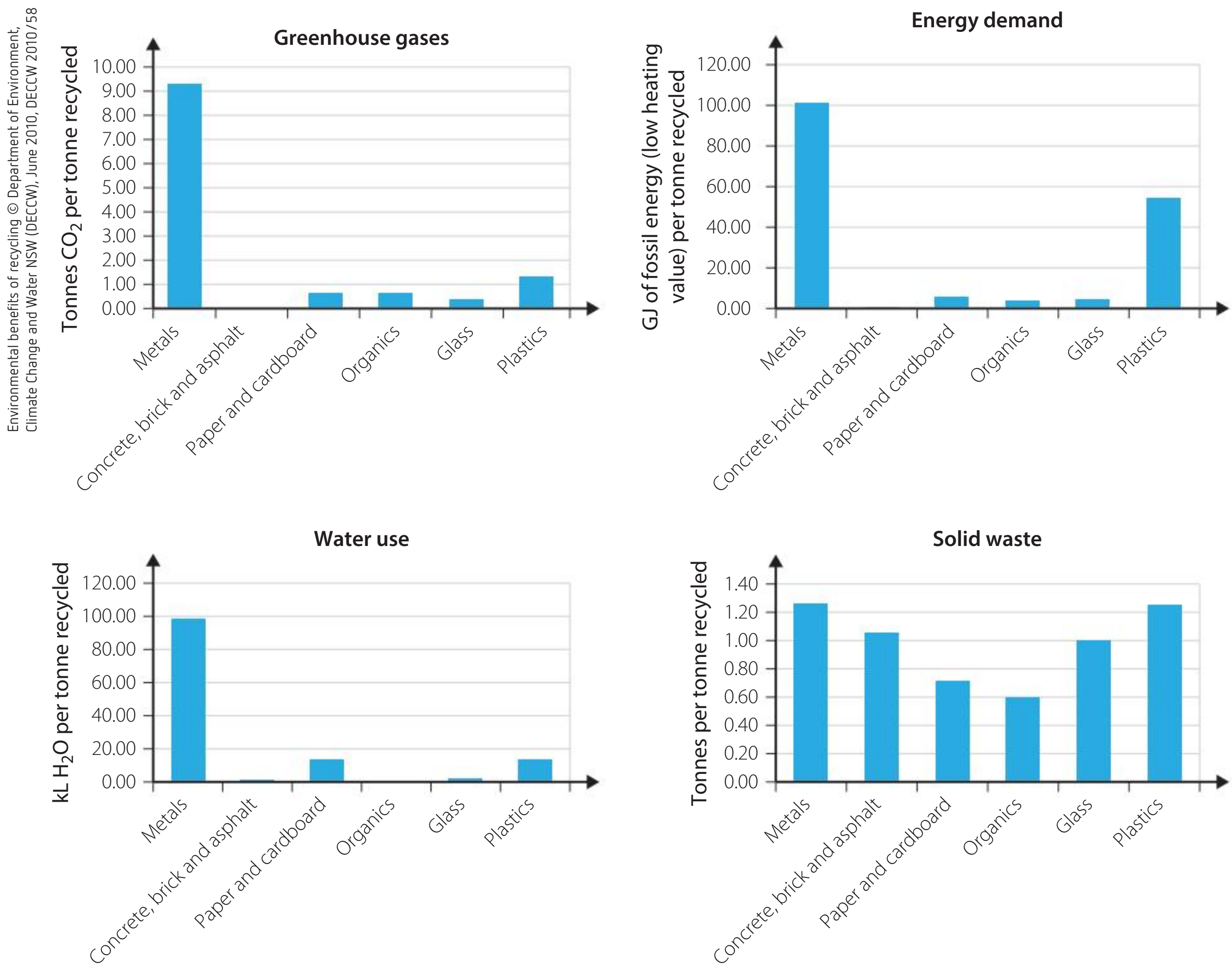

FIGURE 13.11 The average net benefit of recycling 1 tonne of waste by category

TABLE 13.1 The net benefit of recycling 1 tonne of waste material with kerbside collection (positive values are benefits, negative values are impacts)

WASTE MATERIAL	GREENHOUSE GASES (TONNES CO_2)	ENERGY DEMAND (GJ (LOW HEATING VALUE))	WATER USE (kL)	SOLID WASTE (t)
Aluminium	15.85	171.10	181.77	1.4
Steel	0.40	7.311	–2.29	0.95
Cardboard and paper packaging	0.6	9.32	25.41	0.64
Food and garden organics	0.25	0.18	0.44	0.35
Glass containers	0.56	6.07	2.30	0.94
PET plastic #1	0.95	48.45	–20.38	0.78

TABLE 13.2 Mass (in tonnes) of different types of waste in my local community

WASTE MATERIAL	WASTE PERCENTAGE	MASS OF WASTE PER PERSON (t)	LOCAL POPULATION (SAME NUMBER IN ALL ROWS)	TOTAL TONNES OF WASTE PRODUCED ($\frac{\text{WASTE PERCENTAGE}}{100}$ × MASS OF WASTE PER LOCAL PERSON × POPULATION)
Aluminium		0.473		
Steel		0.473		
Cardboard and paper packaging		0.473		
Food and garden organics		0.473		
Glass containers		0.473		
PET plastic #1		0.473		

TABLE 13.3 Net benefit of recycling waste in my local community*

WASTE MATERIAL	TOTAL GREENHOUSE GASES (TONNES CO_2) (TOTAL TONNES OF WASTE × TOTAL GREENHOUSE GASES)	TOTAL ENERGY DEMAND (GJ (LOW HEATING VALUE)) (TOTAL TONNES OF WASTE × TOTAL ENERGY DEMAND)	TOTAL WATER USE (kL) (TOTAL TONNES OF WASTE × TOTAL WATER USE)	TOTAL SOLID WASTE (t) (TOTAL TONNES OF WASTE × TOTAL SOLID WASTE)
Aluminium				
Steel				
Cardboard and paper packaging				
Food and garden organics				
Glass containers				
PET plastic #1				

*Total benefit = benefit from Table 13.1 × total tonnes of waste material

DISCUSSION

1 Which waste material in Figure 13.11 has the greatest environmental savings?
2 Analyse your graphs of environmental impact.
3 Which material recycling should be the first priority for your local council? Justify your answer using your data and knowledge of environmental impacts.

CONCLUSION

Write a suitable conclusion for your investigation

Energy recovery

Incineration has long been used overseas to reduce the volume of waste and recapture energy. There are about 450 waste-to-energy facilities in Europe that directly heat homes or generate electricity. Australia's first waste-to-energy project was approved in Western Australia in October 2018 for completion in 2021. More than 30 other projects were being considered in 2019.

The benefits of energy recapture are reducing methane from landfill and reducing the volume of waste. However, burning waste releases toxic pollutants and generates greenhouse gases, making it a poor long-term strategy for waste management.

Energy recovery can also take place when processed engineered fuels are produced from waste timber, plastics and textiles. These are used in cement kilns or industrial furnaces as a substitute for fossil fuels. Combustion of methane from landfill is also a form of energy recapture.

Landfill

In the past, landfill and incineration were the default options for waste management. Valleys were filled with waste that was sometimes burned to reduce the volume. Australia stopped incinerating waste in the mid-1900s, but about 40% of waste is still disposed of in landfill. Any solid waste can be put into landfill, but this is a poor solution for many items in the waste stream.

Decomposing organic material and liquids that are in landfill form **leachate**. The composition of leachate depends on the waste stream and may include harmful microbes and dissolved substances. Simple compaction and burial of waste can lead to leachate contaminating ground and surface waters, soil contamination and the release of methane. Modern engineered landfill is lined to prevent leachate from escaping (Figure 13.12). Pipes drain leachate for treatment and recirculation to speed up anaerobic decay. Methane is collected through a series of wells in the waste layer. The methane can be flared to reduce environmental impact or used to generate electricity. Rainwater is usually diverted around the site in stormwater drains so that it does not add to the volume of liquid in the landfill.

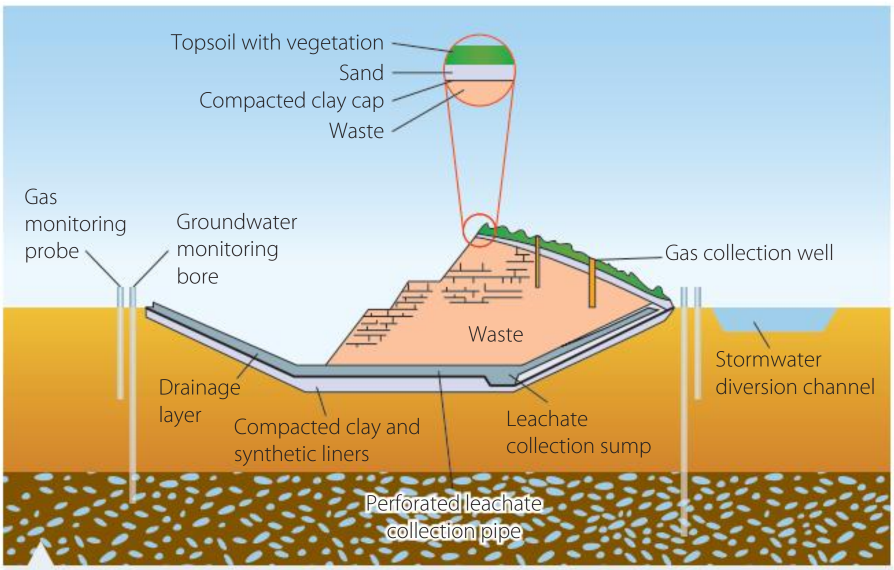

FIGURE 13.12 A cross-section of an engineered landfill

KEY CONCEPTS

- Avoiding and reducing waste are the most important methods of management.
- Re-use requires no extra energy or processing.
- Many different materials can be recycled, including metal, masonry, glass, paper, organics, plastic and e-waste.
- Recycling often requires less energy than producing the original product.
- Energy recapture involves incinerating waste to produce heat for homes or electricity.
- 40% of solid waste is disposed of in landfill.

CHECK YOUR UNDERSTANDING 13.2

1 Outline how you have re-used an item rather than disposing of it.
2 Explain the difference between re-using and recycling.
3 Which materials can be infinitely recycled?
4 Give an example of one material that can be recycled into a different form.
5 Identify two benefits of incinerating waste.
6 Outline the features of engineered landfill that protect the surrounding environment.

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13.3 Sustainability of waste management

The sustainability of waste management requires consideration of the space and energy required, the environmental impact of disposal, the availability of facilities and the demand for any end products. For example, primitive landfill requires a lot of space, harms the surrounding water and soil, releases the powerful greenhouse gas methane, and yields no useful products. This makes it a poor option and it has been abandoned by developed countries.

You will explore the concept of sustainability in depth in Chapter 14.

Companies have begun to innovate towards zero waste. An example from New South Wales involves the unlikely combination of increasing biodiversity near a mine site while creating skincare products and sustainable building materials. Phil and Cherie Thompson of Native Secrets skincare are working with Alkane Resources to create a habitat for the vulnerable pink-tailed worm-lizard in a biodiversity offset area adjacent to a rare earth mine near Dubbo. The offset area is overpopulated by the invasive white cypress. Native Secrets will thin out the cypress trees, allowing understorey plants to regrow, thus increasing local biodiversity and improving the habitat for the pink-tailed worm-lizard. They will extract essential oils from the cypress trees and use them for skincare products (Figure 13.13a). The leftover cypress pulp (Figure 13.13b) will be manufactured into building panels in a process developed by the Sustainable Materials Research and Technology Centre at the University of New South Wales. The oil extraction and panel manufacturing will take place locally, reducing the emissions from transport and the need for storage of raw materials.

Courtesy of Native Secrets

Courtesy of Native Secrets

FIGURE 13.13 **a** Cypress essential oils are used to manufacture skincare products. **b** Cypress pulp is manufactured into building panels.

Re-use

You can sell second-hand goods at garage sales, markets and shops or on the Internet. Many people donate their unwanted items to charitable organisations for resale. The National Association of Charitable Recycling Organisations helps avoid 588 000 tonnes of landfill by reselling items. However, unusable donations cost the organisations $13 million per year for disposal. Sorting, cleaning and redistributing goods require much less energy and water than manufacturing new articles from raw materials.

