



EARTH AND ENVIRONMENTAL SCIENCE IN FOCUS

YEAR

11

Christopher Huxley
Thomas Hubble
Steven McClean
Susan Filan





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Earth and Environmental Science in Focus Year 11

1st Edition

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Aboriginal and Torres Strait Islander peoples are advised that this text may contain the names and images of people who have passed away.

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INTRODUCTION

Earth and Environmental Science in Focus Year 11 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 of 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, graphical), or physical constructions. Looking at the 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 11 is written by academic and classroom teaching experts. They 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 students can reach the highest possible standard. The intention has been to ensure all students achieve the level of depth and interest necessary to pursue tertiary studies in Earth and Environmental Science.

Each chapter of the *Earth and Environmental Science in Focus* 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 within the chapter. Relevant diagrams that are easy to interpret and illustrate important concepts support the text. New terms are introduced in **bold type** and defined in a glossary at the end of the book. Important concepts are summarised to assist 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, using the investigative skills of a working scientist. The hands-on activities introduce, reinforce and enable students to practise first-hand the Working Scientifically strand of investigation skills of the NSW syllabus, especially experimental design, data collection, analysis and conclusions. Chapter One explores in detail the concepts of reliability, validity and the nature of scientific investigation using the scientific method, and provides valuable information for performing and analysing investigations and carrying out depth studies. Detailed information is provided that is designed to enhance students' experiences and to provide them with information that will maximise their marks in this fundamental area, and 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, concepts that are also introduced in the first chapter. This invaluable tool supports student learning through chapter questions and investigations.

Earth and Environmental Science in Focus Year 11 provides students with a comprehensive study of modern Earth and Environmental Science that will fully prepare them for exams and any future studies in the area.

AUTHOR TEAM

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Christopher Huxley is an experienced teacher of Earth and Environmental Science with 36 years in the teaching profession. He has degrees majoring in applied biology, geology and geophysics, as well as teaching and learning Science. He works in an independent school in the Blue Mountains and has worked previously in state and Catholic high schools. Chris has extensive experience in curriculum writing and assessment, and has previously co-authored a two-volume text on Earth and Environmental Science.

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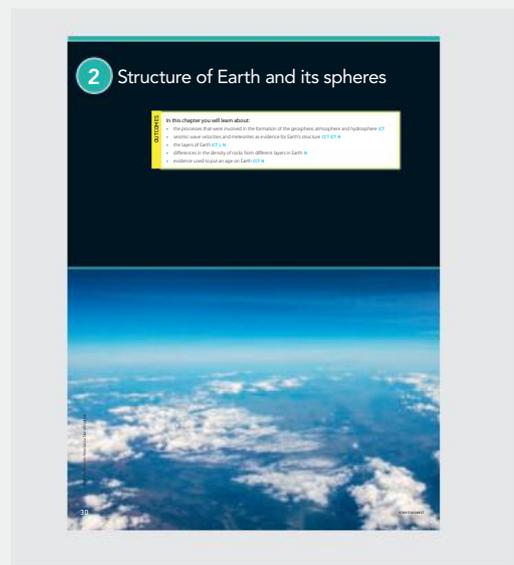
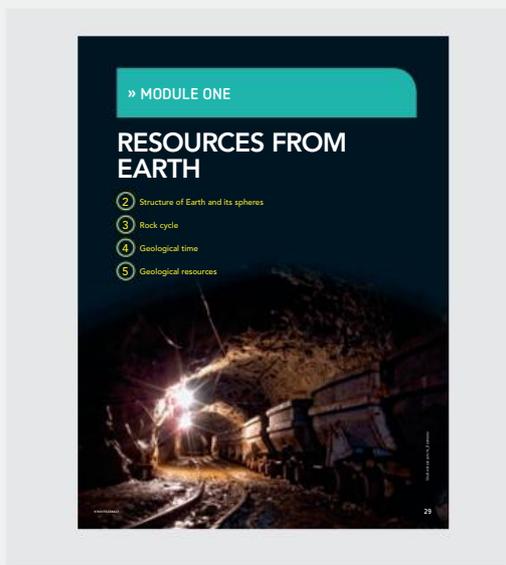
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USING EARTH AND ENVIRONMENTAL SCIENCE IN FOCUS

Earth and Environmental Science in Focus Year 11 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 within 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, a number of strategies have been applied to the preparation of our 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**. This provides repetition and summary for improved assimilation of new ideas.

- KEY CONCEPTS**
- Humans use natural ecosystems for a variety of purposes.
 - The introduction of an exotic species can disrupt the fragile balance of an ecosystem.
 - To become 'invasive', introduced species must meet stated criteria.
 - Human behaviour sometimes favours introduced species over native species.

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.

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

INVESTIGATION 13.1

Soil compaction and water infiltration

AIM
To investigate the effect of compaction of soil on the rate of infiltration of water

MATERIALS

- 2 x 250 mL beakers
- 2 x 100 mL measuring cylinders
- 2 retort stands
- Bosshead and clamp
- 2 large filter funnels
- Filter paper to fit funnels
- Plastic spoon
- 200 mL water
- 2 stopwatches
- Electronic balance
- 100 g soil
- Disposable gloves
- Facemask
- Small container to compress soil (such as a 50 mL beaker)

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION? HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

Soil contains microbes that could make you ill.	Wash your hands at the end of this investigation. Wear gloves and a face mask when handling soil.
Glassware can break and cause cuts.	Take care when handling glassware and do not leave it near the edge of the bench. If breakage occurs, inform your teacher.

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

METHOD

- 1 Set up the apparatus as shown in Figure 13.8 twice so you have two identical sets of equipment.
 - a Place a filter paper in a filter funnel.
 - b Using the bosshead and clamp, attach the filter funnel to the retort stand.
 - c Place a beaker under the filter funnel.
- 2 Place approximately 50 g soil in a weigh boat and measure its mass using the electronic balance.
- 3 Place the soil in one of the filter funnels.
- 4 Repeat for the other 50 g of soil, placing it in the other filter funnel.
- 5 Using the provided container, carefully compress one of the soil samples in the funnel.
- 6 Measure 100 mL of water into each of two measuring cylinders so each contains 100 mL water.

FIGURE 13.8 Equipment set-up

CHAPTER 13 • INTRODUCED SPECIES 329

CHECK YOUR UNDERSTANDING
21

- 1 What is the name of the scientific theory that explains the formation of Earth?
- 2 Name the four elements most abundant on Earth.
- 3 Which elements dominate the composition of the atmosphere?
- 4 Name the two materials that dominate the composition of the hydrosphere.
- 5 Name the layer of Earth that contains most of Earth's iron.
- 6 Where is most of Earth's oxygen located?
- 7 Construct a labelled sketch of Earth's geosphere. Indicate the most common materials composing each of the layers.
- 8 What are the average densities of the mantle and the core?
- 9 Why is the inner core solid?
- 10 Why is Earth special in comparison to the other planets of the solar system?

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.

13 CHAPTER SUMMARY

- The environment is the non-living component of the ecosystem.
- The ecosystem is the non-living and living components and their interactions.
- Abiotic factors are the non-living components of the ecosystem.
- Biotic factors are the living components of the ecosystem.
- Terrestrial ecosystems occur on land.
- Abiotic effects of introduced plant species include changing the soil and water chemistry.
- Abiotic effects of introduced animal species include disrupting the soil crust and soil compaction, leading to erosion and possibly siltation of waterways.
- Biotic effects of introduced plant species include outcompeting native plants for space, light, water and nutrients.
- Biotic effects of introduced animal species include outcompeting for space, water and food; predation upon and poisoning of native species and introduction of exotic diseases.
- Aquatic ecosystems are based on a body of fresh water.
- Introduced fish species affect aquatic ecosystems by:
 - increasing turbidity, which lowers the amount of light that reaches plants, limiting oxygen production
 - decreasing availability of food for native species.
- In aquatic ecosystems, introduced plant species block light reaching photosynthetic plants, limiting oxygen production.
- Marine ecosystems are based in a body of salt water.
- Introduced species affect marine ecosystems by outcompeting native species for food.
- Rabbits are the most invasive introduced animal pest species in Australia.
- Rabbits were released into the environment so they could be hunted for sport.
- Rabbits graze on native plants, seeds, roots and agricultural pastures.
- Rabbits out-compete native animals for food.
- Removal of grass and tree cover by rabbits leaves soil vulnerable to wind and water erosion.
- Due to their adaptability, rabbits quickly spread across rural and suburban Australia.
- Human behaviours have encouraged the spread and population increase of rabbits.
- Various control methods have been tried, including physical destruction of warrens, poison and biological controls.
- It has been estimated that the total annual cost of rabbits in terms of lost agricultural production is \$206 million.
- Humans use natural ecosystems for a variety of purposes.
- The introduction of an exotic species can disrupt the fragile balance of an ecosystem.
- To become 'invasive', introduced species must meet stated criteria.
- Human behaviour sometimes favours introduced species over native species.
- Introduced species can either cause the decline or extinction of native species through:
 - destroying their habitat
 - outcompeting them for food and water
 - preying upon them
 - spreading disease to them
 - poisoning them.

342 MODULE FOUR • IMPACTS OF HUMANS

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 (SDS) for certain chemicals. All teachers are required to follow the safety guidelines of their specific school and associated government legislation when students are in their care.



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.

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

Links between concepts that occur on other pages and chapters are indicated using the **margin notes**.

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

13 CHAPTER REVIEW QUESTIONS

- Complete the table below to show the biotic and abiotic effects of introduced species on terrestrial and marine ecosystems.

TYPE OF ECOSYSTEM	INTRODUCED SPECIES IMPACTS IN THE ECOSYSTEM	
	BIOTIC	ABIOTIC
Terrestrial		
Marine		
- Describe three reasons for the deliberate introduction of either a plant or an animal into Australia.
- Describe three ways in which an exotic species could be accidentally introduced into Australia. Provide one example.
- Explain how abiotic constraints have placed a limit on the distribution of rabbits in Australia.
- Choose one introduced species, such as camel, fox, wheat, goat.
 - Describe three different human activities that have encouraged its spread across Australia.
 - Provide at least two different points of view about the value or harm caused by your chosen species.
 - List at least three native species that your chosen species competes with directly.
- Provide two examples of biological control of a named introduced species. Assess the success of one of these methods.
- Refer to Figure 13.17.
 - Identify the three introduced species.
 - Describe the density of the rabbit population from 1880 to 1910.
 - Provide three reasons for the shape of the eastern grey kangaroo graph from 1885 onwards.
- Sydney is unique among world cities in having national parks within its borders. Suggest how each of us might be able to assist the work of the National Parks and Wildlife Service in maintaining native animal and plant populations within these national parks.
- Justify the continued contribution of money to research organisations, both government and non-government, in finding ways to combat invasive pest species.
- Cats are recognised as one of the greatest threats to native animals and birds. Suppose a virus was developed that, if released, could sterilise any cat that it infected. Present and analyse arguments both for and against the release of this virus.

FIGURE 13.17

CHAPTER 13 ■ INTRODUCED SPECIES 343

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 relationship between pedestrian traffic and soil compaction in different areas of your school campus or a local park.
- Measure water quality in a local creek before and after a heavy rain. How does stormwater input affect the volume and quality of the water?
- Compare soil features, including nutrient and pH levels, in an area of native vegetation and an area with heavy weed infestation.
- Quantify the amount of soil erosion in similar areas with and without erosion control measures. What methods are most effective in preventing erosion?
- Extract data from a large data set such as the Aussie Backyard Bird Count to document changes over time in your local area. Investigate possible reasons for these changes.
- Design and test a scale model of an artificial wetland. Test the water to determine its effectiveness at removing sediment and then see if this can be improved.
- Determine whether inputs and extractions from groundwater are being managed sustainably in your local area.
- Model dryland salinity and native vegetation in large containers with a deep salt layer.
- Investigate and document the process of salinisation over time and its effects on vegetation and soil-surface salt content.

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 ③: TRANSFORMING ENERGY

Answer the following questions.

- The water cycle describes how water moves between the atmosphere, lithosphere and ocean.
 - Name the source of energy that drives the water cycle.
 - Draw a labelled diagram to show four processes that operate as part of the water cycle.
 - Account for the length of time water molecules exist in the deep ocean compared with the length of time water molecules stay on the surface of the ocean.
- Discuss the role of heat and gravity in the vertical and horizontal motion of the lithosphere.
- Account for the differences in the types of volcanoes and their distribution on Venus and Earth.
- Assess the factors that determine the amount of energy released and the duration of an earthquake.
- The table shows information about rocks from four different layers in the same volcano.

LAYER	A	B	C	D
SILICA (% SiO ₂)	75	65	60	50
IRON OXIDE MAGNESIUM (% Fe ₂ O ₃ + % MgO)	3.3	11.0	12.6	18.8
POTASSIUM (% K ₂ O)	4.2	2.9	2.0	0.1
AGE (MILLIONS OF YEARS)	3	7	12	18

 - Construct a graph to show how silica content changes with time.
 - Explain why Layer A is more likely than the other layers to contain ash.
 - Evaluate the data as evidence of magmatic differentiation.
- As part of this module you modelled movement caused by gravity and heat.
 - Construct a labelled drawing to show how your model caused movement.
 - Describe the source of the energy in Earth that enables the process you modelled.
 - Evaluate how accurately your model represented the cause of movement.
- The map in Figure EOM 3.1 shows the location of four volcanic eruption sites, labelled A, B, C and D.
 - Identify the site that is not likely to be currently active.
 - Contrast the origin of the magmas found at locations B and D.
 - Explain the difference in volcanic eruptions at sites B and D.