Recycling

In January 2018, China banned the importation of many types of recyclable materials from Australia. This ban affected 1.3 Mt of recyclable waste. Local councils stockpiled waste and desperately searched for new waste management options. The 2018 National Waste Policy encompasses the principles of the circular economy and estimates that a 5% increase in the recycling rate could add $1–24 billion to Australia's gross domestic product. The small number of Australian recycling facilities and limited end markets mean that this potential has not been realised.

Alamy Stock Photo/Gaertner

FIGURE 13.14 Mounds of asphalt ready to be recycled.

Shutterstock.com/Vitalii Petrushenko

FIGURE 13.15 Glass wool insulation can be made from 80% recycled glass.

Kimbriki Environmental Enterprises Pty Ltd

FIGURE 13.16 The Buy Back Centre at Kimbriki has an ever-changing stock of items for re-use.

Recycled materials in construction and building

Construction waste recycling grew by 35% between 2006 and 2017, the greatest recycling increase for any waste stream over that period. One example of this is the Sustainable Resource Centre established by Fairfield City Council in 1992. The centre diverts more than 100 000 tonnes of material from landfill each year, producing material such as 95% recycled concrete and 65% recycled asphalt (Figure 13.14). Materials that would have gone to landfill have been used again, saving new materials and valuable land.

Another option for road construction is a bitumen substitute called PlastiPhalt®. Glass that is unsuitable for normal recycling can be ground into sand and mixed with plastic waste pellets to create PlastiPhalt. The first PlastiPhalt road in New South Wales was installed on the Old Princes Highway, Engadine, in 2018.

Recycled glass is also useful for homes. Fletcher Insulation uses about 80% post-consumer waste to produce glass wool insulation (Figure 13.15). The Australian glass wool industry produces up to 80 000 tonnes of insulation per year with the potential to recycle more than 50 000 tonnes of glass.

Resource management at Kimbriki

The Kimbriki Resource Recovery Centre in Terrey Hills, New South Wales, is an innovative waste and recycling centre with a dry landfill. It accepts a wide variety of non-organic waste, garden organics and useable goods. Useable items are sold in the on-site Buy Back Centre (Figure 13.16). By partnering with a wide variety of recyclers, Kimbriki diverts more than 80% of waste away from landfill.

- Australian Native Landscapes recycles vegetation and wood waste. Garden waste is ground up and composted, while wood and branches are chipped for mulch.
- Concrete Recyclers turns concrete, brick and roof tiles into road base, sand and landscaping aggregate.
- IQ Renew accepts glass, plastic and aluminium cans, which are sorted and distributed for recycling.
- IQ Renew also collects cardboard and paper for recycling at Visy's Smithfield Paper Mill, which processes up to 1000 tonnes of material daily.

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- Used lead acid batteries are recycled at several Sydney locations.
- Motor oil is collected by Nationwide Oil and recycled by removing water and heavy metals.
- Techcollect, a product stewardship organisation, oversees the recycling of televisions and computers brought to Kimbriki.

Kimbriki makes it convenient for local councils and residents to recycle goods, but also provides a landfill option. The bulk of goods coming to the site provides a steady flow of resources to recyclers.

INVESTIGATION 13.4

Evaluating a local waste management option

Sustainability

Critical and creative thinking

Literacy

Civics and citizenship

The availability of local recycling and waste management is a major factor in how willing people are to recycle. As the distance to recycling bins decreases, more people separate, sort and collect their household waste. People in apartments are much more likely to recycle if there is a chute for recycling rather than having to carry waste to the ground floor. The amount of space available is also important, with better recycling rates occurring when there is more space and larger containers to store recyclable waste.

AIM

To develop an evidence-based star rating for a local waste management facility

METHOD AND ANALYSIS

1. Choose a waste management facility that serves your local area. Council websites often provide information about domestic waste services. There may also be an industrial waste treatment facility in your area (e.g. concrete or metal recycling).
2. Research the following five aspects of sustainable waste management.
   - Energy used to recycle the waste (Is it lower than that needed to make new materials?)
   - Environmental impact
   - Space required for storage and disposal
   - Proximity to your home or school
   - Demand for the re-used or recycled waste
3. Outline the performance of the facility for each of the five aspects and decide if your facility earns a star for good performance.
4. Present your rating as an online review article, justifying the star rating.

DISCUSSION

1. How did you find reliable and valid information about this waste facility?
2. Discuss any difficulties you had in evaluating the five aspects of sustainability.
3. What items from your waste audit in Investigation 13.1 could be sent to this facility?
4. Recommend one way to improve either the service itself or community use of the service.

CONCLUSION

Evaluate the overall level of sustainability for this waste facility.

The problem with plastic

WS
What is the best shopping bag?

In 2015, a total of 381 Mt of new plastic was produced. This is equivalent to two-thirds of the mass of the world population. Every person on Earth used an average of 53 kg of plastic in 2018 and this is predicted to double by 2030. Forty-two per cent of global plastic is used for packaging and is responsible for almost half of the 300 Mt of plastic waste generated every year. In 2010, it was estimated that 8 Mt of plastic ended up in the oceans. By 2025, there will be more plastic than fish in the world's oceans (Figure 13.17).

Shutterstock.com/Rich Carey

FIGURE 13.17 By 2025, there will be more plastic than fish in the world's oceans.

What can we do about the staggering amount of plastic waste? In 2016–17, most (70%) of Australia's plastic recycling was sent overseas, mainly to China. When China banned the importation of many waste materials in 2018, Australia exported more to Indonesia, India, Vietnam and Malaysia. India banned imports in 2019, Malaysia and Thailand will ban imports by 2021, and Vietnam will soon follow suit. This means that local councils that were paid for waste suddenly have to pay for disposal. As a result of increasing pressure from consumers, South Australia was the first state to ban some single-use plastics.

Australian recycling options include Replas, which recycles soft plastics into furniture, and Visy, which produces 100% recycled PET and HDPE plastics. The use of recycled plastics is voluntary in Australia, but in other countries it is mandatory. The Waste Management Association of Australia is lobbying for assistance in expanding the recycling industry and creating local jobs. The Association is

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pushing for an approach like that in the European Union where manufacturers are responsible for the life cycle of products, encouraging a circular economy.

There are three options for handling plastic waste: landfill, incineration and recycling. All of these have economic and environmental costs.

Landfill

Landfill is a cheap disposal option. Most developed countries use modern engineered landfill to safely manage plastic waste. However, many lower-income countries have open landfills and there is a high risk of plastic waste entering the ocean. Even well-managed landfill has negative environmental impacts. Some types of plastic, such as PVC, can degrade to contribute chemical additives and plasticiser compounds to leachate. Proper leachate containment and treatment is needed to keep these compounds out of the surrounding water and soil.

Incineration

Solid plastic waste can be burned as processed engineered fuel to replace fossil fuels in industrial applications or waste-to-energy plants (Figure 13.18). Combustion always produces CO_2. Incomplete combustion can release carbon monoxide and dioxins, both of which are dangerous to humans and ecosystems. Advanced incineration technologies combine efficient combustion with end-of-pipe treatment to remove dioxins from flue gas. Thus, incineration must be carried out in a highly efficient way. If managed in technologically advanced incinerators, plastic waste can profitably be used as a solid fuel.

Alamy Stock Photo/yardbirdstock.com

FIGURE 13.18 The Amager Bakke combined heat and power complex in Copenhagen, Denmark, is an advanced waste-to-energy plant.

If plastic is chemically treated by gasification or pyrolysis, it can be broken down into gas or oil and used as transportation or boiler fuel. This has the advantage that the liquid and gas fuels can be used in a wider range of applications than solid plastic fuel. However, the release of greenhouse gases from all types of plastic incineration means that waste-to-fuel should only be considered if fossil fuel use is otherwise unavoidable.

Recycling

Recycling has the lowest global warming potential of the plastic management options. However, plastic is not infinitely recyclable, as glass or metal are, and some types of plastic cannot be recycled at all. The cost of crude oil determines whether plastic recycling is economically viable. It is often cheaper to make new plastic than to recycle. If plastic waste is incorrectly sorted, it may be more cost-effective to divert it to landfill than to process it. Without economic incentives to promote recycling, companies will opt to keep prices low and use new materials. Finally, most plastic can only be recycled once or twice, after which it will end up in landfill or be incinerated. Recycling simply delays this fate.

KEY CONCEPTS

- Innovating towards zero waste is the goal of future waste management.
- Re-use shops divert waste from landfill.
- Glass, concrete and plastic can be recycled into roads and building products.
- Kimbriki Resource Recovery Centre is a centralised facility for recycling many types of waste.
- Plastic waste is a problem both in terms of the amount of waste and the challenges of recycling it.
- All plastics will eventually end up in landfill or incineration.

CHECK YOUR UNDERSTANDING 13.3

1 List the important factors used to determine the sustainability of waste management.
2 Explain how thinning cypress trees in the Alkane Resources biodiversity offset area is a zero waste process.
3 Outline one problem faced by charitable re-use organisations.
4 How can waste be recycled for roads?
5 Justify naming Kimbriki a resource recovery centre rather than a waste disposal centre.
6 Outline the challenges for managing plastic waste.

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13 CHAPTER SUMMARY

- Australia generates 67 Mt of waste each year.
- Waste comes from households, businesses, industry, construction, power plants and mining.
- Waste can pose physical, chemical and biological hazards.
- The largest component of household waste is organic material.
- Avoiding and reducing waste are the most important methods of management.
- Re-use requires no extra energy or processing.
- Many different materials can be recycled, including metal, masonry, glass, paper, organics, plastic and e-waste.
- Recycling often requires less energy input than producing the original product.
- Energy recapture involves incinerating waste to produce heat for homes or electricity.
- Forty per cent of solid waste is disposed of in landfill.
- Innovating towards zero waste is the goal of future waste management.
- Re-use shops divert waste from landfill.
- Glass, concrete and plastic can be recycled into roads and building products.
- Kimbriki Resource Recovery Centre is a centralised facility for recycling many types of waste.
- Plastic waste is a problem both in terms of the amount of waste and the challenges of recycling it.
- All plastics will eventually end up in landfill or incineration.

13 CHAPTER REVIEW QUESTIONS

Review quiz

1. Australians produce more than 2000 kg of waste per person, but only 560 kg of this is from households. Identify the sources of most of this waste.
2. Identify the major component of household waste and justify a sustainable strategy to manage this waste.
3. Outline the advantages and disadvantages of re-use as a waste management option.
4. Discuss the impact of bans on importing waste by China and other countries.
5. Analyse the possible impact of a law requiring the use of recycled material in consumer packaging.
6. Recycling programs are well established in major metropolitan centres such as Sydney. Recycling rates are much lower in rural areas and smaller centres. Compare the sustainability of recycling in a major city and in a small community.
7. Remote communities generally manage waste by burning and landfill. Suggest more environmentally friendly practices that might be appropriate for a city 100 km from the nearest recycling facility. Use Figure 13.2 to inform your recommendations.
8. Plastic is light, easy to shape and used in millions of different products, many of which have short lifespans. Using items from your everyday life, give three examples of plastic items that could be replaced by other materials and one example of a long-life product that might be made of recycled plastic.
9. Figure 13.19 represents the waste hierarchy.

FIGURE 13.19 The waste hierarchy

Identify practices at each of levels 1–4 that can lead to the target at level 5 and justify the order of importance.

14 Sustainability

OUTCOMES

In this chapter you will learn about:
- defining sustainability S, AAEA, CCT, IU
- how humans affect sustainability CCT
- Aboriginal and Torres Strait Islander resource management ATSIHC, S, CC
- local sustainability initiatives. S, CCT, ICT, L, N, CC, DD

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In 1833, economist William Forster Lloyd introduced the concept of overuse of shared resources by a collective group. Ecologist Garrett Hardin explored the problem in 1968 and called it 'the tragedy of the commons'. In Hardin's example, a shared pasture can support a certain number of animals, but each herder wants to graze as many animals as possible (Figure 14.1). The benefit to a herder of having an extra animal is great, while the cost of overgrazing is shared among all. The 'tragedy' is the inevitable overuse of resources that are irreversibly damaged.

The tragedy of the commons cannot be solved by technology. It requires a change in human attitudes and behaviour. As the world's population increases and we find more ways to use natural resources, everyone needs to work together to ensure we have resources for the future. This is the essence of sustainability.


Alamy Stock Photo/Kumar Sriskandan

FIGURE 14.1 Grazing cattle on Selsley Common, Gloucestershire, England, is an example of sharing resources.

Fish game
Play the fish game and be challenged to avoid the tragedy of the commons.

14.1 Defining sustainability

The German term *Nachhaltigkeit*, meaning sustained yield, first appeared in 1713 and was used in a discussion of forestry management. In 1847, US politician George Perkins Marsh gave a prescient speech in which he not only noted evidence of warming climate but also discussed the effects of deforestation and wetland destruction. Marsh recognised that everything humans need to survive depends, directly or indirectly, on the environment.

Modern use of the term 'sustainability' is generally credited to the 1987 report *Our Common Future* by the World Commission on Environment and Development. The report defined sustainable development as that which 'meets the needs of the present without compromising the ability of future generations to meet their own needs'. The idea of sustainable development gives rise to a model of sustainability with three aspects (or 'pillars') – planet, people and profit – as shown in Figure 14.2.

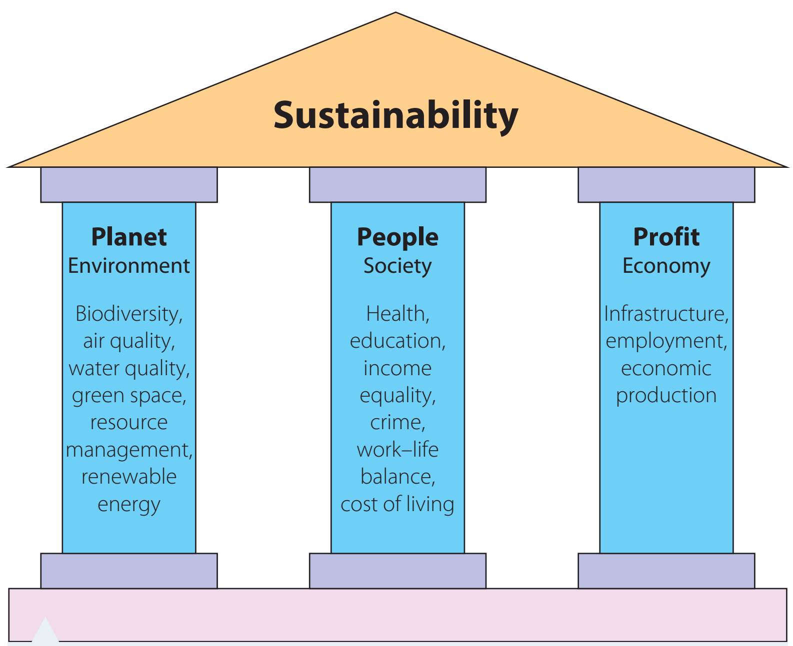

FIGURE 14.2 The pillars of sustainability require a balance of planet, people and profit.

If the three pillars are not balanced, the system becomes unstable, leading to environmental destruction, economic collapse and social unrest.

Environmental destruction is the greatest global threat to sustainability. Governments often measure their success in terms of gross domestic product (GDP). GDP measures the value of the goods and services produced in a country. If GDP is used as a measure of success, then governments may focus on economic growth rather than the environment. If people are ill, hungry or in the midst of war, they want their governments to address the immediate problems rather than prioritise long-term environmental health. Thus, the vision of balanced, sustainable development is not realised.

INVESTIGATION 14.1

Sustainability

Asia and Australia's engagement with Asia

Critical and creative thinking

Intercultural understanding

Definitions of sustainability

Words have different meanings to different people. Definitions of sustainability are influenced by culture, age and background. To an ecologist, sustainability refers to biological systems remaining healthy, diverse and productive over time. To an economist, sustainability is the ability of a business or economy to function profitably over time. To a person from a small language group, sustainability may be the continued survival of rich cultural traditions and the language that expresses the traditions.

AIM

To document definitions of sustainability and explore ideas about sustainability in your local area

METHOD

1. Copy the table in the Results section.
2. Ask different people to define 'sustainability'. Choose people of different ages and backgrounds. Work with classmates to ensure you get a large and diverse sample.
3. Record the definitions and basic data about the respondents in your table. Do not record the person's name but use an identifier such as ID001, ID002

RESULTS

Copy and complete this table. Add more rows as required.

IDENTIFIER	AGE	BACKGROUND	DEFINITION OF SUSTAINABILITY
ID001			
ID002			

ANALYSIS OF RESULTS

Examine your results to determine whether the definition seems to be influenced by age or background. For example, a gardener may focus on ecological aspects of sustainability, whereas an accountant may focus more on economic aspects.

DISCUSSION

1. Did age or background influence the definitions of sustainability?
2. What were common ideas about sustainability?
3. How do the ideas you encountered relate to the models in section 14.1?

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4 Would you expect the same results if you repeated this survey in a different country? Explain your answer.
5 Analyse whether your study provides a fair representation of views in your community.

CONCLUSION

What are common features of the definition of sustainability in your community?

Can economic growth and development be sustainable?

The economist Kenneth Boulding said, 'Anyone who believes that exponential growth can go on forever in a finite world is either a madman or an economist'. The idea of sustainable development has been questioned by those who consider economic growth and sustainability to be incompatible. Some economists and environmental scientists advocate for 'de-growth' where society functions without producing ever-increasing volumes of products that require ever-increasing amounts of material and land. Growth is always at the expense of the environment because resources required for growth are extracted from the environment.

A focus on prosperity and well being may be a better measure of development and national success than growth in GDP. The United Nations Sustainable Development Goals were proposed in 2014 with an awareness of the ecological limits of Earth and the desire to make progress fair and available to all people (Figure 14.3). The 17 goals aspire to a sustainable future with an emphasis on people and environment. Economic growth is still included (goal 8). Environmental goals include clean water (goal 6), alternative energy (goal 7), climate action (goal 13) and biodiversity (goals 14 and 15). Each country must commit resources and gather data on progress towards each of the goals.

Sustainable Development Goals

Explore the Sustainable Development Goals to determine whether they are an elaboration of the pillars of sustainability or a new approach.

https://www.un.org/sustainabledevelopment/sustainable-development-goals/

FIGURE 14.3 The United Nations Sustainable Development Goals

Aboriginal and Torres Strait Islander concepts of sustainability

Aboriginal and Torres Strait Islander peoples have a long history of systems thinking and cultural traditions that encompass sustainability. The holistic concept of caring for Country incorporates notions of sustainability discussed previously in a larger whole called *ngurra-kurlu* by the Warlpiri. This concept includes land, law, language, kinship and ceremony.

For further discussion on Aboriginal and Torres Strait Islander concepts of sustainability, see section 14.3.

Courtesy of Lola Brown and Ric Farmer – Yubu Napa Art Gallery

FIGURE 14.4 Water Dreaming by Lola Brown shows Mikanji, a watercourse west of Yuendumu. Mikanji is usually dry but contains three different water Dreaming tracks.

Aboriginal and Torres Strait Islander peoples do not see land as a commodity or a means of production, but instead as an integral part of existence that connects all living beings and spirituality. They have a traditional and spiritual relationship to Country and Place. These are much more than an area on a map. Anthropologist Deborah Bird Rose explained it as:

> Country is multi-dimensional – it consists of people, animals, plants, Dreamings, underground, earth, soils, minerals and waters, surface water, and air.

Source: Rose, Deborah Bird (1996). *Nourishing Terrains: Australian Aboriginal Views of Landscape and Wilderness.* Canberra: Australian Heritage Commission.

Knowledge of country is passed down through experience, story and artwork (Figure 14.4).

Aboriginal peoples base their care for Country and Place on a long history of observation and stewardship that has led to a deep knowledge of management and the ability to respond to changing conditions. The goal is balance and maintenance, rather than development and growth. Aboriginal peoples have a shared obligation to safeguard and protect Country for future generations.

INVESTIGATION 14.2

Sustainability

Critical and creative thinking

State of the environment

All levels of government must publish State of the Environment reports detailing environmental quality. This information is used to track environmental pressures and progress in addressing these. It is effectively a sustainability report card.

AIM

To investigate the state of the local environment

METHOD

1. Find the State of the Environment report for your local council or region. These are usually available on local council websites.
2. List two management priorities and the type of data used to report on these priorities.

ANALYSIS

1. Relate each management priority to either a pillar of sustainability (Figure 14.2) or a UN Sustainable Development Goal (Figure 14.3).
2. Evaluate the accuracy, validity and reliability (see pages 16–17) of the data used for reporting.

DISCUSSION

1. Analyse the management priorities in the State of the Environment report. Are they narrowly defined or holistic?
2. Do you think the State of the Environment report is a valid reflection of sustainability in your local area? Justify your answer with regard to the types of data used and identified priorities.

»

CONCLUSION

Give your local region a sustainability grade based on your findings and write a report comment to support the grade.

EXTENSION

Compare the local State of the Environment report to the state or national report. Are the data sources and priorities similar or different? Account for differences.

KEY CONCEPTS

- The tragedy of the commons refers to the over-use of common resources for individual benefit and to the detriment of all.
- The concept of sustainability requires management of resources so that they will be available for future generations.
- Sustainable development must balance the needs of the planet, people and profit.
- Development and growth may not be sustainable, despite our best efforts.
- Other definitions of sustainability call for no economic growth and a focus on the well being of people and planet.
- Aboriginal and Torres Strait Islander peoples have a holistic view of sustainability that encompasses care for Country, cultural practices, language and kinship.

CHECK YOUR UNDERSTANDING 14.1

1 What is the solution to the tragedy of the commons?
2 List the ecological challenges recognised by G.P. Marsh.
3 Explain the goal of sustainable development.
4 Outline the argument against sustainable development.
5 How does the Aboriginal concept of caring for Country differ from sustainable development?

14.2 How humans affect sustainability

Human impacts on the natural world affect all aspects of sustainability because they affect our ability to extract the resources needed for life. As humans have extracted more resources for themselves, other species have suffered. Noted entomologist Edward O. Wilson was one of the first people to formalise the concept of biodiversity and emphasise the role of humans in perpetuating the current mass extinction. Wilson summarised the causes of extinction (in order of magnitude of impact) with the acronym HIPPO: Habitat destruction, Invasive species, Pollution, human over-Population and Overharvesting. A 2019 United Nations report came to similar conclusions, identifying changes in land and sea use, exploitation of organisms, climate change, pollution, and invasive species as our greatest extinction threats.

Habitat destruction

In Chapter 10, you learnt about the wide-ranging effects of climate change. Rapid warming affects global habitats by changing temperature zones and weather patterns, as well as causing many cold-climate habitats to shrink in size. Warming is also causing coral bleaching of the Great Barrier Reef.


Shutterstock.com/worldswildlifewonders

FIGURE 14.5 Koalas were endangered by overharvesting until hunting was banned in 1927. The species had recovered by the 1990s but is now threatened by habitat destruction. Bushfires in late 2019 killed approximately 30% of koalas on the New South Wales mid-north coast and destroyed vast areas of remaining habitat.

In addition to the effect of climate, land clearing is a major threat to habitats. Scientists estimate that 62% of threatened species are vulnerable as a result of agricultural activity. In Australia, nearly 60 000 hectares of land were cleared for housing, pasture and agriculture in 2016–17, a substantial increase on the 39 000 hectares cleared in 2015–16. In 2017, the New South Wales government revamped environmental laws, repealing some and introducing the *Biodiversity Conservation Act* 2016. The overall effect was to streamline processes for land clearing. Environmental groups claim that these laws will lead to the extinction of koalas by 2050 (Figure 14.5). Although it is hard to determine the exact status of land clearing and koala numbers, the fact remains that land clearing removes habitat for all animals and leads to degradation of the environment. Current forecasts are that global tree cover will shrink by 223 million hectares by 2050.

The Queensland government found that land clearing has been directly responsible for two plant species becoming extinct in the wild and is a key reason that many species are considered threatened. In addition to directly removing species, land clearing causes sediment run-off, habitat fragmentation, changes to rainfall and climate change (Figure 14.6).

In 2019, ecologists Robin Chazdon and Pedro Brancalion calculated that 9×10^8 hectares of land are available to be reforested. If these were planted with native trees, it would store 205 Gt of carbon – enough to buy us 20 years in fighting climate change and protect a huge amount of biodiversity. Conservation of coastal


Shutterstock.com/Bellamaree

FIGURE 14.6 Land clearing at Lake Macquarie, New South Wales, for a new housing development means loss of habitat and biodiversity.