FIGURE EOM 3.1

CHAPTER 10 ■ HEAT, THE ATMOSPHERE AND HYDROSPHERE 277

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The **depth study** provides you with the opportunity to pursue a topic of interest from within the course. It enables you to study a topic in more depth and present

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 is 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.





Shutterstock.com/Ivan Chudakov



FIGURE 1.1 Collecting soil samples. 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 the verification and testing of 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 that contribute to solutions to environmental issues. The subject has its origins in the study of nature that predated 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 with 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 hypotheses 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 one's confidence in one's 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 test and formulate hypotheses. The body of scientific knowledge that we accept today has been accumulated from such investigations.



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. This hypothesis could be tested by performing experiments in which we measure the size of crystals formed in 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 further to a change in hypothesis and a redefinition of the experimental design. The scientific method is summarised in Figure 1.2.

Experiment design and validity of results

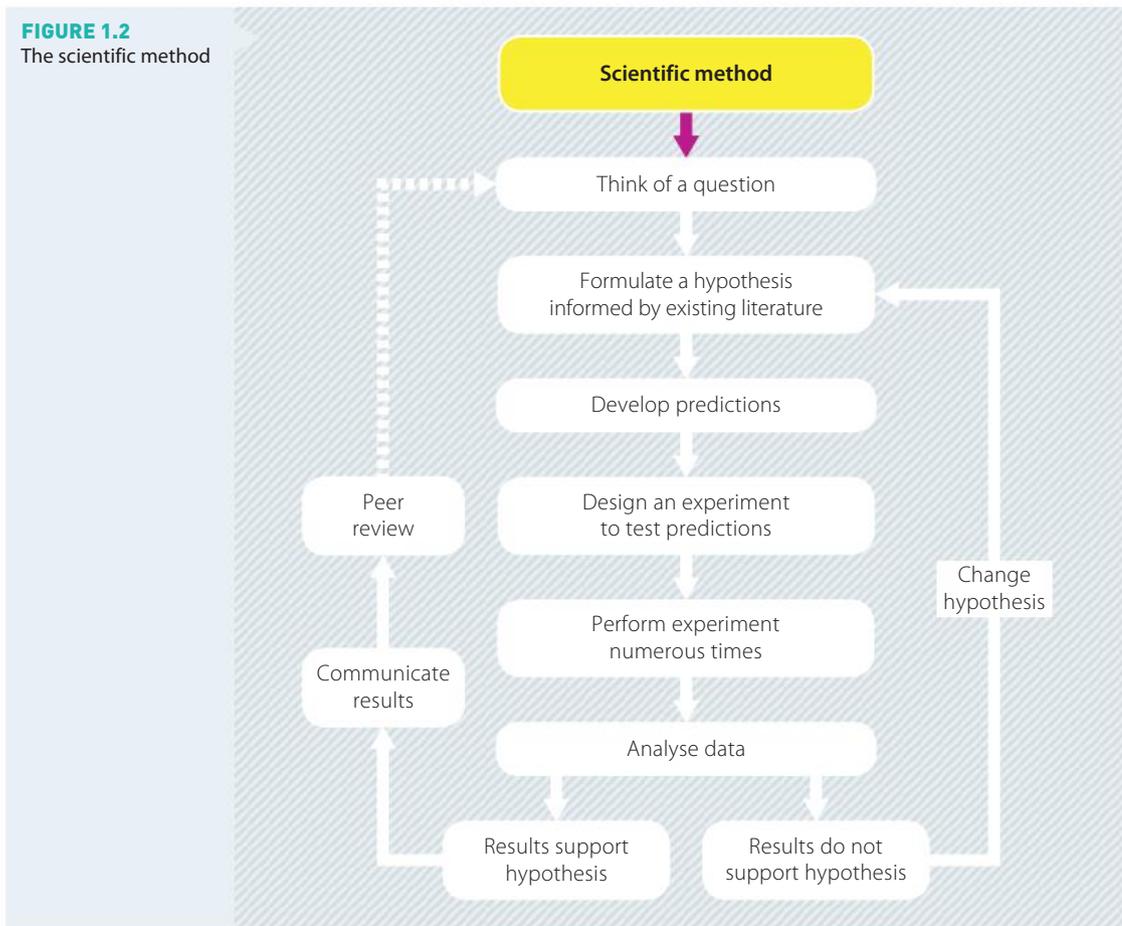
An experiment is designed and performed to test a hypothesis and the results are analysed. If the results of the experiment agree with the hypothesis, then the hypothesis is supported. Note, however, that it is not proved but only supported. There may be other explanations that would also be supported 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. Experiments are considered **reliable** when they 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 15).

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 then considered to make a useful contribution to science, and the experiments and analysis are valid, it will be published. Other scientists can have access to 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, experiments are done, or observations are made, 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.

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.



Science and
pseudoscience

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

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 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 mapping distributions with tape measures and observing with hand lenses through 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; 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 is no birth, death 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 'right' 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

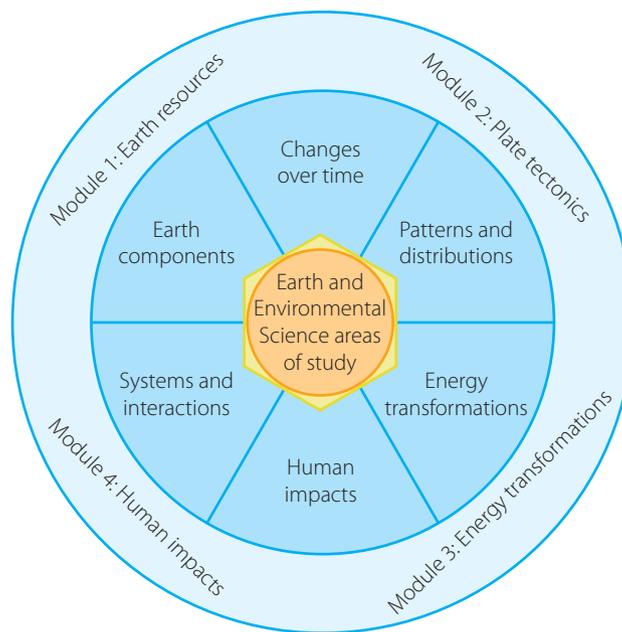
- Earth and Environmental Science uses physical, mathematical and conceptual models to describe Earth systems and to make and test predictions. Models are constantly being refined as we learn more.

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 need to create your own mental models to help you understand it. Concept maps and labelled drawings are useful ways of representing your mental models. They help to remind you that what you are studying is not simply a collection of facts. Every idea is connected to other ideas. For each module, you should create a concept map to record the content that 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 there you have studied in the module.

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 existing 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 needs 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 in which this can be done, and you need to choose the method most appropriate to 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, some of which include:

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

All depth studies will involve the analysis of data, either from **primary data** that you collect first-hand or **secondary data** that you collect from analysing research, such as longitudinal data or resource-management data. Looking for patterns and trends in data will involve analysing and constructing graphs, tables, flow charts, diagrams, keys, spreadsheets and tables and/or databases. This will be dealt with in more detail in the section 'Designing and planning your scientific investigation' (page 15). You may also wish to refer to the NESAs 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 a field of study may be identified

by your teacher, 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 some other topic.

Depth studies provide you with 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 NESAs 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. Also in this stage of your study, you will 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 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 it. This will involve some selection and arrangement of data, perhaps into new tables, and preparation of 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, it is important to 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.

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.





Alamy/ Jim West

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 shortlist of questions but keep a long list too for the moment. Once you have your shortlist 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).

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 NESAs 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 at the same time 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.


Six methods of data collections and analysis

 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 and/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 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. It 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 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 procedures, techniques, and research designs. 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:

- ▶ to extract information from sources
- ▶ to consider the validity of views expressed in each source
- ▶ to 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
- ▶ to be a conclusion; for example, to use the findings of a secondary-sourced research assignment to support a concluding judgement
- ▶ to 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 specific 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, Purpose) test to websites that you find. The most reliable sites are from education 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.

Make sure you keep a record of the information that you find as well as the sources, so 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.

Proposing a research question or hypothesis

If you are doing a primary-sourced investigation, you need to define a research question and/or hypothesis. For example, you may begin by thinking how evaporation of water affects the warming of water. However, to turn it into a more 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 (measured temperature changes).



The CRAAP test

Apply the CRAAP test to any websites that you find.



Alamy Stock Photo / Gregg Vignal

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

Once you have decided on your research question, further reading will guide 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 on what specifically you will be changing (such as varying the rate of evaporation from a surface) and exactly 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 to 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. It 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 water from the surface 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.

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 different fertilisers rather than only 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 actually 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.

Alamy Stock Photo/MSHieldsPhotos



FIGURE 1.6 You need to frame your research question carefully. The significance of the height of a plant depends on the question you wish to answer.

- 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

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 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 / 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 / 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. week 1–2)	<p><i>Questioning and predicting:</i> formulate questions and / or a hypothesis; make predictions about ideas, issues or problems.</p> <p><i>Planning:</i> 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.</p>	
2 Implementing and recording When? (e.g. week 2–4)	<p><i>Conducting investigations:</i> safely carry out valid investigations; make observations and/or accurate measurements; use appropriate technology and measuring instruments.</p> <p><i>Processing and recording data and information:</i> collect, organise, record and process information and / or data as you go.</p>	
3 Analysing and interpreting When? (e.g. week 4–mid week 5)	<p><i>Analysing data and information:</i> reduce large amounts of data by summarising or coding it; begin looking for trends, patterns or mathematical relationships.</p> <p><i>Problem-solving:</i> evaluate the adequacy of data (relevance, accuracy, validity and reliability) from primary and / or secondary sources.</p>	
4 Communicating When? (week 5–mid week 6)	<p><i>Presenting your depth study:</i> Use appropriate language, scientific terminology, calculations, diagrams, graphing and other models of representation; acknowledge your sources.</p>	
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

You may be required to complete a risk assessment before you begin your investigation. 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 resultant 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.



Ethical understanding



Work and enterprise



Personal and social capability

TABLE 1.3 Risk matrix for assessing severity of risk

CONSEQUENCES → LIKELIHOOD ↓	NEGLECTIBLE	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

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 the 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, concerned with protecting the environment, the lives of animals and humans. You need to take ethical principles into consideration 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.

- 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

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 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 be performing 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 its value. 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 which, if repeated multiple 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.



Literacy



Numeracy



Information and communication technology capability

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 any 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 resultant data that you measure is 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 actually 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?

- An experiment will have three types of variable: dependent, independent and controlled.
- Reliability of first-hand data is the degree to which repeated observation and/or measurements taken under identical circumstances will 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 investigation, evaluate how closely the processes and resultant data measure what was intended.
 - In a secondary 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 take 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 more 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 more rapid.

You will need to keep a record of what you do during your investigation. You do this in a hard copy or 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; for example, in patent disputes. Every entry in a scientist's logbook is dated, records are kept in indelible form (pen, not pencil), and entries may even be signed. Never record data onto bits of scrap 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.

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.

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 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 concerned. 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 on 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 and/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.



FIGURE 1.7 Make sure you keep an accurate record of what you do as you do it.

- Concluding stage: evaluate the validity of the investigation and discuss any sources of error, as well as 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 your measurement of 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.

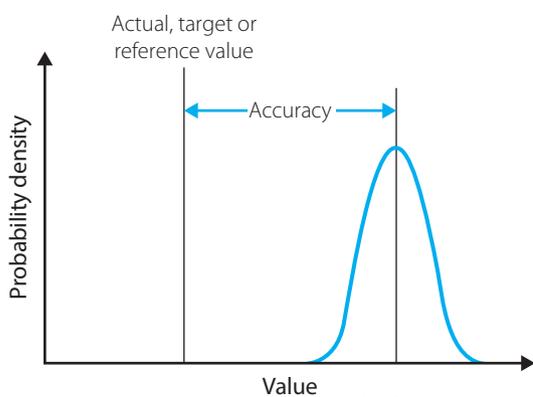
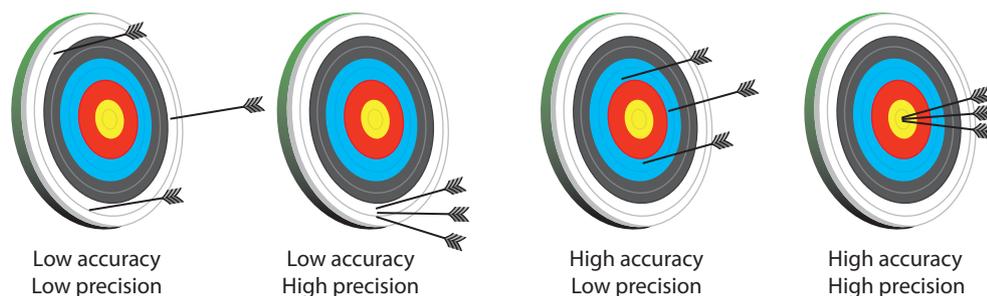


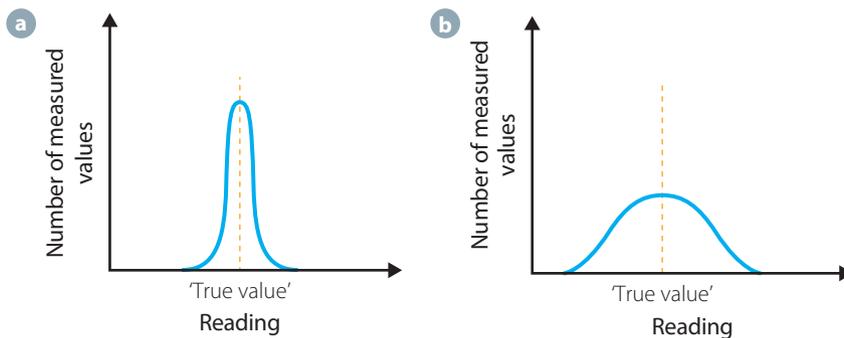
FIGURE 1.9 Graph distinguishing between accuracy and precision

When looking at precision and accuracy in scientific measurements, 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 also be used to show the relationship between accuracy and precision, as in Figure 1.9.