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ecosystems such as mangroves and seagrass is vital because they may can draw down carbon up to 40 times faster than terrestrial ecosystems. Moving from habitat destruction to habitat creation would be a huge step towards global sustainability.

You learnt about the biotic and abiotic effects of introduced species in Australia in Chapter 13 of *Earth and Environmental Science in Focus Year 11*.

Invasive species

The Australian Academy of Sciences estimated that the combined cost of invasive species is more than $13.6 billion per year. At least 22 native mammals have been driven to extinction by cats and foxes. Despite the high death toll, cats are fourth in terms of overall damage and foxes are sixth (Figure 14.7).

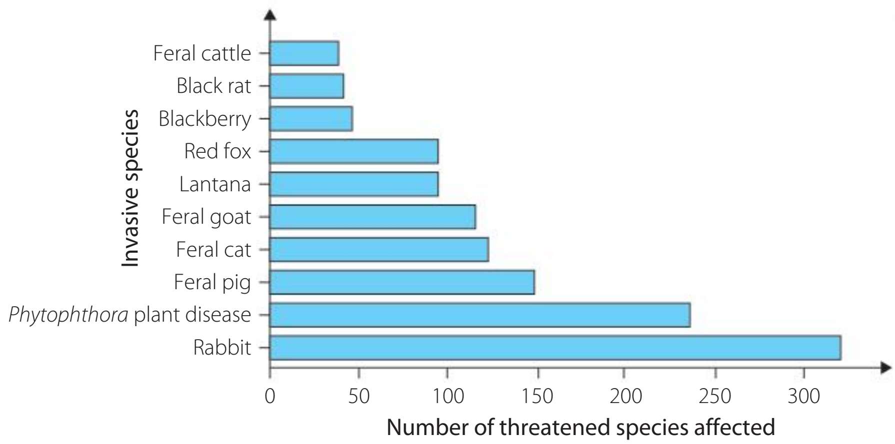

FIGURE 14.7 The top 10 invasive species in Australia and the number of threatened species they affect.

WS Rabbit control

Rabbits remain the greatest threat to sustainability because they damage the abiotic environment by burrowing, eat threatened plants, compete with native grazers and boost the number of predators such as cats and foxes. *Phytophthora*, a root rot fungus, affects native plants (Figure 14.8). Feral pigs affect plants and animals by eating both and destroying habitat.

Alamy Stock Photo/Denis Crawford

FIGURE 14.8 The parsley plant on the right is infected with *Phytophthora*, the invasive root rot fungus.

Pollution

The Lancet Commission on Pollution and Health estimated that 9 million deaths per year are caused by pollution. In 2015, this number was three times more than deaths from HIV/AIDS, tuberculosis and malaria combined, and 15 times more than deaths from all wars and other forms of violence. In the most severely affected countries, pollution accounts for more than a quarter of all deaths. Pollution affects all organisms.

Water pollution

Sediment, nutrients and contaminants in run-off are a significant threat to the Great Barrier Reef (Figure 14.9). Nutrient run-off contributes to outbreaks of crown of thorns starfish and overgrowth of algae. Cloudy water reduces the amount of sunlight available for corals and coral diseases increase.

Australia's inland waters are also in poor condition. In rural areas, pesticide and fertiliser run-off pollutes rivers and streams. In urban areas, there is increased run-off from impervious surfaces into local waterways. Stormwater contains topsoil, rubbish, nutrients, chemicals, oil and grease. These substances may directly harm aquatic life or cause algal blooms that lead to fish kills. High flow leads to erosion and habitat loss.

You learnt about the importance of water and factors affecting water quality in Chapter 11 of *Earth and Environmental Science in Focus Year 11*.

AAP Photo/James Cook University

FIGURE 14.9 A flood plume containing sediments, nutrients and pesticides flows onto the Great Barrier Reef from Bundaberg, Queensland.

Urban rivers around the world are affected by pollution. Sydney's Parramatta River was closed to swimming in the 1960s when run-off, effluent and industrial pollution made swimming a health hazard. Efforts to improve water quality began in 2008 when the Paramatta River Catchment Group was formed. The group brought together local councils, community groups and state government agencies to work collaboratively to improve water quality. Improvements include stormwater harvesting and re-use systems, gross pollutant traps, artificial wetlands, biofiltration systems next to roads and reducing run-off from building sites. Stormwater flows remain a challenge to water quality, but improvements led to the opening of Lake Paramatta for swimming in the summer of 2014–15 and subsequently swimming sites at Chiswick Baths, Dawn Fraser Pool and Cabarita Beach.

Water pollution has an enormous effect on humans, with sewage-contaminated water causing at least 1.8 million deaths per year. The United Nations estimates that the worldwide disease burden could be reduced by 10% if everyone had access to clean water. The improvement in environmental health has not been estimated.

Air pollution

Ground-level ozone, sulfur and nitrogen emissions affect the ability of organisms to function and grow. Sulfur dioxide and nitrogen oxides dissolve in water and fall as acid rain. A lowered pH affects nutrient uptake in plants and damages leaves (Figure 14.10). Ground-level ozone also damages plants, as does particulate matter. Lowered or lost primary production affects the entire ecosystem.

iStock.com/marnag

FIGURE 14.10 Acid rain has caused needle loss and yellowing of these fir tree branches.

Air pollution has a greater impact than water pollution on humans, equating to 6.5–7 million deaths annually. Particles from vehicles, smokestacks and fires cause 58% of air pollution deaths; household air pollution from cooking and heating fuels causes 39% of deaths; and the remainder are caused by ozone pollution. Air pollution leads to respiratory disease, heart disease, stroke, nervous system damage, and irritation of eyes, nose and throat. The ill, very young and very old are worst affected. Fossil fuels are major contributors to air pollution, so efforts to decrease these benefit the climate and air quality.

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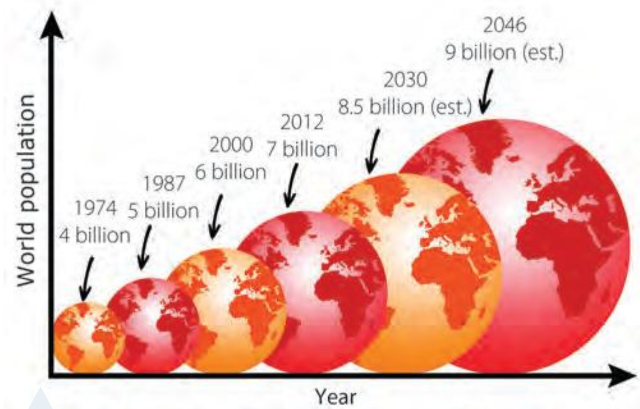
Human over-population

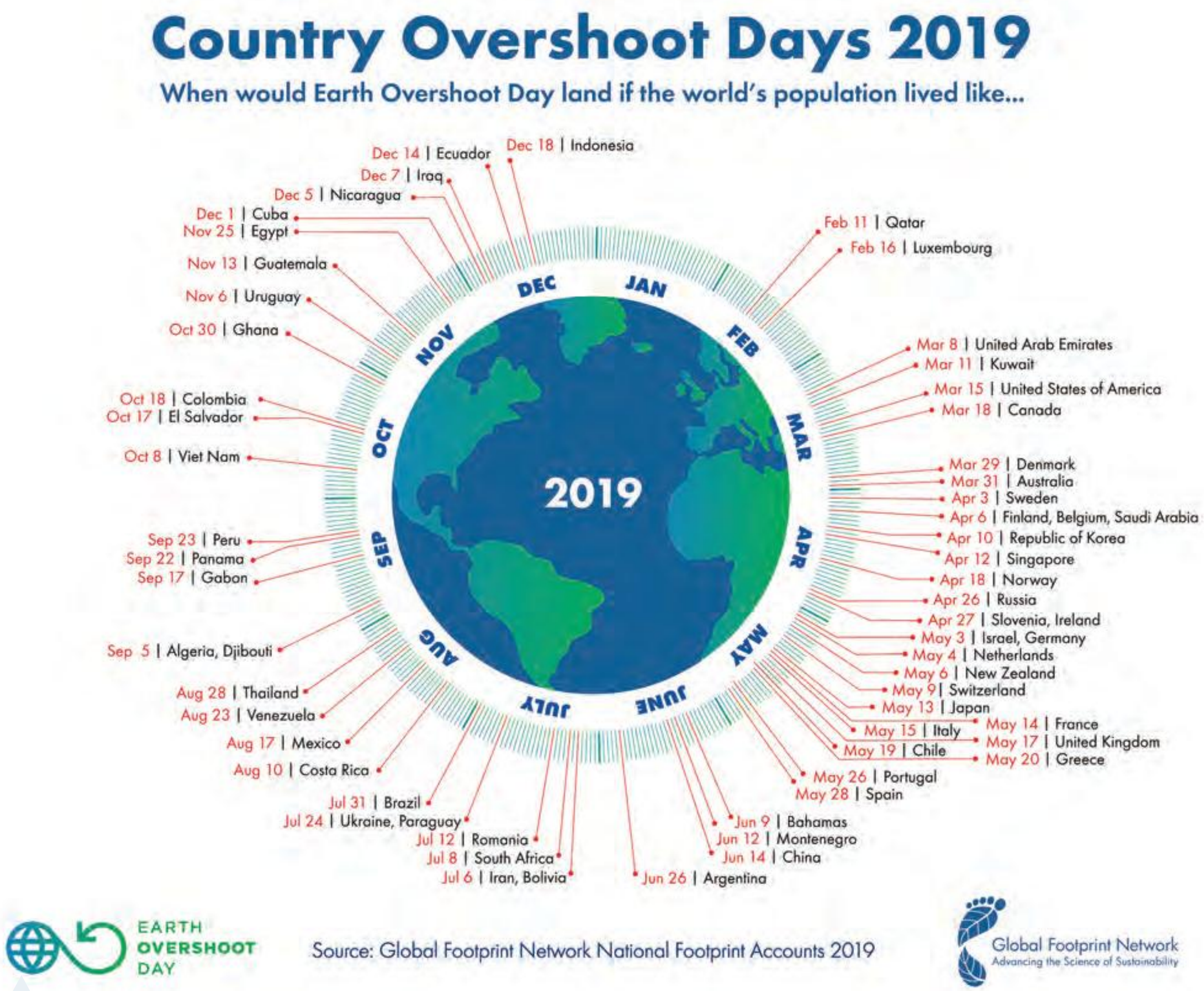
The 20th century saw the biggest increase in the world's population in human history and a similar increase in resource use. The world's population was 6 billion in 2000, grew to 7.3 billion in 2015 and is predicted to reach 8.5 billion in 2030 (Figure 14.11). More people require more resources and produce more waste, increasing the pressure on Earth.

The number of people that Earth can support depends on the resources consumed by each person. Estimates of Earth's **carrying capacity** – the number of people Earth can support indefinitely – vary from 2 billion to 1024 billion, with most estimates at 8 billion. Carrying capacity depends on the resources needed to support each person, but some people use more resources than others. A middle-class American consumes 3.3 times the food and 250 times the water required for basic subsistence. At this level of consumption, the carrying capacity of Earth is about 2 billion people. The Global Footprint Network calculates the environmental footprint and capacity of Earth with current data, declaring an Earth Overshoot Day each year when humans have used the quantity of resources that can be sustainably produced in one year (Figure 14.12). In 2019, Earth Overshoot Day was 29 July.



Shutterstock.com/desdemona72

FIGURE 14.11 Earth's population is rapidly increasing, but how many people can it support?



Source: Global Footprint Network, www.footprintnetwork.org.

FIGURE 14.12 Country Overshoot Days represent the date when each country has used the amount of resources that can be renewed in a year.

Alamy Stock Photo/Science History Images

FIGURE 14.13 The passenger pigeon was once the most common bird in North America. It was hunted to extinction in 100 years.

Overharvesting

Overharvesting is the removal of species from the wild at rates that cannot be replaced – exemplified by the tragedy of the commons. Overharvesting has imperilled 72% of threatened species, including the African elephant, Sumatran rhinoceros, western gorilla and Chinese pangolin. In 1800, the passenger pigeon had a population of billions, but it was extinct 100 years later due to overhunting (Figure 14.13).

Marine species are particularly vulnerable to overharvesting for several reasons: there is a lot of money to be made from fishing; advanced technology makes it easier to find and catch fish; and in unregulated areas, fishing methods such as blast fishing, gill nets and bottom trawling not only catch vast quantities of fish, they also destroy ecosystems. Threats from commercial fishing are rarely identified until species suffer a population crash and fisheries must be closed. Analysis of marine ecosystems data suggests that commercial fish and seafood fisheries may all crash by 2048.