In the scientific definition, precision is described as a measure of the variability of the measurements, so it affects 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 data sets are centred on the same average, so they have the same accuracy.

FIGURE 1.10 In a plot of number of measured values versus reading, **a** results have a small spread about the mean and are, therefore, more precise; **b** has a larger spread about the mean and is 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.

Look at the weblink *Accuracy and precision* to increase your understanding of minimising error and to clarify some concepts about processing of 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 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
- the precision of measuring devices
- the 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 a numerical scale. 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.

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.



Resolution and precision

Analysing data



Critical and creative thinking



Numeracy



Information and communication technology capability

When you have collected all your data you will need to analyse it. 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 means, or how it was 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 is what you actually measured (with units and uncertainties). **Derived data** is 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 this 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 lots 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. This will often mean that the origin is not shown in your graph. Usually there is no reason why it should be. 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 (give 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.

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 (hrs)	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

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

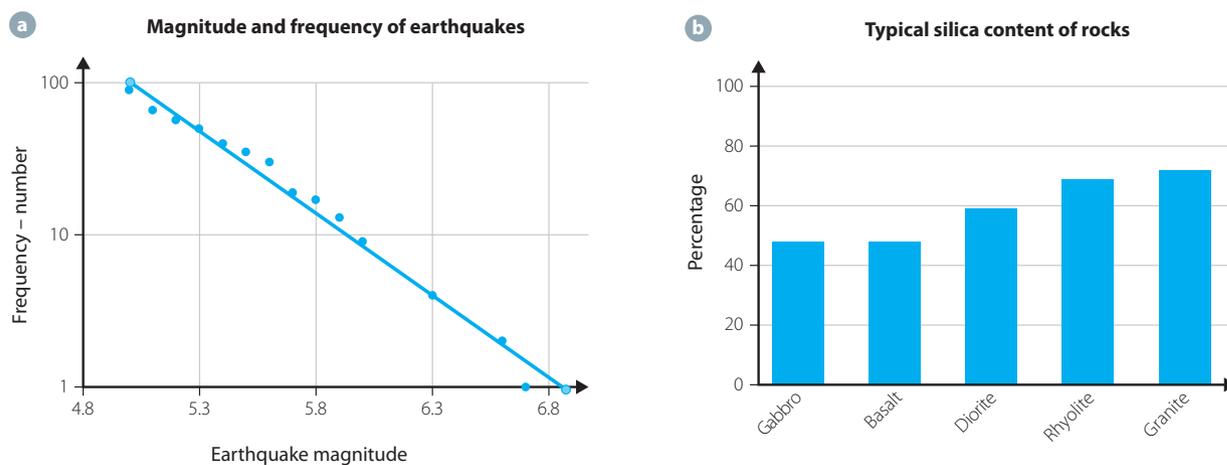


FIGURE 1.12 a A scatter plot demonstrating a mathematical relationship b A column graph comparing different categories

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 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

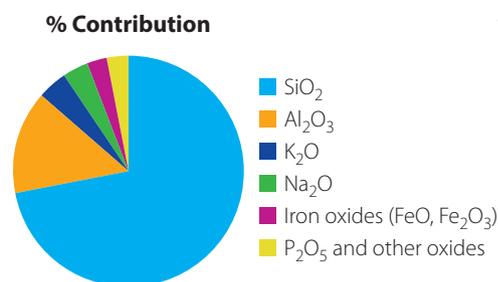


FIGURE 1.13 Data in Table 1.8 shown as a pie graph

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 is 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, suppose you have hypothesised that the maximum temperature range in which a native species of fish will reproduce 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°, then the results are not consistent with the hypothesis. If the uncertainty is 2° 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?

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

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 and demonstrations, public lectures, websites, videos and blogs. All of these are useful ways of communicating your understanding too, 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. 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, 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 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.

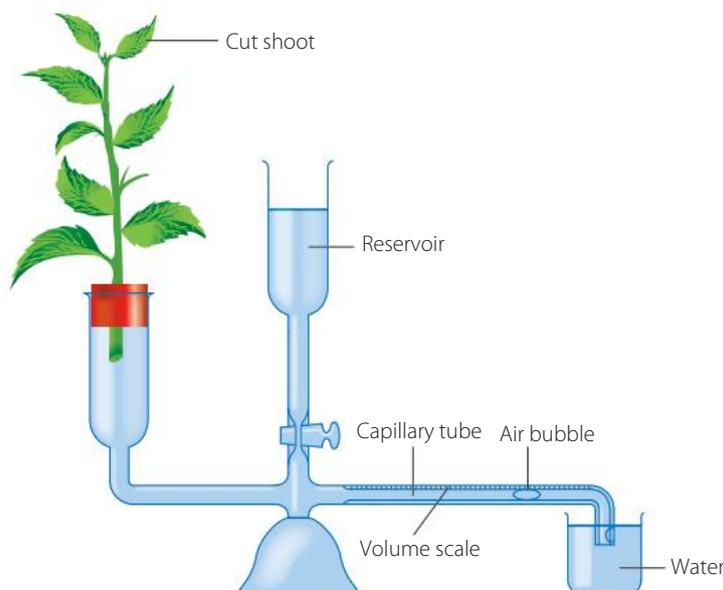
Method

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. This might be from a depth study analysing evapotranspiration, for example.

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 data sets. 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, for example [2], or the author and year of publication, for example (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.

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-source 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.

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.



Referencing guide

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



Referencing i-tutorial

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

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.

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 own 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 from other areas, 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.



Website accessibility

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

» MODULE ONE

RESOURCES FROM EARTH

- ② Structure of Earth and its spheres
- ③ Rock cycle
- ④ Geological time
- ⑤ Geological resources



2

Structure of Earth and its spheres

OUTCOMES

In this chapter you will learn about:

- the processes that were involved in the formation of the geosphere, atmosphere and hydrosphere **ICT**
- seismic wave velocities and meteorites as evidence for Earth's structure **CCT ICT N**
- the layers of Earth **ICT L N**
- differences in the density of rocks from different layers in Earth **N**
- evidence used to put an age on Earth **CCT N**





Earth is unique among the solar system's planets and moons. It alone has land, oceans, air and life present on its surface. These components are called the geosphere, hydrosphere, atmosphere and biosphere respectively (Figure 2.1).

There are many reasons why this unique combination exists, and the fact that they do is sometimes described as an example of the *Goldilocks effect*. The physical conditions required for a hydrosphere, atmosphere, geosphere and biosphere to coexist have to be 'just right'. Earth is not too big and not too small, it's not too hot and it's not too cold, just like Goldilock's porridge.



NASA Images. Credit: Data: AVHRR, NDVI, SeaWiFS, MODIS, NCEP, DMSF and Sky2000 star catalog; AVHRR and SeaWiFS texture: Reto Stockli; Visualization: Marit Jentoft-Nilsen

FIGURE 2.1 A view of our planet from space showing components of the geosphere, hydrosphere, atmosphere and biosphere. Identify areas of land, ocean, ice, cloud and forest.

2.1 Forming Earth's three inorganic spheres

Earth's three **inorganic** spheres developed when Earth was young. Their existence, composition and structure is probably a direct consequence of the way in which a cloud of interstellar gas and dust came together. This cloud formed the Sun, planets, moons, asteroids, comets, meteors and other materials. It was almost entirely composed of hydrogen and helium. The relatively tiny amount of rock and ice dust in the cloud contained the carbon, silicon, oxygen, iron and other elements that were moulded into the metallic cores and rocky mantles of the planets and moons.

There are no direct observations of these events. They are inferred as the sequence of events that led to the formation of Earth with its three spheres and the other objects in the solar system. Models have been created to explain the physical and chemical data that has been collected about the solar system over the last few centuries.

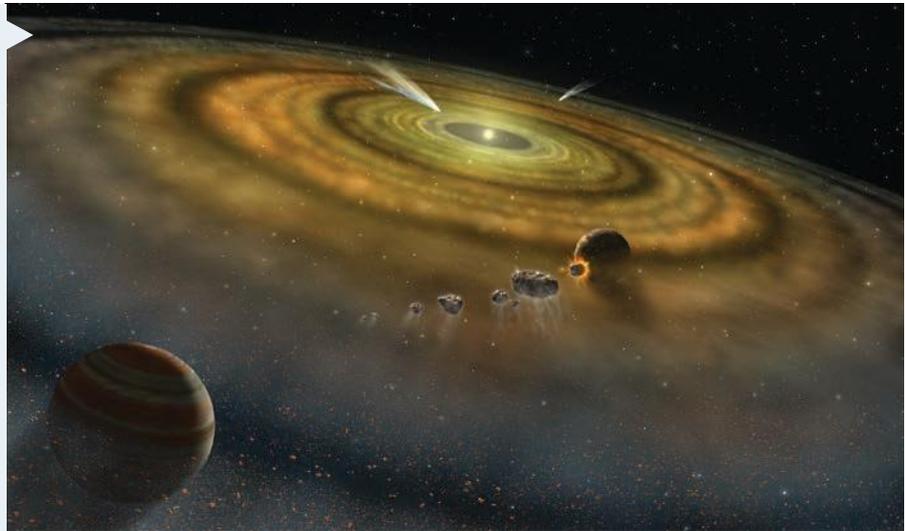
Before 1960, these observations could only be made with telescopes and spectrometers attached to the telescopes. Since 1960, rockets have been used to send probes into space to explore the inner and outer solar system. They have photographed, surveyed, sampled and measured many of properties of the planets and comets with spectrometers of various types. The data obtained has enabled a knowledge base to be assembled concerning the composition, location and surface characteristics of the solar system's objects.

This data has been used to develop the *Planetesimal Accretion theory* to explain the formation of the Sun, the planets and the solar system (Figure 2.2). It explains how the material that formed Earth possibly aggregated together and provides understanding of how the core, the geosphere, the hydrosphere and the atmosphere then separated from each other.



Discover Earth from space

FIGURE 2.2
Artist's impression of
planetary accretion



NASA

The Planetesimal Accretion theory

The Planetesimal Accretion theory is one of the theories that has been put forward to explain the formation of the solar system, including Earth. It states that about 4.56 billion years ago, the Sun and planets coalesced from an interstellar cloud of gas and dust called a solar nebula. A distant supernova explosion may have sent a shock wave through the nebula that caused material in it to concentrate around a particular point. Most of the material condensed into the centre to form the Sun, but some of the material began to orbit the central point.

The orbiting dust collected into clumps that attracted each other. Gravity attracted and concentrated the clumps, gas and dust. Over time this clumping process generated asteroids and tiny planetesimals that were large enough to attract each other and collide. Any object with mass has gravity. The larger the mass, the larger the gravitational pull of materials towards the centre; it is this gravitational pull that makes planets more or less round (Figure 2.3).

As planetesimals attracted each other and collided, they became small planets, which continued to attract and collide with each other. This is called the accretion phase. During the accretion phase, about 4.5 billion years ago, large numbers of smaller planetesimals were sucked into the forming planets by gravitational forces exerted by the larger planets. These collisions converted vast amounts of gravitational potential energy into heat, which melted all the material in the forming planets.

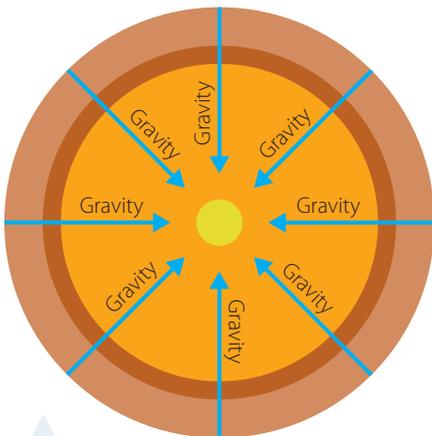


FIGURE 2.3 A planet's gravity pulls equally from all directions. This is the reason for the overall spherical shape of asteroids, planetesimals and planets.

The accretion phase

At the end of the accretion process, the eight large planets of our solar system had been formed. Some of the remaining planetesimals were captured by the gravity of the planets and became moons; others were flung out to the outer solar system by near-miss collisions with the planets – particularly Jupiter and Saturn, which may even be responsible for relocating Neptune and Uranus into their present orbits.

Toward the end of the accretion phase, the planets started to cool by radiating their heat into space. On Earth, the dense metals sank towards the centre of the planet and formed the core. By about 4.4 billion years ago, less dense silicates had formed an outer layer of material around the core and began to cool, crystallise and solidify to form the mantle.

Icy comets and planetesimals are also thought to be involved in the accretion phase. This material was mixed in with the silicates of the mantle as some of the water was released into the atmospheres that were forming on all the planets. Gases are thought to have been released to form atmospheres on all the planets at this time.

Between 4.4 and 4 billion years ago, Earth's surface cooled to a point where it ceased to be a boiling mass of magma. The first rocky crust formed and the mantle began to solidify. This material was probably recycled back into the interior of the planet. Then about 4 billion years ago, two important events occurred. The crust stabilised and became a permanent feature of Earth, and the surface cooled far enough below the boiling point of water for Earth's oceans to also become permanent features. The earliest signs of life and organic processes that have been detected date from about 3.8 billion years ago. The processes that generated Earth's geosphere, atmosphere and hydrosphere were complete.