Is your seafood sustainable?

List three retailers who carry certified sustainable seafood and five species that are certified as sustainable by the Marine Stewardship Council.

Overharvesting: southern bluefin tuna

The southern bluefin tuna is a large marine species that ranges from spawning grounds off Java to South Africa (Figure 14.14). The tuna spend most of their annual migration in Australian waters. The meat is highly prized for sashimi in Japan and a single fish may sell for thousands of dollars. Southern bluefin tuna mature between 8 and 20 years of age and live up to 40 years, reaching lengths of more than 2 metres and weighing up to 200 kg.

Southern bluefin tuna are critically endangered globally because their numbers have fallen to approximately 5% of pre-fishing levels. The southern bluefish tuna is considered conservation dependent in Australia, which a take of 6165 tonnes in the 2017–18 season. Stocks are managed by an international commission that sets quotas for the number of fish that can be caught by each country along the migration route. When significant under-reporting of catches was revealed in 2006, quotas were substantially reduced. CSIRO scientists helped develop the management strategy and have engaged in tracking and population modelling to better understand the breeding capacity of the southern bluefin tuna. These award-winning efforts have informed management and led to a slow rebuilding of stocks.

Alamy Stock Photo/Michael Patrick O'Neill

FIGURE 14.14 The southern bluefin tuna is the rarest and most expensive tuna subspecies.

Sustainable harvest: saltwater crocodile

The saltwater crocodile is the largest living reptile, with males averaging 5 metres long and weighing more than 450 kg (Figure 14.15). Wild populations of saltwater crocodile were harvested extensively from the 1940s to the 1960s, resulting in a population crash to approximately 3000 individuals. Australian saltwater crocodiles became protected in 1974 and the population rebounded, with a current estimate of 100 000 individuals.

Species protection led to increased interaction with humans and fatal attacks. In 1985, a proposal for sustainable management and farming was approved. Under this plan, commercial crocodile farms were started with captive breeding and regulated harvesting of eggs from the wild. Landowners and Indigenous communities can harvest eggs and sell these to farms in the Northern Territory or Western Australia for $20–30 per egg. This provides an income and an incentive to keep large, dangerous predators on their land. Egg harvest has little effect on species numbers because there is high mortality of eggs and the harvest is limited. Graham Webb, who devised the strategy, believes sustainable harvest is a vital tool that can achieve conservation goals and provide an income for local people. Experts from the International Union for Conservation of Nature agree that most conservation will only be viable if it supports local people.

iStock.com/Uwe Moser

FIGURE 14.15 Australian saltwater crocodiles are farmed for their belly skin, which is used to make luxury leather goods.

KEY CONCEPTS

- Human impacts on biodiversity and extinction can be summarised with the acronym HIPPO.
- Habitat destruction is the leading cause of extinction and also contributes to climate change.
- Invasive species threaten vulnerable endemic species.
- Pollution leads to more human deaths than HIV/AIDS, tuberculosis and malaria combined.
- Water pollution damages aquatic ecosystems through eutrophication and sedimentation.
- Air pollution damages plants and causes up to 7 million human deaths annually.
- Human populations may soon surpass Earth's carrying capacity.
- Overharvesting is a particular danger for marine species.
- Sustainable harvesting is possible with research-based management plans.

CHECK YOUR UNDERSTANDING 14.2

1. Outline two factors causing habitat destruction.
2. Why are rabbits a greater environmental threat than cats?
3. How does water pollution affect humans and the environment?
4. List four air pollutants.
5. What determines Earth's carrying capacity?
6. In 2016, the average Australian used resources requiring 6.6 global hectares (gha) of land. Earth had 1.63 gha of land per person in 2016. Calculate the number of Earths required if everyone lived as Australians do.
7. Explain why overharvesting particularly affects marine species.
8. Why does crocodile farming protect wild populations?

14.3 Aboriginal and Torres Strait Islander resource management

Aboriginal and Torres Strait Islander peoples care for Country and Place in ways that extend beyond the strict definition of natural resource management into management of human relationships and cultural responsibilities. In this section, you will concentrate on the management of land, water, flora and fauna.

During 60 000–120 000 years of managing Australia's resources, Indigenous Australians have responded to climate change, sea level fluctuations and natural disasters. They domesticated plants such as kangaroo grass and murnong, growing grain in areas now considered to be desert. They used firestick farming to increase biodiversity and feed game animals. Sophisticated aquaculture systems such as the Baiame's Ngunnhu (Brewarrina fish traps) (Figure 14.16) and the Budj Bim (Lake Condah eel farm) were constructed by altering natural features and augmenting these with artificial ponds and canals.

Collection: Museum of Applied Arts and Sciences. Gift of Australian Consolidated Press under the Taxation Incentives for the Arts Scheme, 1985. Photographer unknown.

FIGURE 14.16 The fish traps at Brewarrina, known as Baiame's Ngunnhu, are a complex of stone walls and holding ponds.

Cultural traditions

Country and Place are central to Indigenous culture. The people have a rich relationship with the land that is embodied in many cultural traditions and practices. One of these is totems. Totems can be an animal, a plant, a landscape feature or even a weather pattern. An individual may have several totems that reflect their kinship, language group and significant events during pregnancy. Totems are given by elders and come with special responsibilities to protect that totem and special relationships to people who share the totem. For example, people in the Gamilaraay language group do not marry within their own totem. People generally do not eat their totem but there may be exceptions for special ceremonies. In the Torres Strait, many people wear carved pendants representing their totems for ceremony.

Every Aboriginal community is responsible for, and belongs to, a particular area of Country. Within the area there are sacred sites – places with special meaning for an aspect of social and cultural tradition. These are often concerned with Dreamings and the actions of the spirit ancestors. Some people are custodians of sacred sites and must keep these safe for proper use such as ceremony. Human activity such as digging in sacred ground or cutting down a sacred tree is thought to disturb ancestral spirits with consequences for the person who disturbs them and the community responsible for that site.

Uluru is a well-known sacred site of the Anangu people (Figure 14.17). Tourists were banned from climbing Uluru in 2019 because traditionally this is a sacred men's activity. In the words of traditional custodian Sammy Wilson, 'It is an extremely important place, not a playground or theme park like Disneyland'.

Shutterstock.com/Maurizio De Mattei

FIGURE 14.17 Uluru is a well-known sacred site.

Engaging with other groups

Aboriginal and Torres Strait Islander peoples engage with many different groups to manage and preserve places and resources. National and regional Landcare programs have partnered with Indigenous groups for a range of activities that include monitoring and protecting biodiversity, recording and using ecological knowledge for cool burning, and sustainable agriculture. One example of this is fire management in the western Top End of the Northern Territory. Government representatives, landholders and traditional owners collaborated to create a fire plan for patchwork burning in the region that reduced the incidence of hot, late, dry season fires. The Fish River Fire Project in the Northern Territory reduced the area of land burned in late fires from 69% to 3%, abating greenhouse gas emissions and delivering carbon credits.

Indigenous ranger groups employ more than 660 people across Australia (Figure 14.18). The CSIRO, James Cook University and ranger groups in Arnhem Land and Cape York work together to monitor invasive species such as buffalo and feral pigs, using GPS tracking collars. Birriliburu Indigenous rangers carry out ecological burns, feral animal control, weed control and waterhole clearing in the Birriliburu Indigenous Protected Area. They also monitor endangered species such as muntarngarku (bilby), great desert skinks and night parrots by applying traditional tracking knowledge. Engaging in natural resource management not only improves Country but also improves the mental and physical health of Indigenous managers.

Alamy Stock Photo/David Hancock

FIGURE 14.18 Derrelene Yeeindilli is a Djelk Ranger helping care for land and sea in the Djelk Indigenous Protected Area, Northern Territory.

The Gundjitmarra people are involved in the Lake Condah Sustainable Development project in Victoria. They have worked with Monash University archaeologists to detail how their ancestors farmed eels at Budj Bim in one of Australia's largest aquaculture systems. They have also investigated the biodiversity of the Budji Bim reserve in partnership with the Australian Biological Resources Study, BHP Billiton and Museums Victoria. In cooperation with scientists and researchers, the Gundjitmarra people have pursued World Heritage status for this site that was returned to their care in 2008. World Heritage listing was granted in July 2019.

Laws and actions protecting Country and Place

The modern land rights movement for Aboriginal and Torres Strait Island peoples started in 1963 when the Yolgnu people from the Yirrkala settlement, Northern Territory, presented Australian Parliament with a bark petition asking to have their land and rights returned after a portion of their land had been set aside for a bauxite mine. The first legislation was the *Aboriginal Land Rights (Northern Territory) Act 1976* passed in 1976. This allowed Aboriginal people to claim land rights for country where traditional ownership could be proven and established four land councils.

The *Aboriginal Land Rights Act 1983* in New South Wales recognised traditional ownership and connection to land, and set up Aboriginal Land Councils. The *Native Title Act 1993* followed the historic Mabo decision and provided a national framework for land claims and outlined the requirements for granting of native title. The result of these laws and subsequent decisions was to return stewardship of Country and Place to traditional owners.

Indigenous Protected Areas are part of Australia's network of parks, reserves and protected areas (Figure 14.19). Indigenous Protected Areas are owned or managed by Indigenous groups through agreements with the Australian government. The Indigenous Protected Area program was established in 1997 to support Aboriginal and Torres Strait Islander peoples in managing Country and Place by combining traditional knowledge and western science.

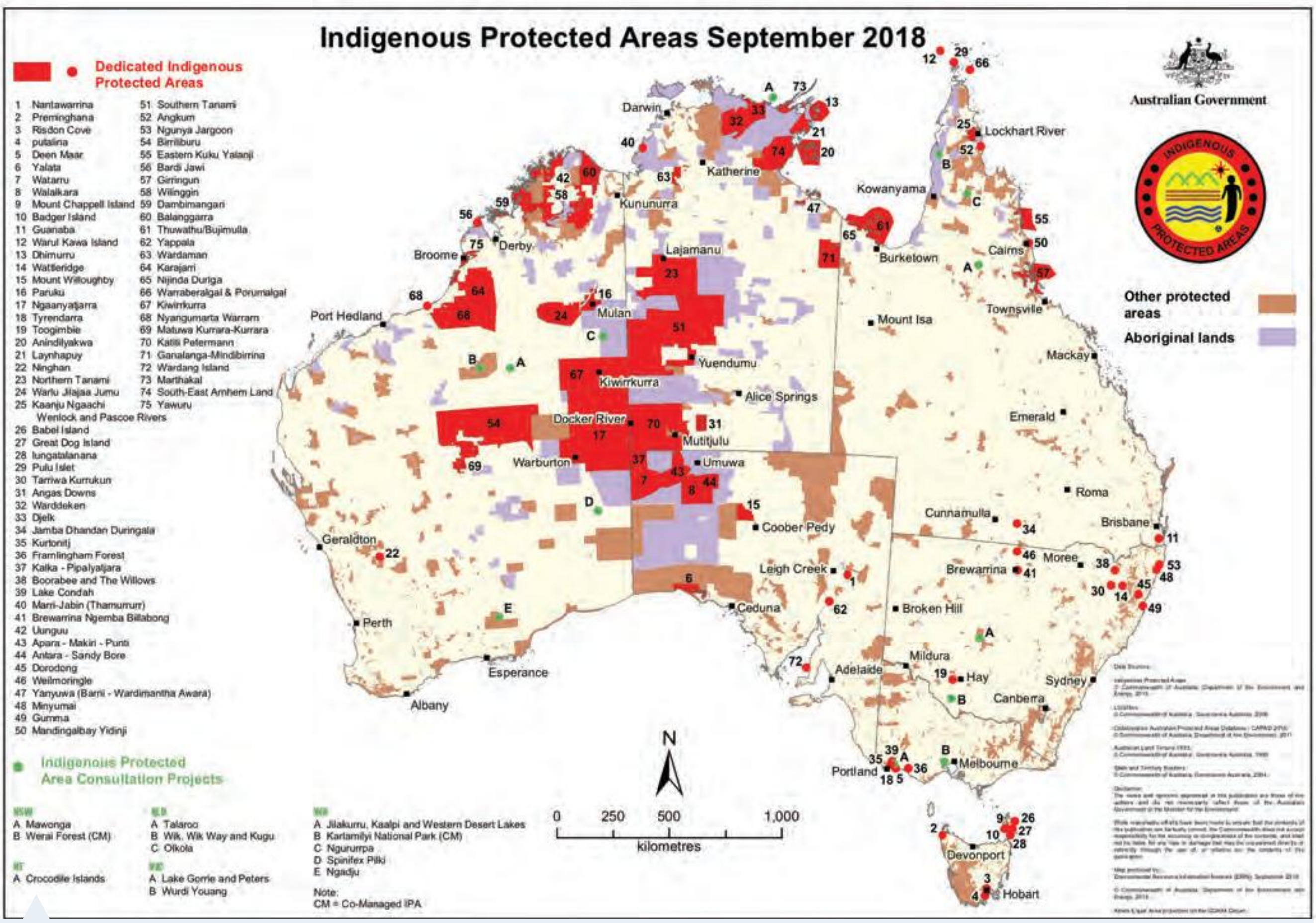


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FIGURE 14.19 Indigenous Protected Areas account for more than 45% of the area in Australia's National Reserve System.

Cultural sites

Many significant cultural sites are on privately held land across Australia. Each state has legislation to protect Indigenous heritage sites. In New South Wales, the *National Parks and Wildlife Act 1974* protects some aspects of Aboriginal cultural heritage, including objects (stone tools, fences and middens) and important sites declared by local Aboriginal communities. In 2019, the New South Wales government was in the process of reforming management and introducing the Aboriginal Cultural Heritage Bill. An Aboriginal Place declaration recognises the special significance of an area and gives it a higher level of protection but does not remove ownership.

There are more than 65 000 Aboriginal sites in New South Wales. Sites include natural sacred sites, shell middens, ceremonial sites, rock art, cemeteries, story sites, massacre sites, carved trees and stone arrangements. Many of these sites are related to land management and care for Country.

Particularly significant cultural sites may be protected by National or World Heritage listings. These listings cover a range of sites deemed to have outstanding historical or natural heritage. Baiame's Ngunnhu (Brewarrina fish traps) in New South Wales is a National Heritage site. The Willandra Lakes Region World Heritage site in New South Wales (Figure 14.20) is of outstanding ecological and historical value, including the remains of Mungo Man, Mungo Lady and more than 460 fossilised footprints. It is managed by the State and Commonwealth governments, with advice from the Elders Council on Indigenous culture.

Shutterstock.com/Leah-Anne Thompson

FIGURE 14.20 Willandra Lakes is a World Heritage site due to its unique eroded landscape and early evidence of Aboriginal culture.

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INVESTIGATION 14.3

Land management at a local Aboriginal site

Aboriginal and Torres Strait Islander histories and culture

AIM

To create a fact sheet about resource management at an Aboriginal site in your local area

METHOD

1 Learn about a nearby Aboriginal site that is related to land management. If possible, consult a local elder about nearby sites and their stories. Only use stories and sites that are public. Do not report on sacred men's or women's sites. State and local council websites also contain information about Aboriginal sites.

2 Prepare a poster that includes:
- the name of the site (in local Aboriginal language and English if possible)
- the traditional owners of the site
- a photo of the site
- a description of the site
- land management practices reflected at this site.

DISCUSSION

1 How did you pick your site?

2 What aspects of land management are demonstrated at your site?

3 Assess the cultural importance of this site.

EXTENSION

Work with classmates to design a heritage trail of local Aboriginal sites.

KEY CONCEPTS

- Indigenous Australians farmed crops and fish, and used burning to create habitat for game animals.
- Totems are organisms or places that are special to Aboriginal people and they feel must be protected.
- Sacred sites are cared for and are believed to be connected to ancestral spirits.
- Aboriginal and Torres Strait Islanders work with government and researchers to manage land through burning, monitoring biodiversity, weed control and other activities.
- Some areas of Australia are owned by Indigenous peoples.
- Indigenous Protected Areas are managed by traditional owners in partnership with the Australian government.
- Significant cultural sites are protected by state and federal law, even if they are on private land.

CHECK YOUR UNDERSTANDING 14.3

1. Identify four plants and animals farmed by Aboriginal Australians.
2. Outline the construction of fish traps and eel farms.
3. How are totems assigned by Aboriginal people?
4. Explain how the tradition of assigning totems protects resources.
5. What do sacred sites protect?
6. Identify the benefits of traditional burning practices.
7. Describe the benefits of Aboriginal rangers working on Country.
8. List the ways cultural sites may be protected.

14.4 Local sustainability initiatives

WS Insect farming workshop

Many ecological problems are based in local activity and, local initiatives are the best way to address these. In 2002, the World Summit on Sustainable Development launched Local Action 21 (also called Agenda 21) to encourage local governments to identify and remove barriers to sustainable development; reduce resource use and environmental degradation; and ensure effective implementation, monitoring and improvement.

The New South Wales government assists organisations to improve their economic position by better environmental practice through the Sustainability Advantage program. Local councils, clubs, businesses and individuals may implement sustainable practices and technologies. Sustainability initiatives can take many forms including online sharing of tools or goods, community gardens (Figure 14.21), repair cafés to fix broken appliances, waste reduction schemes and energy cooperatives. Local councils are responsible for managing the local environment, assisting local businesses and building community among residents. As such, they are well placed to implement sustainability projects that respond to the needs of the local community and to publicise efforts by community groups.

One example of a local sustainability initiative is the Bathurst Roadside Vegetation Management Plan, winner of a 2018 Local Government NSW Excellence in the Environment Award. Bathurst Council assessed more than 1100 km of roadside vegetation and assigned it a conservation value. The project mapped vegetation, including the conservation category, plant community, likely occurrence of threatened ecological communities and known threatened species locations. The council used this information to set rehabilitation priorities, recommend signage, determine actions needed and create a quick reference guide for working in roadside habitats. One outcome of the study was improving the habitat for the threatened Bathurst purple copper butterfly.

Another local sustainability initiative is Solar my School, a combined effort of the Randwick, Waverley and Woollahra Councils to help schools install solar energy. In two years, 56 of the 63 local schools participated, producing 1839 MWh per year of clean energy and avoiding 1600 tonnes per year of CO_2 emissions. The councils provided solar feasibility assessments and financial advice, helped with the tender process, maintained the solar system for 5 years, and provided curriculum-linked resources for teachers and students. In addition to the benefits for the local schools, the program provided 200 Solar Buddy solar-powered lights to students in developing countries.

Alamy Stock Photo/Karstu Photography

FIGURE 14.21 Community farms, such this one in Camperdown, New South Wales, are local sustainability initiatives.

INVESTIGATION 14.4

Sustainability in the local community

Sustainability

Critical and creative thinking

Information and communication technology capability

Literacy

Numeracy

Civics and citizenship

AIM

To create a video advertisement for a local sustainability initiative

METHOD

1 Identify a sustainability initiative in your local area by using information from the local council or community groups.
2 Determine:
   - the name of the initiative
   - what community members are involved
   - how this initiative is supported by community members or organisations
   - environmental, social and economic impacts of the initiative
   - details for people seeking more information.
3 Create a storyboard for your advertisement, mapping out the major visual elements and deciding what footage or photos you will use to add interest.
4 Write a script for your advertisement.
5 Film the advertisement with a camera, phone or video camera.
6 Use editing software to create a polished advertisement with titles, credits etc.

DISCUSSION

1 Discuss the aspects of sustainability that are improved through your chosen initiative.
2 Are there similar initiatives on a larger scale, or is there potential for this project to be used in other communities?

CONCLUSION

Summarise your findings.

KEY CONCEPTS

- Local initiatives are an effective way to address ecological problems in local areas.
- Sustainability initiatives build community among local residents.
- Bathurst Council improved biodiversity by mapping and rehabilitating roadside vegetation.
- Solar my School resulted in substantial greenhouse gas reductions by installing solar panels in schools.

CHECK YOUR UNDERSTANDING 14.4

1 What international program encourages local sustainability?
2 Who may initiate local sustainability actions?
3 Does the Bathurst Roadside Management Plan or the Solar my School program address more aspects of sustainability? Justify your answer.

14 CHAPTER SUMMARY

- The tragedy of the commons refers to over-use of common resources for individual benefit and to the detriment of all.
- The concept of sustainability requires management of resources so that these will be available for future generations.
- Sustainable development must balance the needs of the planet, people and profit.
- Development and growth may not be sustainable, despite our best efforts.
- Other definitions of sustainability call for no economic growth and a focus on the well being of people and planet.
- Aboriginal and Torres Strait Islander peoples have a holistic view of sustainability that encompasses care for Country, cultural practices, language and kinship.
- Human impacts on biodiversity and extinction can be summarised with the acronym HIPPO.
- Habitat destruction is the leading cause of extinction and also contributes to climate change.
- Invasive species threaten vulnerable endemic species.
- Pollution leads to more human deaths than HIV/AIDS, tuberculosis and malaria combined.
- Water pollution damages aquatic ecosystems through eutrophication and sedimentation.
- Air pollution damages plants and causes up to 7 million human deaths annually.
- The human population may soon surpass Earth's carrying capacity.
- Overharvesting is a particular danger for marine species.
- Sustainable harvesting is possible with research-based management plans.
- Indigenous Australians farmed crops and fish, and used burning to create habitat for game animals.
- Totems are organisms or places that are special to Aboriginal people and which they feel must be protected.
- Sacred sites are cared for and are believed to be connected to ancestral spirits.
- Aboriginal and Torres Strait Islanders work with government and researchers to manage land through burning, monitoring biodiversity, weed control and other activities.
- Some areas of Australia are owned by Indigenous peoples.
- Indigenous Protected Areas are managed by traditional owners in partnership with the Australian government.
- Significant cultural sites are protected by state and federal law, even if they are on private land.
- Local initiatives are an effective way to address ecological problems in local areas.
- Sustainability initiatives build community among local residents.
- Bathurst Council improved biodiversity by mapping and rehabilitating roadside vegetation.
- Solar my School resulted in substantial greenhouse gas reductions by installing solar panels in schools.

14 CHAPTER REVIEW QUESTIONS

Review quiz

1. Explain the tragedy of the commons, using overfishing as an example.
2. Compare the Aboriginal way of caring for Country with Western notions of sustainability.
3. Analyse factors that may contribute to the sustainability of water resources.
4. How does habitat destruction impact on sustainability? Include examples in your explanation.
5. Outline two ways that pollution may damage named aspects of sustainability.
6. Assess which human threat to sustainability is the greatest challenge for Australia.
7. Trophy hunting of species such as lions or elephants is an emotionally charged issue. The International Union for the Conservation of Nature argues that properly managed trophy hunting can be a conservation tool. Discuss the risks and benefits of this strategy, using examples from this chapter.
8. Explain how Aboriginal agriculture provides evidence of sustainable resource management.
9. Evaluate the role of totems and sacred sites in caring for Country and Place.
10. Describe the benefits of Aboriginal ranger groups in resource management. Use named examples in your description.

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11 Why are some Aboriginal cultural sites assigned National or World Heritage status?

12 Evaluate a sustainability initiative in your community.

13 It has been suggested that effective environmental protection involves caring for water and adopting a totem. Discuss the benefits and challenges of these two actions.

14 Maximum sustainable yield is the theoretical number of organisms that can be harvested each year without depleting the population. In theory, this number is half of the maximum population that can live in the environment. Is maximum sustainable yield a fixed number? Analyse factors that may change maximum sustainable yield for a species.