Geosphere

The **geosphere** is composed of all the material below the solid surface of Earth. It consists of the silicate rocky crust and mantle, as well as the metallic core, as shown in Figure 2.4. Until 1936, all of this material was thought to be solid, but then Inge Lehmann's seismological investigations demonstrated that the outer core must be liquid.

The geosphere contains almost all of the mass of Earth, 99.977% by one commonly accepted calculation. A recent estimate of Earth's total mass is 5.9722×10^{21} tonnes. The crust varies in thickness from about 10km to 100km, the mantle–core boundary is located 2900km below Earth's surface and the core is 3500km thick. Temperature, pressure and the velocity of seismic waves change through the layers, as shown in Figures 2.5 and 2.6.

The average chemical composition of Earth has been estimated by combining data from different sources and inferred from complex modelling studies. The starting point for these estimates is based on a determination of the average **density** of Earth as 5510kgm^{-3} (or 5.51gcm^{-3}), based on astronomical measurements of Earth's size and mass. This is a little higher than the density of the iron oxide mineral haematite (5.30gcm^{-3}). This value arises partly because roughly equal proportions of iron and oxygen account for 62% of Earth's total mass. Table 2.1 presents the average elemental composition of the whole Earth, as well as the core, mantle and crust, as percentage by mass.



FIGURE 2.4 Earth as a set of nested spheres: crust, mantle, inner core and outer core

The unit g cm^{-3} makes for easy comparison with the density of water, which is 1g cm^{-3} .

TABLE 2.1 Elements that make up Earth's spheres (percentage by mass)

ELEMENT	SYMBOL	WHOLE EARTH (%)	CORE (%)	MANTLE (%)	CRUST (%)
Iron	Fe	32.1	85.5	5.8	5.0
Oxygen	O	30.1	<0.0001	44.8	46.6
Silicon	Si	15.1	6.0	21.5	27.7
Magnesium	Mg	13.9	<0.0001	22.8	2.1
Sulfur	S	2.92	1.9	0.02	0.05
Nickel	Ni	1.82	5.2	0.1	0.01
Calcium	Ca	1.5	<0.0001	2.3	3.6
Aluminium	Al	1.4	<0.0001	2.2	8.1
Sodium	Na	0.13	<0.0001	0.3	2.6
Potassium	K	0.014	<0.0001	0.03	2.8
Total		98.9	98.6	99.7	98.5

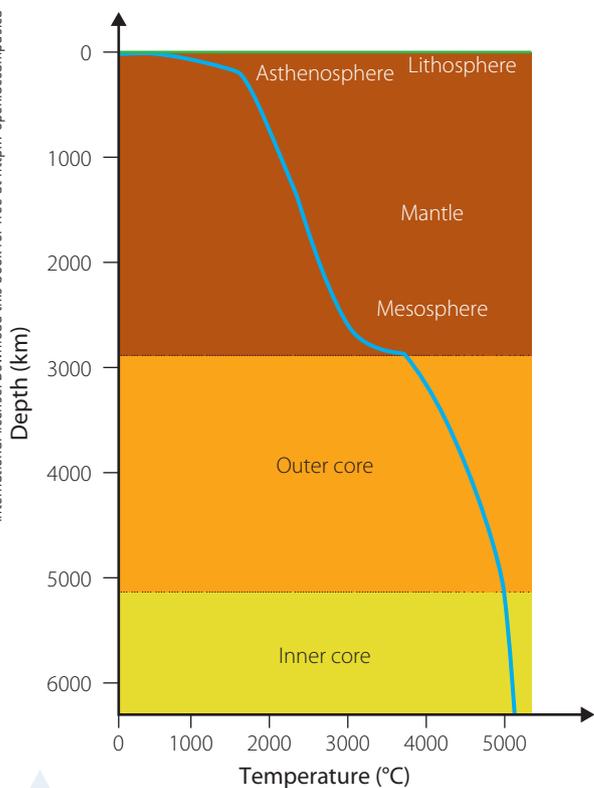


FIGURE 2.5 Estimated temperature profile for planet Earth

Earth's spherical core is about 3500 km thick and consists of a metallic alloy predominantly composed of iron, with small amounts of nickel, silicon and sulfur. The inner core is thought to have begun solidifying about one billion years ago and is surrounded by a liquid outer core. The core contains almost all (99%) of Earth's iron.

Convection currents in the liquid core are thought to be responsible for Earth's magnetic field. The **temperature** of the inner core's surface has been estimated to be about 5000°C, which is about the same temperature as the surface of the Sun. The immense pressure generated by the rest of the overlying geosphere maintains the inner core in its solid state. The temperature of the outer core's surface has been estimated to be about 3700°C.

The **mantle** is a spherical shell of crystalline material about 2900 km thick that surrounds the core. It is predominantly composed of magnesium, silicon and oxygen, with small amounts of iron, aluminium, calcium and sodium. These chemical components combine to form low-density crystalline magnesium iron silicates in the upper mantle and a combination of higher density crystalline magnesium iron silicates and magnesium iron oxides in the lower mantle. The temperature of the mantle ranges from about 500°C at the top of the mantle to about 3750°C at the base of the mantle.

The crust is the outermost layer of the geosphere and is a thin spherical shell of crystalline material 10–100 km thick that encloses the mantle. It is predominantly composed of silicon and oxygen,

moderate amounts of aluminium and iron, and small amounts of calcium, magnesium, potassium and sodium. These chemical components combine to form crystalline calcium magnesium iron silicates, calcium sodium aluminium silicate, potassium aluminium silicate and silicon dioxide. The temperature of the crust ranges from about 500°C at the base of the crust to about 15°C at the top of the crust. Earth's estimated temperature profile is graphed in Figure 2.5 and the density and seismic velocity profiles in Figure 2.6.

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

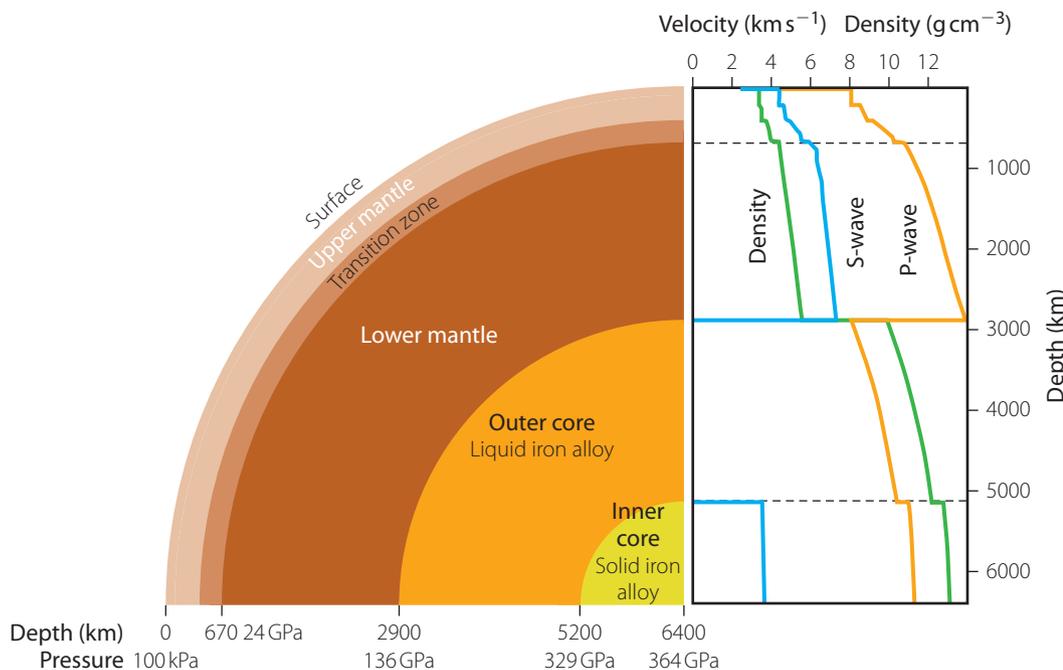


FIGURE 2.6 Estimated density and seismic velocity profile for planet Earth

Figure from press release, 'Liquid acoustics half way to the Earth's core', November 24, 2015, RIKEN

Atmosphere

Earth's **atmosphere** is its outer gas layer. Nitrogen (78%), oxygen (21%), argon (0.9%) and carbon dioxide (0.04%) make up almost all of this gas, as shown in Figure 2.7. Other gases present are neon, helium, methane, krypton, nitrous oxide, sulfur dioxide and hydrogen, but these are present in very small amounts. Water vapour is also commonly present in the air near Earth's surface but the amount of this gas present is highly variable. Very cold air is usually dry and contains almost no water, whereas hot surface air can contain up to 4% by weight of water vapour. The atmosphere has a mass of about 5.15×10^{18} kg.

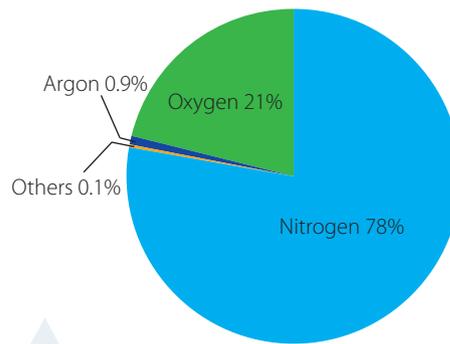


FIGURE 2.7 Composition of the atmosphere

Hydrosphere

The **hydrosphere** includes all the water that is present on Earth. It includes the water that is present in rivers, lakes and oceans; within ice sheets; in the atmosphere; and Earth's subsurface groundwater.

The total amount of water on Earth has a mass of about 1.4×10^{21} kg, which is about 0.023% of the Earth's entire mass. Most of Earth's water, about 96.5%, is present in the oceans; 1.74% is present in the ice sheets and glaciers; 1.69% is groundwater. The rest, 0.76%, is the surface water present in lakes, rivers, streams and swamps (USGS figures). The oceanic water also contains a considerable amount of dissolved salt (NaCl); about 3.72×10^{19} kg according to one estimate.

Water is one of Earth's most important chemical compounds (Figure 2.8). This is because water is essentially involved in many of Earth's internal and surface processes. Without water, Earth's soils would be barren sandy dusts and there would be no plate tectonics. Water is also a vital component of the planet's atmosphere and is the necessary medium in which the chemistry of life occurs.



Shutterstock.com/Philip Schubert

FIGURE 2.8 Water is a vital compound in the formation of Earth.

INVESTIGATION 2.1

Modelling the separation of Earth's core, mantle, crust and atmosphere



Critical and creative thinking



Information and communication technology capability

INTRODUCTION

A physical model can be used to demonstrate how the layers of Earth separated from one another when Earth was young, hot and mostly molten. This investigation is a type of analogue model in which different materials are used to represent actual materials.

AIM

To model the formation and separation of the core, mantle, crust and atmosphere

MATERIALS

- 1 L watertight plastic container with a tight-fitting lid (such as a PET bottle)
- 300g of 6 mm diameter steel ball bearings (or similar)
- 400 mL undiluted green cordial or thick sugar syrup
- 100 mL olive oil
- Funnel
- Stopwatch
- Digital camera with time-lapse function



WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?

If you shake the container too hard, it might shatter and break, creating a slip hazard.

HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

Perform the experiment in a safe space and don't shake the plastic container too hard.

What other risks are associated with this investigation? How should you manage them?

METHOD

- 1 Pour the ball bearings into the plastic container.
- 2 Use the funnel to pour the cordial or sugar syrup into the container.
- 3 Use the funnel to pour the oil into the container. Do not fill the container completely. Make sure that you have left a little space at the top.
- 4 Take a series of photographs using the time-lapse function and make notes that describe how the materials appear.
- 5 Put the lid on tightly and shake the container fairly vigorously but not too hard. This will mix the materials.
- 6 Put the container down on the desk. Photograph it and take notes that describe how the materials appear in the container just after it has been shaken.
- 8 Take a series of photographs using the time-lapse function and make observations about the changes that occur within the container. Record your observations for 20 minutes.
- 9 Leave the container for a day and then photograph it again and record your observations.
- 10 Shake the container very gently. Record your observations.

RESULTS

Record your observations in a table. Create a labelled or narrated presentation using your time-lapse photographs to show what happened in your model.

DISCUSSION

- 1 Describe the changes that occurred within the container over the first 20 minutes.
- 2 What property of each layer caused it to separate out as it did?
- 3 Identify which layer within Earth is represented by each of your analogue materials.



- 4 Describe the change that occurred within the container when it was left standing overnight.
- 5 Describe the layering that developed within the container after the shaking that mixed the materials into a homogenous mixture.
- 6 Explain the layering and the changes that occurred within the container over the course of the experiment.
- 7 What does the release of bubbles late in the investigation represent?
- 8 Was this model a good representation of the separation of Earth's layers? Did it help you understand why Earth's different compositional layers separated from each other?

CONCLUSION

Your conclusion needs to outline the reason(s) why the materials in the model were able to separate out, and how this relates to the formation of layers in the early Earth.

KEY CONCEPTS

- Earth is unique among the solar system's planets because it has land, oceans and air present on its surface. These components are known as the geosphere, hydrosphere and atmosphere.
- The distance between Earth and the Sun and the mass of Earth create the necessary conditions of temperature and pressure for water to be present on Earth's surface as a solid, a liquid and a gas.
- Earth is predominantly composed of four elements: iron, oxygen, magnesium and silicon.
- Almost all of Earth's mass (99.977%) is contained within the geosphere.
- Most of Earth's iron is contained in the core. Most of Earth's oxygen, silicon and magnesium is contained in Earth's mantle.
- The geosphere is divided into three layers: a thin silicate crust, a thick silicate mantle and a metallic iron core.
- The atmosphere is predominantly composed of nitrogen and oxygen.



Earth's four spheres

- 1 What is the name of the scientific theory that explains the formation of Earth?
- 2 Name the four elements most abundant on Earth.
- 3 Which elements dominate the composition of the atmosphere?
- 4 Name the two materials that dominate the composition of the hydrosphere.
- 5 Name the layer of Earth that contains most of Earth's iron.
- 6 Where is most of Earth's oxygen located?
- 7 Construct a labelled sketch of Earth's geosphere. Indicate the most common materials composing each of the layers.
- 8 What are the average densities of the mantle and the core?
- 9 Why is the inner core solid?
- 10 Why is Earth special in comparison to the other planets of the solar system?

CHECK YOUR UNDERSTANDING

2.1

2.2 Investigating the structure of Earth

There is little direct physical evidence for the composition or structure of the interior of Earth. The deepest drill holes on land have penetrated to depths of 10 to 12 km below the surface. This was about one-third of the distance to the mantle at those locations. The drilling bits disintegrated and the drill pipe distorted and broke due to temperatures measured to be in excess of 350°C and pressures of 40 000 atmospheres (4.053×10^9 Pa).

Earth's vast subsurface volume is instead explored using a variety of geophysical methods and by examining materials formed at depth that have been brought to the surface by a variety of natural processes. Igneous magmas generated in the upper mantle or lower crust often collect fragments of rock as they move up from the site of magma formation to Earth's surface. These **xenoliths**, or foreign rocks, provide us with physical samples of upper mantle and lower crustal rocks.

Using seismic waves to probe Earth's interior

The internal layered structure of Earth has been inferred from mathematical models of how **seismic waves** travel through Earth. The compositional characteristics of those layers has been estimated with calculations based on our knowledge of the average density of the planet, the composition of Earth's crust and mantle rocks, and the relative abundances of elements in the solar system. Seismic waves are monitored and measured with special instruments called **seismometers**, as shown in Figure 2.9.



See seismometers in action.

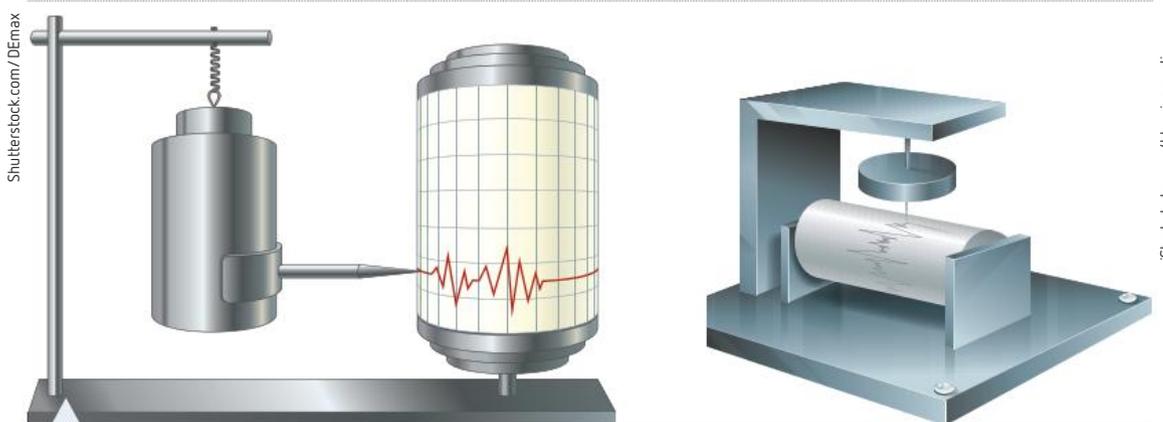


FIGURE 2.9 Simple static seismometers. An inertial weight remains virtually stationary in space while its frame moves with the ground. The earthquake waves are recorded on a chart recorder.

The study of seismic waves generated by earthquakes and large artificial explosions has provided most of the evidence used to determine Earth's internal structure.

The way seismic waves move through Earth's interior depends on the composition, density and physical state of the subsurface layers. Just like other waves, seismic waves bend or **refract** as they pass from one material into another. They are also **reflected** (bounced back) from boundaries between materials of different density or stiffness. Reflection of seismic waves generated by underground nuclear bomb tests has been used to detect the boundaries between the crust and mantle, the mantle and the core, and between the outer core and inner core. Figure 2.10 shows a recording from a seismometer, known as a seismogram, from a deep earthquake.

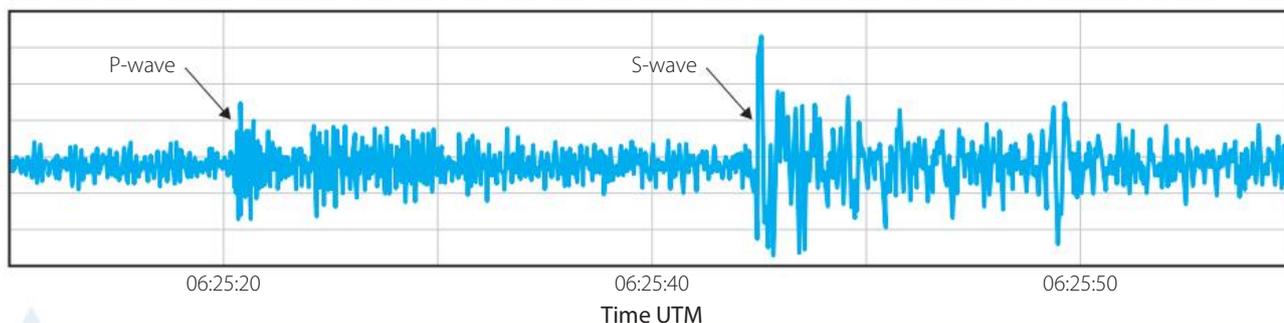


FIGURE 2.10 Body wave seismogram from a deep focus earthquake. UTM is the unit of Universal Time.

Earthquakes occur when two large blocks of Earth's crust or mantle suddenly slide past each other after there has been a period of very slow relative motion between the blocks. The surface of rupture on which the sliding occurs is called the **fault plane**. When the build-up of stress and deformation generated by the slow motion becomes too great, the **fault** breaks, and the blocks slide past each other. The main features of an earthquake are shown in Figure 2.11.

Strong vibrations generated by the blocks sliding past each other on the fault oscillate the material in the blocks. The **energy** from these vibrations is transmitted away from the fault in the form of seismic waves. When the seismic waves arrive at the ground surface, they shake it vertically up and down as well as laterally from side to side. This process causes the mild, strong or catastrophic groundshake that we associate with earthquakes.

There are two types of seismic waves that travel through Earth. These body waves are called P-waves or primary waves, and S-waves or secondary waves (Figure 2.12). P-waves travel, or propagate, through Earth at higher speeds than S-waves. The P-waves are always the first to arrive at a seismogram after an earthquake. The difference in the arrival times between P-waves and S-waves can be used to determine the distance to the location of the fault that ruptured to produce the earthquake (Figure 2.13).

P-waves are compressional waves that propagate through material as a pulse in much the same way that sound waves propagate through the air. Particles in the material oscillate in the same direction that the wave travels by moving backwards and forwards in the direction of travel. Compressional waves can travel through solids, liquids and gases.

S-waves are shear waves, which are also known as transverse waves. S-waves propagate by oscillating particles in a direction that is transverse, or perpendicular, to the direction the wave is travelling in. They shear the material up and down as the wave moves through the material. This type of motion requires the material to be stiff, and for this reason shear waves can only propagate in solids.

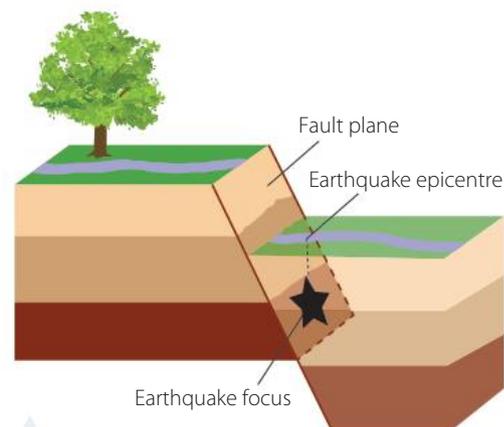


FIGURE 2.11 The area where a fault ruptures and generates an earthquake is called the focus. The point on the ground surface above the focus is called the epicentre.

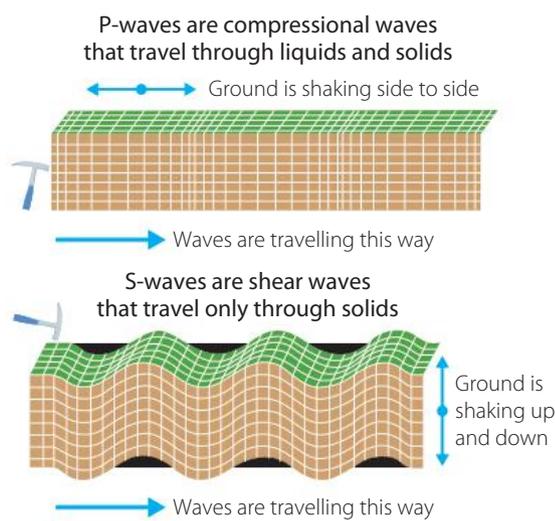


FIGURE 2.12 P-waves shake the ground from side to side while S-waves shake the ground up and down.

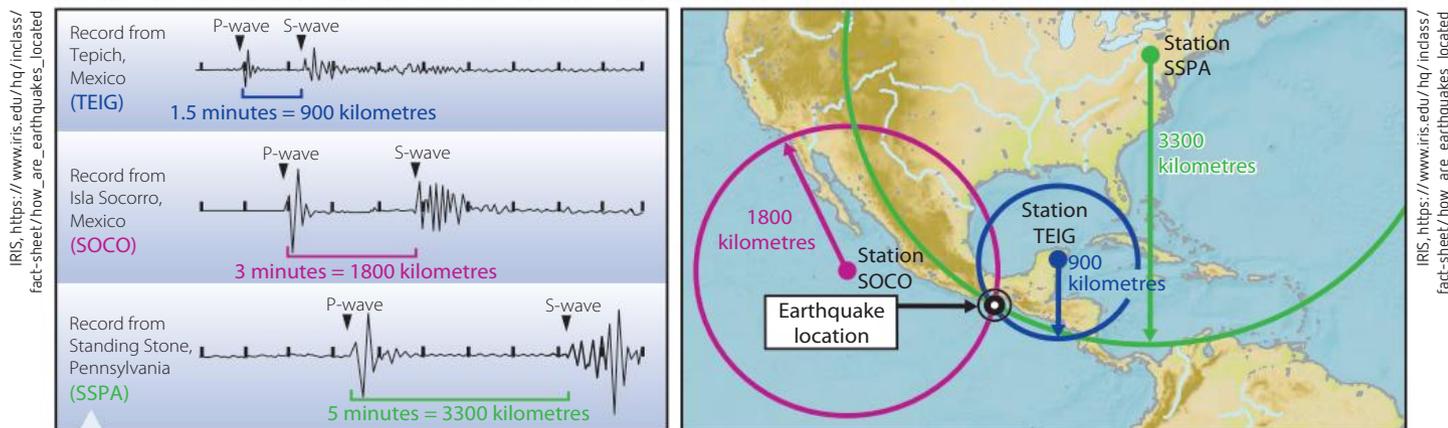


FIGURE 2.13 Location of earthquake epicentre by distance triangulation

INVESTIGATION 2.2

Modelling P-waves and S-waves



Critical and creative thinking

AIM

To use two slinky springs to produce and describe:

- Part A: compressional pulses (P-waves)
- Part B: transverse pulses (S-waves)

MATERIALS

- Two slinky springs, one with a large diameter and one with a significantly smaller diameter
- Two stick-on coloured dots
- Safety glasses
- Digital camera (optional)

METHOD

Work with a partner to prepare a complete risk assessment.



RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?

The springs will be stretched and could whip into your eye if accidentally released.

HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

Wear safety glasses and take care when handling springs.

Part A: Investigating a compressional wave (P-wave)

- 1 Use the larger diameter spring. Choose one point in the slinky and stick on one coloured dot.
- 2 Stretch the slinky to a low tension (turns about 10mm apart).
- 3 Create a compressional wave pulse in the spring. To do this, have your partner hold one end stationary while you give the spring one vigorous push to send a single pulse down the spring in the direction of your partner.

RESULTS

- 1 Draw a diagram, or make a video, showing the direction of travel of the wave.
- 2 Comment on the direction of movement of the coloured dot that you placed on the slinky.

Part B: Investigating a transverse wave (S-wave)

- 1 Use the smaller diameter slinky. Choose one point in the slinky and attach one coloured dot.
- 2 Stretch the slinky out along a bench or on the floor so there is a small amount of tension in it (turns about 5 mm apart).
- 3 Create a transverse wave in the spring. To do this, have your partner hold one end stationary while you give the spring one vigorous shake sideways to send a single pulse down the spring.

RESULTS

- 1 Draw a diagram, or make a video, showing the direction of travel of the wave.
- 2 Comment on the direction of movement of the coloured dot that you placed on the slinky.