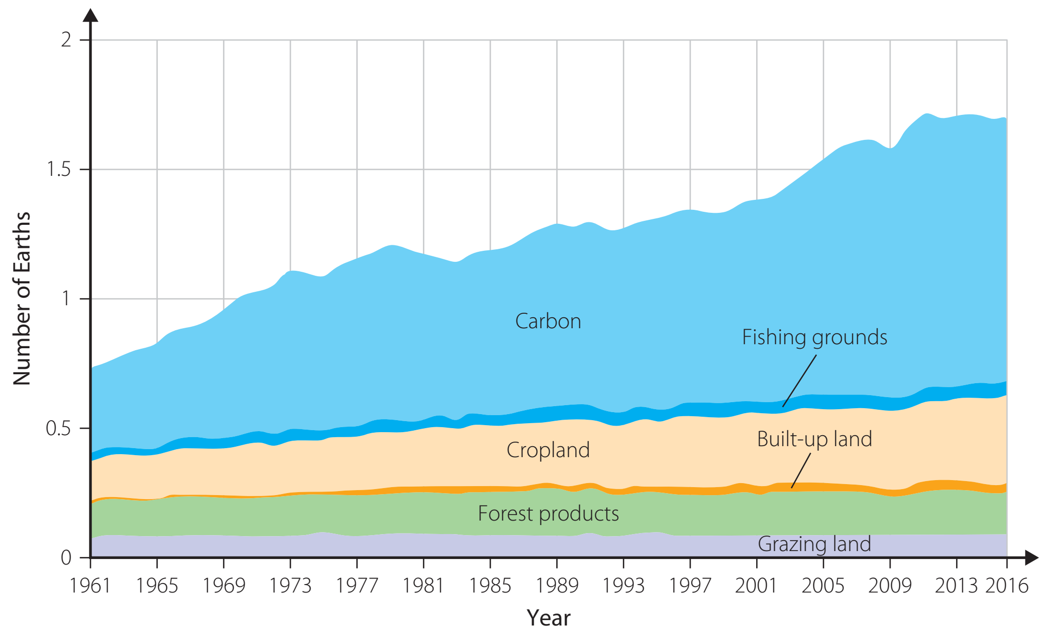
15 Figure 14.22 shows data from the Global Footprint Network.

a In what year did humans begin using more resources than Earth can sustain for a year?

b Which land use accounts for the greatest growth since 1961?

c What factors might account for the relative levelling of footprint from 2011 to 2016?

d Assess the flow-on effects of current global land use and suggest strategies for reducing our resource use to achieve sustainability.



Source: Global Footprint Network, www.footprintnetwork.org.

FIGURE 14.22 World ecological footprint by land type. 'Carbon' represents the amount of forested land necessary to sequester the CO_2 produced from burning fossil fuels.

» END-OF-MODULE REVIEW

MODULE 8: RESOURCE MANAGEMENT

Answer the following questions.

1 The Murray–Darling Basin is home to more than 2 million people and 40% of Australia's agricultural production. Discuss the challenges in designing a sustainable management plan for this vital natural resource.

2 The table below summarises the amount of waste sent to a recycling facility from a large business.

RESOURCE	PROPORTION OF WASTE (%)	MASS (t)
Paper and cardboard recovered	29	151.1
Mixed metals recovered	6	31.3
Mixed organics recovered	14	73.0
Processed engineered fuel manufactured	43	224.1
Residual waste	8	41.7
Total	100	521.2

Paper and cardboard and metals are recycled. Organics are composted. Processed engineered fuel is burned for manufacturing, replacing fossil fuels. Residual waste is sent to landfill.

Evaluate the long-term sustainability of waste management at this company, using data from the table and named examples in your response.

3 A mining company is applying to build an openpit silver, copper and lead mine.

a Describe two likely effects on the environment from this open pit mine and how they may be addressed during or after the mining process.

b Discuss best practice for involving traditional owners in the mining process, using named examples.

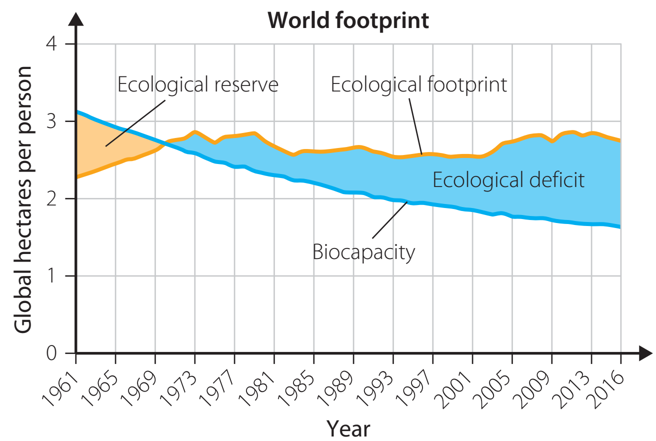
4 What material recycling would most effectively reduce landfill? Recommend two different recycling targets based upon your knowledge of current Australian recycling and waste.

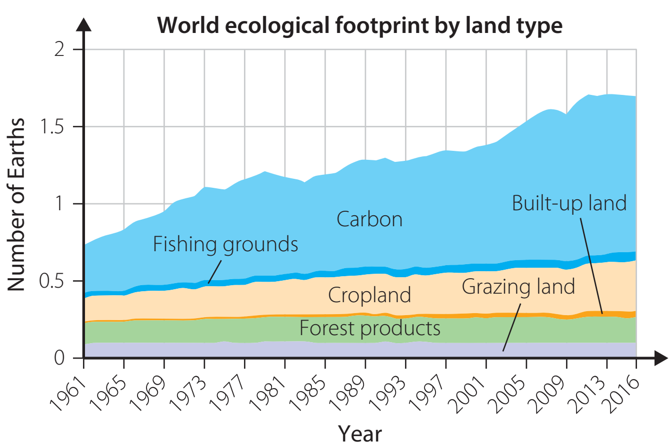
5 Explain the benefits of creating a market for recycled products.

6 Outline ways in which poor waste management may damage sustainability.

7 The graphs below show humanity's ecological footprint, using data from the United Nations. Biocapacity represents the sustainable productivity of Earth's ecosystems.

As of 2016, 86% of the world's population lives in a country with an ecological deficit. Assess the flow-on effects of current global resource use and suggest strategies for reducing these impacts based on a knowledge of Earth and Environmental Science. Use data from the graphs in your response.





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DEPTH STUDY SUGGESTIONS

- Pick one material from your waste audit. Investigate how we find, use and dispose of this substance. Evaluate the sustainability of waste management options for this material in your local area.
- Find out about the traditional owners of the land where your school is located. Record the traditions that help to preserve local resources and how they are involved in managing the land now.
- Audit your home to identify ways in which you could improve sustainability. Quantify your impact before and after taking action. Quantify the amount of waste or greenhouse gases avoided, water saved or other outcomes. Calculate the impact if you maintain this for a year and if your entire school or suburb adopted more sustainable practices.
- Investigate the management of a renewable resource. Determine whether the resource is being sustainably managed, the options for disposal or recycling and how management could be improved.
- Research land management practices to improve sustainability such as regenerative agriculture. Describe the practices and explain how they improve the land and benefit land owners.
- Develop a case study of the environmental impact of a mine. Find out what impacts were expected at the start of mining and how the company planned to manage these impacts. Determine the permanent changes that will occur to the environment of the mine area.
- Document the water sources available for your community, both surface and groundwater. Recommend ways to improve water capture and/or reuse.
- Design the ultimate sustainable home for your area. Explain your choice of building materials and features to improve energy efficiency. Contrast innovative features of the sustainable home with less efficient options that are commonly used.
- Australia has a third of the world's uranium reserves but does not use nuclear power. Olympic Dam in South Australia is the world's largest deposit. Investigate the use of nuclear power and recommend whether Australia should or should not build nuclear power plants.
- The Great Australian Bight may have the largest untapped oil reserve in Australia, but it is also an area of great biological value. Assess the sustainability of oil drilling in the Bight and its impacts on the local ecosystem.

GLOSSARY

A

abiotic not derived from biological organisms

ablation processes that remove ice from a glacier

absolute dating process of determining the age in years of geological or fossilised materials using isotopic clocks

accumulation processes that add ice to a glacier

accuracy closeness of a measured value to what is known to be correct

acid mine drainage acidic water that flows from a mining site leaching toxic elements that may enter surface or groundwater, harming or killing aquatic and terrestrial organisms

adaptation strategy reduction strategy to lessen climate change impact due to greenhouse emissions

adaptive radiation rapid diversification of organisms particularly in response to environmental changes

aerosol substance made of small solid particles or liquid droplets suspended in air

albedo proportion of light falling on a surface that is reflected without being absorbed

alternative energy source of energy other than fossil fuels

amalgamate combine to form a single thing

anhydrous containing no water

anoxic without oxygen

anthropogenic greenhouse gas gas generated by human activity that captures and reradiates infrared radiation

apex predator animal at the top of the food chain

aphelion point in an orbit of a planet when it is furthest from the Sun

Argo network worldwide network of floating buoys that measure ocean temperatures and currents

B

bagasse fibrous organic waste left after sugar-cane processing

base isolation method of building construction in which a suspension system (pads, springs or bearings) separates the building from its base; earthquake mitigation building method

bilaterally symmetrical division into two symmetrical halves

biochar charcoal produced from scorching plant material stored in the soil as a means of removing CO_2 from the atmosphere and adding to soil fertility

bioenergy energy derived from the combustion of organic material to generate heat or electricity

biofuel fuel derived from organic material

biogas gaseous fuel, such as methane, produced by fermentation of organic material

biomarker naturally occurring characteristic that can be used to identify a process

biomass biological material used as fuel

biosphere sum of all living things on Earth

black body object that absorbs all the electromagnetic radiation that falls on it

bloom rapid growth of micro-organisms in water, often resulting in a film or discoloration of the water surface

body fossil preserved hard parts of living things, such as teeth, bones and tree trunks

C

calcareous hard parts of organisms composed of calcium carbonate

calcareous microfossil microfossil that builds its shell from calcium carbonate

calcification process by which something acquires a layer of calcium carbonate

caldera circular crater formed when the volcano conduit erupts explosively outwards or the area collapses

Cambrian explosion event in the Cambrian about 541 million years ago when most phyla began appearing in the fossil record

capacity maximum energy a power source can generate at some point in time

carbon cycle model describing how carbon is stored or moved in Earth systems

carbon sequestration process that removes CO_2 from the atmosphere and stores it in Earth

carbon sink something capable of absorbing more carbon than it emits

carbonic acid weak acid formed when CO_2 dissolves in water

carrying capacity maximum population Earth can support indefinitely

cast fossil formed when an organism has died and decomposed to leave an imprint of its shape in soft material that gradually mineralises

chemosynthetic process by which carbon-containing molecules are converted into organic matter

circumequatorial current westward current flowing along the Equator without a continent deflecting its path

circumpolar current eastward flowing current that surrounds a polar region

climate set of measured averages, variations and extremes of phenomena such as temperature, precipitation and wind conditions throughout the year

climate attribution field of science that aims to establish the cause of an effect in the climate system

climate forcing difference between the incoming energy (from the Sun) and outgoing energy (radiation back into space), also known as radiative forcing

climate proxy physical evidence used to estimate climate conditions of the past

climate system sum of Earth's components and their interactions

column or bar graph type of graph used to show counted objects in unrelated categories; columns do not touch

continent expansive land mass

controlled kept constant

controlled variable constant variable that does not interfere with experiment outcome

craton crust and upper mantle of ancient lithosphere

cropping belt climatic zone suitable for growing crops

cryosphere parts of Earth where water exists as ice

cumulonimbus tall cloud with a flat base often producing thunderstorms

cumulus fluffy cotton-wool-like cloud

D

decile subdivision of a population of items into ten equal sections

delta-13-C value based on the proportions of carbon isotopes, which is used as a proxy for organic productivity ($\delta^{13}C$)

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delta-15-N value used to understand how the nitrogen cycle operated in the oceans in the past ($\delta^{15}N$)

delta-O-18 value comparing isotopes of oxygen that is used as a temperature proxy ($\delta^{18}O$)

dendrochronology scientific study of plant growth rings

dependent variable variable being measured in an experiment

depth study topic of interest explored by students in the form of an investigation or activity

derived data data deduced from raw data by mathematical manipulation, such as graphs, algebraic equations and geometric constructions

desiccation moisture removal from a thing

displace move from its usual place

drought prolonged period of below average rainfall

E

east coast low low-pressure system off the east coast of Australia that can produce cyclones, flooding, storms, destructive winds and subsequent damage to property

eccentricity deviation of Earth's orbit from a circle

Ediacaran period spanning about 95 million years between Cryogenian and Cambrian periods

efficiency amount of useful work a system does using the energy supplied to it

effusive volcanic activity at divergent plate boundaries; a result of crust thinning

embryophyte multicellular eukaryotes with ability to reproduce

empirical can be verified by gaining evidence through observation and experimentation

energy density amount of energy contained in a certain volume of a material

equilibrium state of balance

eukaryote cell with a nucleus enclosed by a membrane

extant still living

extreme weather event unexpected, severe or unseasonal weather

F

falsifiable can be disproved

fault creep measurable earth displacement without accompanying earthquake

faunal overturn change in animal species represented in the fossils

flexible (material) material that can be flexed or compressed without cracking or breaking

flux flow of matter or energy

foram micro-organism of the Foraminifera that built calcium carbonate shells (test)

fossil impression and remains of a once-living plant or animal preserved within sedimentary rock

fractionation process in which two substances are separated based on a common property (e.g. proportions of isotopes change through evaporation or photosynthesis)