ANALYSIS OF RESULTS

- 1 Provide a reason why compressional P-waves are also called longitudinal waves.
- 2 Provide a reason why transverse S-waves are also called shear waves.
- 3 After viewing both types of waves, suggest why P-waves arrive at a destination before S-waves.
- 4 Describe the direction in which the coloured dots moved in your model P-waves and S-waves. How would this direction of movement affect the direction of groundshake in an earthquake?

CONCLUSION

Summarise your observations about the propagation of compressional and shear waves.

- There is little direct physical evidence about Earth's internal structure or its composition.
- Our knowledge about Earth's layers and their composition is inferred from seismic wave studies and determination of the average density of the planet using astronomical measurements.
- Earthquakes occur on faults and generate seismic waves that are detected and measured with special instruments called seismometers.
- P-waves are compressional seismic waves that can travel through solids, liquids and gases.
- S-waves are transverse seismic waves that only travel through solid materials.



CHECK YOUR UNDERSTANDING

2.2A

- 1 How are seismic waves generated?
- 2 What is a P-wave?
- 3 What is an S-wave?
- 4 What type of seismic waves are transmitted through solid materials?
- 5 What type of seismic waves are transmitted through liquid materials?
- 6 Explain how a seismometer works.
- 7 State some of the scientific facts that seismometers have been used to establish.

Identifying boundaries with seismic waves

Geologists and engineers began to undertake routine instrumental studies of seismic waves and earthquakes towards the end of the 19th century. Initially these studies were focused on understanding how the ground shook during an earthquake so that earthquake-resistant buildings could be designed.

The Moho and the crust–mantle boundary

In 1909, Andrija Mohorovičić observed that the same earthquake produced nearly identical pairs of seismic signals. These signals arrived just after each other on seismographs located more than 250 km from the epicentre of the earthquake. Mohorovičić plotted the arrival times of the seismic waves against distance on a graph similar to that shown in Figure 2.14. He decided that a set of slower moving P-waves was travelling directly through the crust to the seismographs located close to the earthquake epicentre. They were travelling at about 6 km s^{-1} . The second set of P-waves that appeared on the seismograph records at the more distant seismographs was travelling faster, at about 8 km s^{-1} .

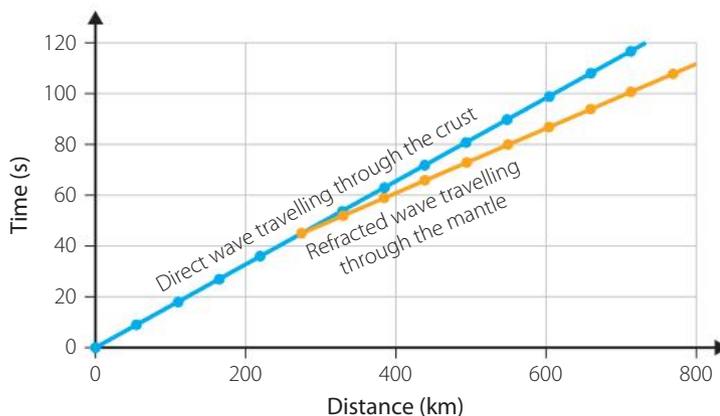
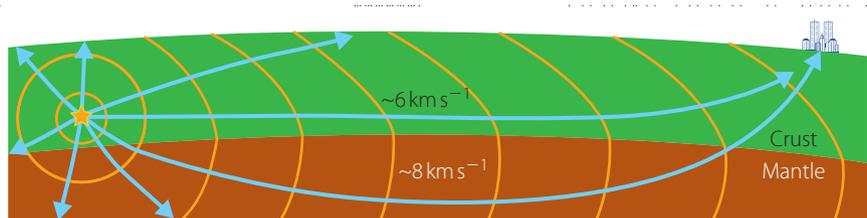


FIGURE 2.14

A graph of crustal earthquake P-wave arrival times versus distance. It is similar to the one Mohorovičić used to identify slower, direct crustal waves and faster refracted mantle seismic waves.

Mohorovičić concluded that the faster set of P-waves was travelling through denser, stronger material. These seismic waves had been refracted into the faster material at the boundary between the two materials, as shown in Figure 2.15. This boundary between the slower material and faster material is called the Mohorovičić discontinuity, commonly shortened to the 'Moho'. It is now known that this boundary separates the lower crust from the upper mantle.

FIGURE 2.15
Andrija Mohorovičić discovered the mantle. His conceptual model for the refraction of earthquake waves at the crust–mantle boundary.



Physical Geology by Steven Earle used under a CC-BY 4.0 International license.

The depth to the Moho (which is the thickness of the crust) can be determined from the distance of the crossover point (the intersection of the direct wave line and the refracted line) on the travel-time graphs where the faster waves are first detected. The greater the distance to the crossover point between the direct wave and the refracted wave on the travel-time graph, the thicker the crust is in that area.

P-wave speeds measured in the laboratory for dense, crystalline rocks called peridotites are the same as the P-wave speeds measured for Mohorovičić's lower, fast layer. Peridotites are striking green rocks composed of magnesium and iron silicate minerals and are relatively rare at the surface.

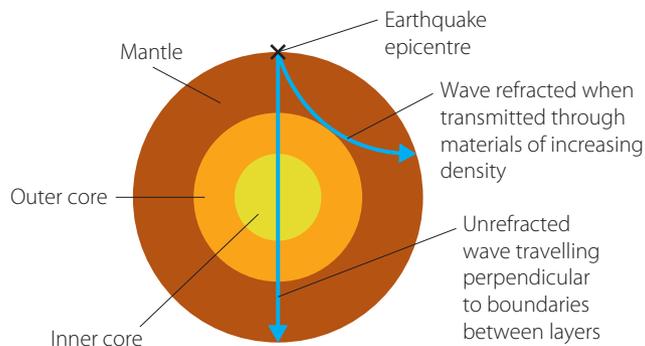
High temperatures and pressures equivalent to those generated at depths greater than 60km are generally required to form peridotites. This information was used to infer that material beneath the Moho boundary was probably peridotite, often referred to as mantle peridotite. These upper mantle rocks have a density of about 3.3gcm^{-3} . Crustal rocks have a density of about 2.6gcm^{-3} , but the average density of Earth is 5.6gcm^{-3} . This means that there must be still denser material located deeper down in the Earth's interior.

You will learn more about rocks and minerals in Chapter 3.

The core–mantle boundary

Most seismic waves follow curved paths as they travel through Earth because they are progressively refracted as they encounter materials of gradually increasing density, as shown in Figure 2.16. Refraction occurs when waves cross a boundary between two different materials at an angle. Waves travelling on paths perpendicular to a boundary are unaffected by refraction and keep moving in the same direction.

FIGURE 2.16
The paths of seismic waves as they travel through Earth



Seismic wave energy can also be reflected from a boundary. When this happens, the wave is reflected symmetrically about a line perpendicular to the boundary. If there is a large contrast in density or strength of the materials at the boundary, more of the wave's energy is reflected from the boundary and

less is refracted across the boundary. We also know that S-waves do not travel through liquids, whereas P-waves are transmitted through liquids.

These principles have been used to interpret the characteristics of the P-wave and S-wave distributions produced across the entire planet when large earthquakes occur. For each earthquake, refraction of the seismic waves inside the planet generates areas where no P-waves or S-waves arrive at Earth's surface. These areas are called **seismic wave shadow zones**.

The shape of seismic wave shadow zones for S-waves is less complex than the P-wave shadow zone and easier to understand. Because S-waves cannot travel through the liquid core, the shape and size of the S-wave shadow zone is directly related to the size of the core.

S-waves generated by an earthquake that occurs near Earth's surface travel out from the focus on a variety of pathways. They all travel on curved pathways due to refraction. One of these pathways follows a curve that just misses the core. It grazes the edge of the core and keeps going. These pathways are detected at Earth's surface at locations that range from the earthquake's epicentre, or 0° , all the way to 103° away from the epicentre. If the core was larger the shadow zone would be larger and its outer boundary would be closer to the epicentre. Reflection and refraction patterns for P- and S-waves are shown in Figure 2.17.

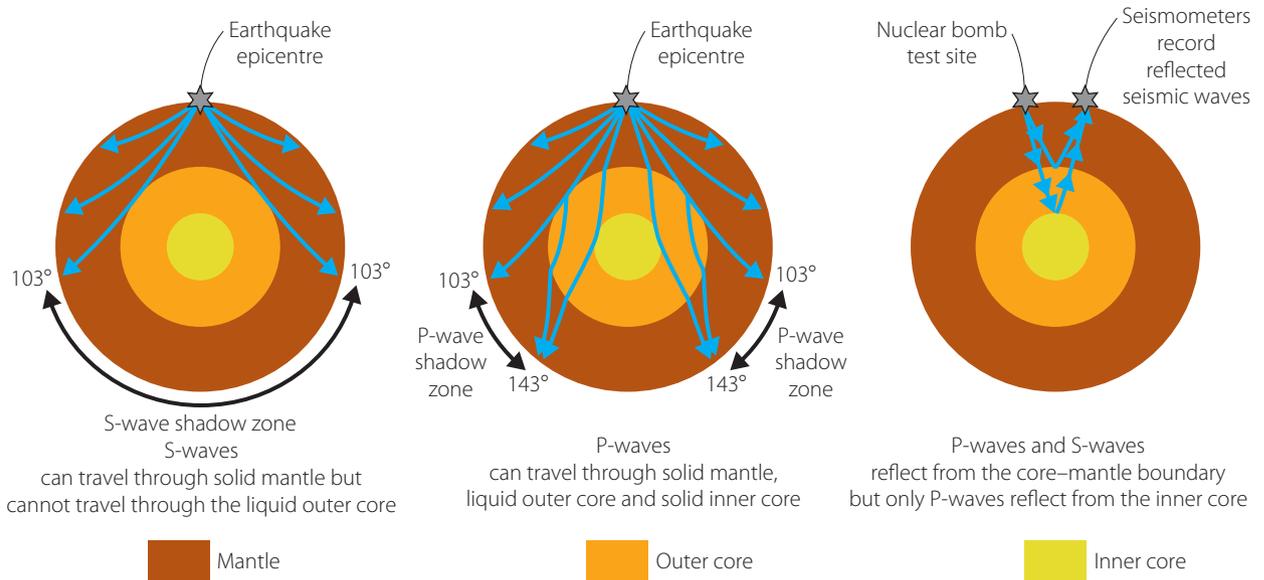


FIGURE 2.17 The differences between the characteristics of P-waves and S-waves travel paths through Earth provide the evidence used to determine the presence and the size of both the liquid outer core and solid inner core.

The shape of the seismic wave shadow zone for P-waves is more complex because some P-waves travel through the core and are sharply refracted by the strong density contrast across the mantle–core boundary. These P-waves are detected in a zone directly opposite the location of the earthquake epicentre, at sites between 143° and 180° from the earthquake's epicentre. Some other P-waves travel on pathways identical to those taken by the S-waves and produce the same distribution on Earth's surface.

In 1936, Inge Lehmann was the first person to demonstrate the possibility that there could be an inner core of solid material. She did this by identifying a set of very weak P-waves within the P-wave shadow zone. She proposed that these rogue waves were present in the P-wave shadow zone because they were reflected from the boundary between the inner core and the outer core.

Lehmann's observations were confirmed during the 1960s when seismometers were placed in an experiment to detect P-waves and S-waves reflected from the core. The seismic waves used to probe the core were generated by nuclear bomb tests in the US state of Nevada. P-waves and S-waves were

reflected, as expected, from the outer core boundary. Only P-waves bounced off the inner core boundary. This was expected because the outer core is liquid and the inner core is solid.

The time these reflected waves took to travel from the surface and back helped to determine the depth of the core–mantle boundary and the boundary between the outer core and inner core. The travel speeds were also used to determine the chemical composition of the core. A metallic alloy composed mostly of iron mixed with small amounts of nickel, silica and sulfur produces a material that transmits P-waves at the measured travel speeds.

INVESTIGATION 2.3

Density of Earth's layers



Numeracy

AIM

To identify materials that could be representative of the crust, mantle and core by calculating their density

MATERIALS

- Samples of rocks and minerals (Your teacher will provide a variety of samples to work with.)
- Electronic balance
- 250 mL measuring cylinder
- Water



WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?

Some of the samples may be composed of material that is toxic if ingested.

Breakage of the measuring cylinder or damage to the balance

HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

Wash your hands regularly and after you have completed the investigation.

Take appropriate care with the laboratory equipment.

METHOD

- 1 Using the electronic balance, measure the mass of the sample. Record the mass.
- 2 Add approximately 150 mL of water to the measuring cylinder.
- 3 Measure and record the volume of water in the measuring cylinder.
- 4 Measure the volume of a test sample by gently lowering it into the measuring cylinder and observing the height increase of the water in the cylinder. The difference between the 'after volume value' (step 4) and the 'before volume value' (step 3) is volume of the test sample.
- 5 Record the volume of the test sample.
- 6 Repeat this procedure for each of the other samples.

RESULTS

- 1 Record the data from the investigation in a carefully planned table.
- 2 When you have finished measuring the mass and volume of each rock sample, calculate the density of each sample using the following formula:

$$\text{Test sample density} = \frac{\text{Test sample mass}}{\text{Test sample volume}}$$

- 3 For each test sample, identify whether the density is similar to the density of the continental crust (density less than 2.8 g cm^{-3}); the oceanic crust (density of $3.0\text{--}3.5 \text{ g cm}^{-3}$); the mantle (density of $4.2\text{--}4.7 \text{ g cm}^{-3}$); or from the core (density above 10.0 g cm^{-3}).
- 4 Draw a suitable graph of your results.



» EXTENSION

Most rocks of the crust have densities less than 2.8g cm^{-3} and the density of the mantle rocks varies between 3.3 and about 4.5g cm^{-3} . The average density of Earth is 5.6g cm^{-3} . Explain why the materials of the core must be significantly more dense than the crust and the mantle materials.

KEY CONCEPTS

- The Moho is the boundary between the crust and the more dense upper mantle.
- The Moho was detected by studying and interpreting the arrival times of P-waves generated by earthquakes.
- Seismic wave travel paths through Earth are curved towards the surface because the seismic waves speed up and refract as they pass through denser material.
- The size of the S-wave and P-wave shadow zones is used to identify the presence and size of Earth's metallic core.
- The presence of the solid inner core was confirmed by studying the reflections of P-waves.

- 1 What is the Moho?
- 2 How was the Moho identified?
- 3 Refer to Figure 2.14. How fast are the waves travelling? (Hint: speed = distance/time or the slope of the graphed lines).
- 4 Create a diagram that shows the distribution of the P-wave and S-wave shadow zones.
- 5 Use your diagram to explain the different distributions of the P-wave and S-wave shadow zones.
- 6 Refer to Figure 2.17. Why is there no reflection of S-wave energy from the inner core?
- 7 Describe how nuclear bomb tests were used to confirm the existence of the inner core.

CHECK YOUR UNDERSTANDING

2.2B

Identifying the base and location of the lithosphere

The **lithosphere** is the **brittle** outermost shell of the geosphere. It is made up of Earth's crust and the underlying stiff and brittle mantle. There are two types of crust. Oceanic crust is predominantly composed of basaltic material, while continental crust is predominantly composed of granites, metamorphic rocks and sedimentary rocks.

Locating the base of the lithosphere and the extent of the lithospheric **plates** is a much more difficult task than identifying the location of the crust–mantle boundary. This is because seismic waves slow down and bend in towards the centre of Earth when they pass through the boundary between the brittle, lithospheric upper mantle into the softer, ductile **asthenosphere**.

A much more complex seismic wave detection and analysis method is used to map the boundaries and thickness of the lithospheric plates. The method is called **seismic tomography**. It uses the same principles and computer codes that are used to make three-dimensional ultrasound and CT scans used in medicine.

Seismic data from thousands of large and small earthquakes is processed to create three-dimensional images of Earth's interior. Variations with depth and location in P-wave and S-wave **velocity** are determined, and this information is used to generate images of Earth's subsurface.

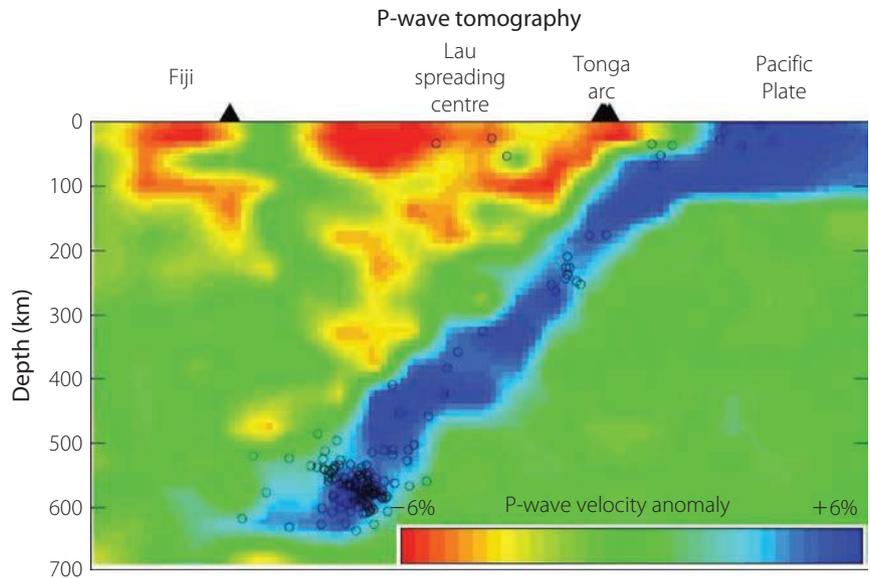
The variations in seismic wave velocity are expressed in terms of how much faster or slower the P-waves are in comparison to the average P-wave velocity for the surrounding material. The difference between the measured P-wave speed and the average P-wave speed is called a velocity anomaly. Maps and cross-sections like the one shown in Figure 2.18 depict the anomalies and are used to identify the dimensions and locations of the lithospheric plates.

The base of the Australian Plate is located on this image at a depth of about 120km. The top and base of the descending Pacific Plate present sharp boundaries between the fast P-wave velocity anomaly (blue) and

You will learn more about rock types in Chapter 3 and the lithospheric plates in Chapter 6.

slower green material. The circles on the diagram represent the locations of the faults where earthquakes occurred. The faster velocities indicate that the **subducting** Pacific Plate is colder, stiffer and denser than the mantle material that surrounds it. One of the reasons why the plate sinks is because it is denser.

FIGURE 2.18 Seismic tomographic image of the Pacific Plate (blue area) descending beneath the Australian Plate near Tonga and Fiji. (The pixillation is real and not an artefact of the image rendering.)



From Depth Extent of the Lau Back-Arc Spreading Center and Its Relation to Subduction Processes BY Daqeng Zhao, Yingbiao Xu, Douglas A. Weins, Leroy Dorman, John Hildebrand, Spahr Webb. SCIENCE10 OCT 1997 : 254-257 Reprinted with permission from AAAS.

Seismic tomography is also used to identify several other boundaries within the mantle and the core (Figure 2.19). At depths of 200 km below Earth's surface, high temperatures cause the mantle rocks to soften, slowing the P-waves. This occurs in the asthenosphere, the top of the region of the mantle where it is **ductile** and can flow.

Deeper down in the mantle the intense pressure causes the minerals in the mantle rocks to convert into denser minerals that occupy less volume. The P-waves speed up across this boundary. This region of the lower mantle is called the **mesosphere**. Deeper still, the tomographic studies also identify the mantle–core boundary and the inner core's boundary.

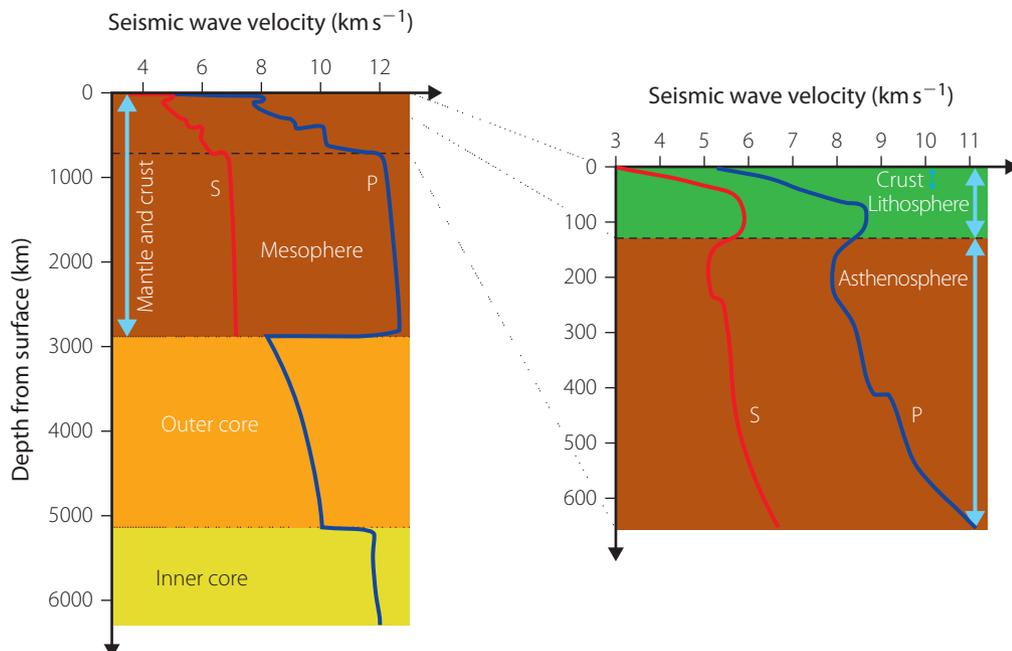


Figure from Physical Geology by Steven Earle used under a CC-BY 4.0 International license. Download this book for free at <http://open.bccampus.ca>

FIGURE 2.19 Boundaries between Earth's internal layers determined from seismic tomography and the P-wave velocities determined for the mantle and the core

- Seismic tomography is used to identify the lower boundary of the lithospheric plates and boundaries between the asthenosphere and mesosphere.
- Seismic tomography determines the variation in seismic wave velocity relative to average seismic velocity.
- High pressures deep in the mantle cause some minerals to convert into higher density forms that occupy less volume.

- 1 Name the seismological method used to identify the base of the lithospheric plates.
- 2 Name the two materials that make up the lithosphere.
- 3 List the following layers of Earth in order from the shallowest layer to the deepest layer: asthenospheric mantle; crust; lithospheric mantle; mesospheric mantle.
- 4 What occurs to some minerals when they are subjected to the very high pressures of the deep mantle?
- 5 Give one piece of evidence to support the claim that the Pacific Plate is sinking into the mantle and one explanation for why this is happening.

2.3 Age of Earth

It has not been possible to determine the age of Earth directly because Earth is an active planet. The materials of the planet's surface are continually weathered and converted into other rocks as they are reworked back into the interior of the planet by geological processes. It is unlikely that we will ever identify materials that have survived from the very earliest years of Earth history.

A minimum age of 4.4 billion years has been determined for Earth from **radiometric dating** of its oldest rocks and zircon crystals. A probable age for the planet is inferred from the oldest dated materials in the solar system. These materials are meteorites that fall to Earth regularly and samples of Moon rock that were recovered during the Apollo Moon missions between 1969 and 1972. All the dates that have been determined for these materials are between 4.40 and 4.57 billion years old. Earth is assumed to have started to form about the same time as the oldest dated materials of the solar system.

You will learn more about radiometric dating techniques in Chapter 6.

Meteorite evidence

Meteorites are solid pieces of material that survive a passage from outer space through Earth's atmosphere to Earth's surface. In other words, meteorites are shooting stars that have landed.

Most meteorites are fragments of material derived from the solar system's planets, moons, asteroids and comets. Many are thought to be the remains of asteroids, planetessimals and comets that collided with each other and disintegrated during the accretion phase of the solar system's formation. By 2019, about 60000 meteorites had been collected from sites across all Earth. The age and composition of these materials provide us with evidence about the age and the composition of Earth.

Meteorites have been divided into three main groups on the basis of their chemical and mineralogical composition. The most common meteorites are the stony meteorites, which are subdivided into the chondrites, 86% of all meteorites, and the achondrites, 8% of all meteorites. Iron meteorites, 5%, are the next most common group, and stony-iron meteorites, 1%, are the least common group of meteorites.

Chondritic meteorites

Chondritic meteorites, or chondrites, such as the one shown in Figure 2.20, include small round droplets of silicate minerals called chondrules that are thought to have initially been molten globules of material floating freely in space. The chondrules subsequently crystallised into aggregates of pyroxene, olivine



FIGURE 2.20 Primitive chondritic meteorite with large chondrules

and feldspar and were amalgamated together to form larger objects such as meteors, asteroids and planetessimals. Radiometric ages determined for the chondrites indicate that some of them are 4.57 billion years old and so they are the oldest of the solar system's materials. The chondritic material probably accreted into the first planetessimals large enough to differentiate into layers that included metallic cores, mantles and rocky crusts.

Achondritic meteorites

Achondritic means without chondrules; the 'a' means 'without'. Achondrites are usually composed of silicate minerals and silicate rock fragments. They present textures and compositions that are similar to basaltic rocks of Earth's crust. This group of stony meteorites is thought to have formed when material was blasted

off the surface of Mars and Earth's moon as well as from the disintegration of large planetessimals and asteroids when they collided with each other. An achondritic meteorite is shown in Figure 2.21a.

Some of the oldest achondritic meteorites found, such as the one shown in Figure 2.21b, are called angrites. They are rocks very similar in composition, mineralogy and texture to Earth's basalts. Radiometric dating has demonstrated that these angrites formed within ten million years of the birth of the solar system. These are slightly younger than the oldest chondritic meteorites, and their ages and existence indicate that the solar system's first-formed planetessimals were large enough to form a metallic core, a mantle and a basaltic crust.

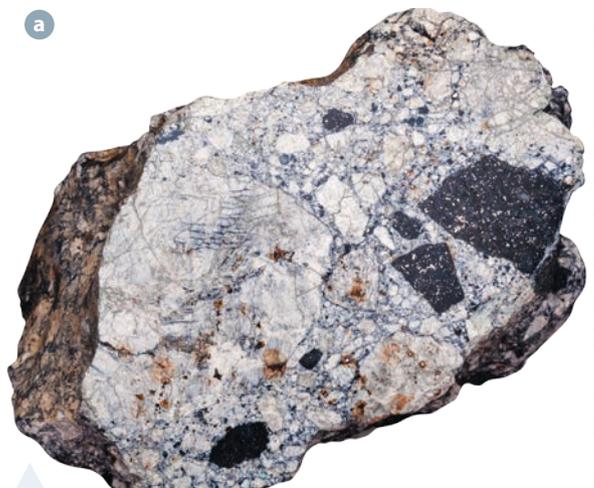


Photo of Cumberland Falls (USNM 604) by Chip Clark, Smithsonian Institution



James St. John (Geology, Ohio State University at Newark)

FIGURE 2.21 **a** A piece of the Cumberland Falls Aubrite meteorite, which is thought to have been blasted off the surface of the Moon **b** An angrite similar to Earth's basalts

Iron meteorites

Iron meteorites, such as the ones shown in Figure 2.22a and 2.22b, are composed of metallic alloys of iron and nickel that have crystallised into the minerals kamacite and taenite. Kamacite is more iron-rich, about 90% iron, than taenite, which is 35–80% iron. Iron meteorites were a source of strong, corrosion-resistant metal that was used to make weapons and ceremonial objects before the invention of iron smelting. The Pharaoh Tutankhamun was entombed with an iron dagger fashioned from meteoric iron. It was a much more formidable weapon than the bronze weapons commonly used at that time.