G

geo-engineering use of an engineered intervention in a natural Earth system process to directly combat climate change

glacial mass balance value describing gain or loss of ice from a glacier

global water budget total amount of water involved in the water cycle over a year

greenhouse climate state of climate marked by globally warm temperatures and an absence of ice sheets and glaciers

greenhouse gas gas that absorbs infrared radiation and then reradiates it, warming the atmosphere (e.g. CO_2 and water vapour)

Gulf Stream warm Atlantic Ocean current that transfers warm water from the Gulf of Mexico to the North Atlantic

gyre circular pattern of an ocean current where water flows one way in an ocean basin (e.g. anticlockwise in the Southern Hemisphere)

H

heliostat reflective mirror tracking the Sun and reflects light to a collector

histogram type of column graph that has columns that touch each other because the data categories have a natural order

holdfasts stalked organ of alga or aquatic plant enabling attachment to substrate

hotspot volcanic activity as a result of plumes of rising molten mantle upwelling, often producing a volcano

hydroelectric power generation of electricity using flowing water that has been stored in dams

hypothesis tentative prediction, usually based on an existing model or theory; also, a tentative explanation of an observation based on an existing model or theory

I

ice core cylindrical core of ice obtained by drilling

icehouse climate climate state marked by globally low temperatures and the presence of ice sheets at the poles

independent variable controlled variable manipulated by the experimenter

index fossil species of fossil organism that was geographically widespread and numerically abundant and lived during a relatively short geological period

Indian Ocean Dipole natural variability in the western Indian Ocean where sea surface temperatures oscillate between warm and cold compared to the eastern Indian Ocean

Industrial Revolution period during the late 18th and early 19th centuries when manufacturing processes transitioned from human or horsepower to steam power

infrared radiation section of the electromagnetic spectrum with wavelengths between 700 nm and 1 mm, felt by humans as heat

infrastructure structures and facilities such as roads and buildings

instrumental record reading made by a scientific instrument such as a thermometer, barometer and rain gauge

interglacial period of warmer climate between periods of glaciation

isotopes atoms of the same element that have different masses

isotopic dating use of minerals with known constant decay times to date geologic materials such as ash and rock

K

Keeling curve graph of changing CO_2 concentration in the atmosphere

krill ocean-living small crustaceans (prawn-like organisms)

L

lahar rapid mudflow from a volcano

land clearing removal of native vegetation and regrowth

landslide downward movement of large amounts of soil, rock and associated debris due to the force of gravity

large igneous province extensive accumulation of intrusive and effusive igneous rocks that are put in place over a relatively short time

leachate liquid that drains from landfill

lignotuber swelling on the base of the trunk of a tree that contains buds and food reserves, activated after fire

limit of reading smallest unit of measurement on a measuring instrument

line graph type of graph used to show the relationship between continuous variables

line of best fit straight line fitted to a graph of data points

literature review report and evaluation of information from secondary sources

lithified deposited sediments buried, compressed and expelled of fluids to form rock

logbook record of an experiment or investigation kept by the scientist performing the experiments; it is a legal record of the experiments and results

M

macrofossil fossil large enough to be studied without the aid of a microscope

magma molten material in the mantle and/or crust that forms igneous rocks

mean sea level pressure average atmospheric pressure at mean sea level

measurand quantity being measured

methanogenic microorganisms that produce methane

microfossil very small fossil, usually less than 1 mm in diameter

Milankovitch cycle change in Earth's climate due to changes in Earth's orbital properties

mineral carbonation process in which CO_2 reacts with minerals removing the gas from the atmosphere

mitigation strategy prevention strategy to reduce greenhouse gas emissions

model representation of a system or phenomenon that explains the system or phenomenon; may be mathematical equations, a computer simulation, a physical object or words, or take another form

mosaic burning small patches of land that are burnt to produce zones with different fire histories and stages of regrowth

mould fossil formed when an organism has been embedded in mud and sediment and decays to leave an imprint of its shape

N

natural disaster natural event that causes vast amounts of damage and loss of life

natural greenhouse effect process that maintains a warm atmosphere when gases interact with infrared radiation

no-till farming methods of growing crops or pastures without disturbing the soil using ploughing

non-renewable not replaceable, or replaceable at a slower rate than the rate at which it is used

nuclear fission splitting of atomic nuclei whereby loss of mass releases energy

nuclear fusion process in which nuclei of hydrogen atoms are combined under immense pressures, converting mass into energy

nucleation point process where a gas touches a surface providing it with a site to condense and form a liquid

O

obliquity angle of a planet's rotational axis to the orbital plane

ocean acidification increasing acidity of the ocean

ocean heat content measure of the energy stored in the ocean

opaque does not allow light to pass through; not transparent

outlier data point that is distant from the other data points in the sample

overharvesting removing species from the wild at rates that cannot be replaced

oxidise chemical process in which a material reacts with oxygen

ozone layer layer in the stratosphere where there is a high concentration of ozone (O_3)

P

palaeoclimatologist scientist who studies the climate of the past

palaeontologist scientist who studies past life

palynology study of pollen and other spores in archaeology and geology

panspermia hypothesis theory that life initiated on Earth from microorganisms or chemical precursors

peer review evaluation of scientific research by others working in the same field

perihelion point in an orbit of a planet when it is closest to the Sun

permafrost ground that remains frozen from one year to the next

petrification replacing organic matter with minerals and converting it into a stony substance

photovoltaic cell two different silicon layers that convert light into electricity

phreatic when magma from a volcano heats up the groundwater, resulting in an explosion of steam, water, ash and rock

phytoplankton microscopic or small marine plants living near the surface of the ocean

plume cloud of ash emanating from a volcano

pollen microscopic grains containing the male reproductive cells of a plant

precession changes in the direction of a rotational axis over time

precise degree to which individual measurements cluster around the mean

primary data first-hand data collected or measured by researcher

primordial soup hypothetical conditions on Earth 4 million years ago

principle of uniformitarianism consistent behaviour of geological processes over time

productivity measurement of life production of an area

pteropod small gastropod that lives in the surface of the ocean; important part of ocean food webs

pumped hydroelectric storage method of storing energy by pumping water into a higher dam so it can be used to generate hydroelectric power at another time

pyroclastic rapidly moving stream of hot gas and other volcanic matter that moves away from a volcano after an eruption

Q

quake lake landslide-forming lake caused when an earthquake dams a river; the natural dam is loose, so it may fail and lead to downstream flooding

quantitative can be measured, such as length, height or mass

R

radiative forcing difference between the amount of sunlight absorbed by Earth and the amount of energy that is radiated back into space

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rain shadow dry area on the opposite side of a mountain to the direction winds come from

raw data original data taken directly from a measurement

regression when sea levels fall and the ocean covers less of a continent shelf

relative dating process of determining the order of past geological events through their position in the rock column

reliable repeated measurements giving the same results within experimental uncertainty

renewable replaceable at a rate greater than the rate at which it is used

reproducibility giving the same result, within uncertainty, when repeated measurements are made

research question specific question a particular experiment or investigation is designed to answer

reservoir area in which something is stored

resolution how well two closely associated events can be separated

ruminant animal animal that has microbiological fermentation in its stomach, or rumen, as part of digestion

S

scatter graph type of graph that shows the relationship between the individual data points of two variables

scientific method systematic process of observation, experimentation, measurement and analysis to either support or disprove a hypothesis

scientific model representation of a phenomenon such as an object, process or system; used by scientists to understand the phenomenon

sea level average level of the surface of the sea

secondary data information or data that has been collected by another researcher

sector or pie graph circular graph that displays data as fractions or percentages of a whole

seismogram record of ground motion from a seismograph

seismograph instrument used to detect and record earthquakes

seismologist scientist who studies the beginnings and propagation of seismic waves that are registered in Earth

seismometer internal part of a seismograph; may be a pendulum or a mass mounted on a spring

sequestration capture and long-term storage of something

serpentinite metamorphic rock created by the action of water on basaltic rocks

shallow-focus earthquake earthquake with focus at no more than 50–70 km deep

shoreline regression movement of the shoreline towards the land due to beach erosion

SI units standard units of measurement in science, based on multiples of the metre, second, kilogram, kelvin and ampere

silcrete hard, silica-rich sedimentary rock

siliceous microfossil fossil of a micro-organism that built its shell from silica

sink something that receives matter or energy in a system

solar farm many solar panels assembled to make commercial amounts of electricity

solar radiation management technologies that aim to reduce the amount of light entering Earth's atmosphere

source something that provides matter or energy in a system

Southern Annular Mode north–south movement of the westerly wind belt that circles Antarctica, dominating the middle to higher latitudes of the southern hemisphere

span length of time covered by a set of data

specific energy amount of energy per unit mass in a fuel

speleothem structure composed of carbonate minerals precipitated from groundwater in caves

spiracle external respiratory opening of an insect and some fish

standard of living wealth, comfort and access to material goods and services that a person, or society, experiences

stratigraphy branch of geology concerned with the study of rock layers

stratosphere layer of Earth's atmosphere above the troposphere

striation linear groove, ridge or scratch

stromatolite deposits of layers of limestone that have formed from primitive unicellular organisms (algae)

structural reinforcement method of building to increase load capacity using a cross-section of structural members

submarine volcano volcano created at divergent plate boundaries in the depths of the oceans

subsidence sinking or displacement of Earth's surface

sulfate aerosol solid or liquid particles containing sulfur suspended in the atmosphere

supercell thunderstorm with a quickly rotating updraught, has the potential to become a cyclone

supercontinent assembly of Earth's cratons to form one landmass

supercycle cycling of Earth's oceans and continents over 400–600 million years

superposition principle of geology that states that the oldest geological sedimentary layer occurs at the bottom and the youngest at the top

supra-seasonal drought extended period of drought

symbiotic interaction between two organisms that usually benefit each other

systematic error error that results in a consistent, predictable offset from the true value; for example, a zero error

T

tailings material left over after the extraction of valuable minerals from a mine site

temperate climate of a region with mild temperatures

temperature anomaly difference between the temperature at a particular time and the average temperature calculated over a certain period

tephra fragments of rock and other materials that are ejected from a volcano

test shell or hard part created by micro-organisms

tetrapod vertebrate group including amphibians, reptiles, birds and mammals

thermal expansion change in volume of a substance due to an increase in temperature

thermal mass amount of heat a substance absorbs and stores

thermal solar power conversion of solar radiation into heat

thermokast lake water body formed by the melting of permafrost and ground collapse

tidal barrage dam-like wall placed in a tidal area to control water flow and use the movement of water to generate electricity

tidal stream system underwater turbine network converting the kinetic energy of flowing water into electricity

trace fossil indirect evidence of past life preserved in fossil form, such as footprints, burrows and scratchings

transgression when sea levels rise and the ocean covers more of a continental shelf

transparent allows light to pass through without major distortion

transpire letting out of water vapour through a plant's stomata

troposphere region of the atmosphere closest to Earth's surface

turbine machine that produces continuous power when blades revolve in a fast-moving fluid such as water, steam or air

U

uncertainty estimate of the range of values within which the true value of a measurement or derived quantity lies

urban design addressing the arrangement, function and design of buildings, public spaces, transport systems and services

urban heat island effect of increased daytime and night-time temperatures in cities when concrete or metal surfaces absorb and re-emit the Sun's energy

V

valid describes results that are affected by a single independent variable and hence are reproducible

variability measure of how much of a pattern something has

vascular plant group of plants that can conduct water and minerals throughout the plant using xylem

volcano structure on the surface of Earth's crust that expels lava, ash and gases from a magma chamber beneath it

volcanologist scientist who studies volcanoes and their form, structure, magma, lava and processes of formation, activity and eruption

W

watt (W) unit of work representing a change of 1 joule of energy in 1 second

weather day-to-day changes in the atmosphere

wind turbine machine with propellers that transforms the kinetic energy of wind into electricity

Z

zircon common igneous mineral that can be dated and acts as a proxy for igneous activity

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INDEX

Notes: Investigations are in bold type. Aboriginal and Torres Straits Islanders is abbreviated to A&TSI.

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