Iron meteorites are thought to have formed in the cores of large asteroids during the early stages of the solar system's formation. The heat required to melt the interiors of the asteroids was generated by

short-lived radioactive elements that were abundant at that time and from collisions with other asteroids and meteors. The kinetic energy of the collision was converted into heat energy.

The solar system's iron meteorites are predominantly composed of iron with minor amounts of nickel and other elements. It is this information that is used to infer that Earth's core is also composed of iron and nickel.



Shutterstock.com/By Mirko Graul



Shutterstock.com/Dmitry Pichugin

FIGURE 2.22 a A slice of iron meteorite b The Hoba iron meteorite in Namibia is the largest known meteorite on Earth's surface.

Stony-iron meteorites

Stony-iron meteorites are mixtures of the iron–nickel alloy minerals kamacite and taenite combined in varying proportions with the magnesium iron silicate minerals olivine and pyroxene (Figure 2.23).

It is difficult to measure the age of the iron nickel alloy minerals in iron and stony-iron meteorites because they do not usually contain elements that can be dated reliably, unlike the elements in the silicate and sulfide minerals. Nevertheless, dates of 4.44–4.54 billion years have been determined for silicate **inclusions** within these two groups. This demonstrates that they are similar in age to the stony meteorites.



Shutterstock.com/Pavel Gabzdyl

FIGURE 2.23 A stony-iron meteorite comprised of iron–nickel alloy minerals and the magnesium silicate mineral olivine

Radiometric ages for the formation of Earth's layers

A variety of detailed analytical and complex modelling studies have established radiometric ages for particular events in the formation of Earth. Based on known rates of radioactive decay, these include uranium–lead ages of between 4.45 billion and 4.55 billion years for the accumulation of the whole Earth; hafnium–tungsten ages for the formation of Earth's core of 4.526 billion years; iodine–xenon ages for the initial outgassing of Earth's atmosphere at 4.45 billion years; and samarium–neodymium ages for Earth's oldest crustal materials of 4.35 to 4.40 billion years.

Zircon crystals and the oldest rocks

The oldest known crystalline materials discovered on Earth so far are zircon crystals that have been found in sand grains in the ancient sedimentary rocks of Western Australia (Figure 2.24a). The Jack Hills zircon grains have been dated at 4.40 billion years old and the Mt Narrier zircons are 4.19 billion years old. The Acasta granodiorite gneiss of northwestern Canada (Figure 2.24b) is Earth's oldest reliably dated rock and is 4.03 billion years old. These dates were determined by the uranium–lead method on single crystals using the SHRIMP microprobe at the Australian National University (page 98).

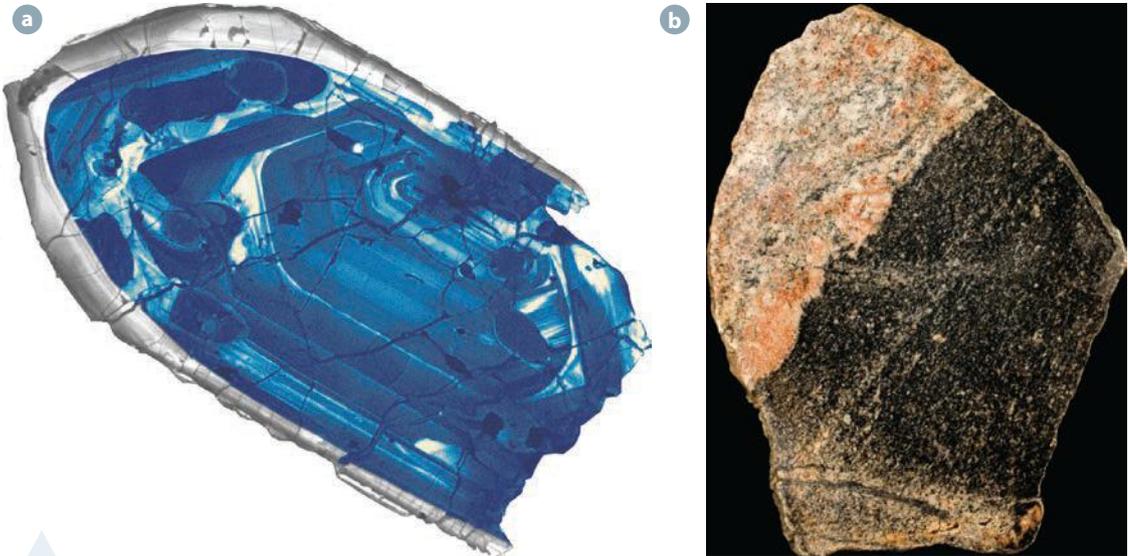


FIGURE 2.24 **a** Jack Hills zircon grains have been dated at 4.40 billion years old. **b** Acasta gneiss is dated at 4.03 billion years.

KEY CONCEPTS

- Earth's age of 4.56 billion years has been inferred from radiometric dating studies of the solar system's oldest known meteorites (4.57 billion years) and the oldest zircons (4.40 billion years) known to have crystallised within Earth.
- There are three main groups of meteorites: stony, which are the most common (94% of all meteorites), iron meteorites (5%) and stony-iron meteorites (1%).
- The stony meteorites are subdivided into two main types: chondrites, 86% of all meteorites, and achondrites, 8% of all meteorites.
- Chondritic meteorites are thought to be slightly older than the other groups of meteorites.
- Chondrites were probably accreted to form the first planetesimals that differentiated into layers that included metallic cores, mantles and crusts.
- Most of the iron, stony-iron and achondritic meteorites formed when the earliest large planetesimals collided with each other and disintegrated.
- The oldest known crystals formed on Earth are the Jack Hills zircons, which are 4.40 billion years old.
- The oldest known rock formed on Earth is the Acasta granodiorite gneiss in Canada, which is 4.03 billion years old.

CHECK YOUR UNDERSTANDING

2.3

- 1 Name the three main groups of meteorites.
- 2 What is the age of the oldest known group of meteorites?
- 3 What is the age of the oldest known Earth material?
- 4 What is the age of Earth's oldest known rock?
- 5 How are the ages of the meteorites and Earth's rocks determined?
- 6 Explain why the oldest chondritic meteorites are thought to be older than the achondritic meteorites and Earth.
- 7 Construct a table to show the available evidence to suggest that Earth is between 4.4 and 4.5 billion years old.

2 CHAPTER SUMMARY

- ▶ Earth is unique among the solar system's planets because it has land, oceans and air present on the surface. These components are known as the geosphere, hydrosphere and atmosphere.
- ▶ The distance between Earth and the Sun and the mass of Earth create the necessary conditions of temperature and pressure for water to be present on Earth's surface as a solid, a liquid and a gas.
- ▶ Earth is predominantly composed of four elements: iron, oxygen, magnesium and silicon.
- ▶ Almost all of Earth's mass (99.977%) is contained within the geosphere.
- ▶ Most of Earth's iron is contained in the core. Most of Earth's oxygen, silicon and magnesium is contained in the mantle.
- ▶ The geosphere is divided into three layers: a thin silicate crust, a thick silicate mantle and a metallic iron core.
- ▶ The atmosphere is predominantly composed of nitrogen and oxygen.
- ▶ There is little direct physical evidence about Earth's internal structure or its composition.
- ▶ Our knowledge about Earth's layers and their composition is inferred from seismic wave studies and determination of the average density of the planet using astronomical measurements.
- ▶ Earthquakes occur on faults and generate seismic waves that are detected and measured with special instruments called seismometers.
- ▶ P-waves are compressional seismic waves that can travel through solids, liquids and gases.
- ▶ S-waves are transverse seismic waves that only travel through solid materials.
- ▶ The Moho is the boundary between the crust and the brittle upper mantle.
- ▶ The Moho was detected by studying and interpreting the arrival times of P-waves generated by earthquakes.
- ▶ Seismic wave travel paths through Earth are curved because the seismic waves refract as they pass through materials of changing density.
- ▶ The sizes of the S-wave and P-wave shadow zones are used to identify the presence and size of Earth's metallic core.
- ▶ The presence of the solid inner core was confirmed by studying the reflections of P-waves off the core.
- ▶ Seismic tomography is used to identify the lower boundary of the lithospheric plates and boundaries between the mantle's asthenosphere and mesosphere.
- ▶ Seismic tomography determines the variation in seismic wave velocity relative to average seismic velocity.
- ▶ High pressures deep in the mantle cause some minerals to convert into higher density forms that occupy less volume.
- ▶ Earth's age of 4.56 billion years has been inferred from radiometric dating studies of both the solar system's oldest known meteorites (4.57 billion years) and the oldest zircons known to have crystallised within Earth (4.40 billion years).
- ▶ There are three main groups of meteorites: stony, which are the most common (94% of all meteorites), iron meteorites (5%), and stony-iron meteorites (1%).
- ▶ The stony meteorites are subdivided into two main types: chondrites, comprising 86% of all meteorites, and achondrites, comprising 8% of all meteorites.
- ▶ Chondritic meteorites are thought to be slightly older than the other groups of meteorites.
- ▶ Chondrites were probably accreted to form the first planetessimals large enough to differentiate into layers that included metallic cores, mantles and basaltic crusts.
- ▶ Most of the iron, stony-iron and achondritic meteorites formed when the earliest large planetessimals collided with each other and disintegrated.
- ▶ The oldest known crystals formed on Earth are the Jack Hills zircons, which are 4.40 billion years old.
- ▶ The oldest known rock formed on Earth is the Acasta granodiorite gneiss, which is 4.03 billion years old.

2 CHAPTER REVIEW QUESTIONS



Review quiz

- 1 Why is Earth known as a Goldilocks planet?
- 2 Using a flow chart, summarise the Planetesimal Accretion theory.
- 3 Evaluate the role of gravity in the Planetesimal Accretion theory.
- 4 Use at least three different criteria to distinguish between the geosphere, hydrosphere and atmosphere.
- 5 Name the two most abundant elements present:
 - a on Earth
 - b in the core
 - c in the mantle
 - d in the crust.
- 6
 - a Contrast the inner core to the outer core.
 - b Account for the different material found in the inner core and the outer core.
- 7 What is the average density of Earth?
- 8 Name a common material that has the same density as Earth and a composition that is like the average composition of the whole Earth.
- 9 Name two types of seismic wave that travel through the interior of Earth. Distinguish between these waves.
- 10 One type of seismic waves travels through the outer core. Which type of wave must it be, and why?
- 11 Construct a labelled sketch that shows typical travel paths for S-waves through Earth's mantle. Name the process that causes these seismic wave travel paths to be curved.
- 12 Construct a labelled sketch that shows typical travel paths for seismic waves that are reflected from the outer and the inner core. Name the types of seismic wave that are reflected.
- 13 Explain how P-wave reflection studies were used to confirm that Earth's inner core is solid.
- 14 Draw a diagram to show the Moho. Explain how its location was inferred.
- 15 Name the two types of stony meteorites. Distinguish between them in terms of composition and age.
- 16 What is the difference between stony-iron meteorites and iron meteorites?
- 17 Explain the origin and formation of the iron meteorites.
- 18 How old is:
 - a the solar system?
 - b Earth's core?
- 19 Why is Earth's oldest rock at least 500 million years younger than the solar system?
- 20 Outline the evidence used to indicate that Earth has a dense, metallic core.
- 21 Use the evidence presented in this chapter to formulate an argument that Earth is between 4.4 and 4.5 billion years old. In your opinion, which piece of evidence is the most compelling? Justify your answer.

3 Rock cycle

OUTCOMES

In this chapter you will learn about:

- the formation and chemical composition of mafic and felsic minerals
- the physical properties that are used to classify minerals
- the formation of rocks as characteristic assemblages of minerals formed through the processes of the rock cycle [CCT](#)
- classifying rocks and minerals using keys
- how Aboriginal and Torres Strait Islander peoples classified minerals and rocks [ATSIHC](#)
- the formation of soils through the interaction of the lithosphere, atmosphere, hydrosphere and biosphere [CCT](#)
- the nature of soil types and their component materials. [WE](#)





Rocks and **soils** create the nature of places, including such places as the Snowy Mountains (Figure 3.1). For Aboriginal and Torres Strait Islander peoples, rocks not only help to define a sense of place but for thousands of years were used to make tools and for ceremonial purposes. Aboriginal people classified rocks and minerals in terms of their use; scientists classify Earth materials in terms of their origin, composition and structure. Composition and structure determine how a rock can be used. In this chapter you will learn about the nature of rocks and the minerals that make them. You will also learn about their scientific classification and origins, and what happens when rocks are exposed to the conditions at Earth's surface.

FIGURE 3.1
Mount Kosciuszko in the Snowy Mountains during spring, with exposed rocky formations



Shutterstock.com/Milosz Masianka

3.1 Nature and origin of minerals

Getty Images/frenchmen77



FIGURE 3.2 Specimens of fluorite

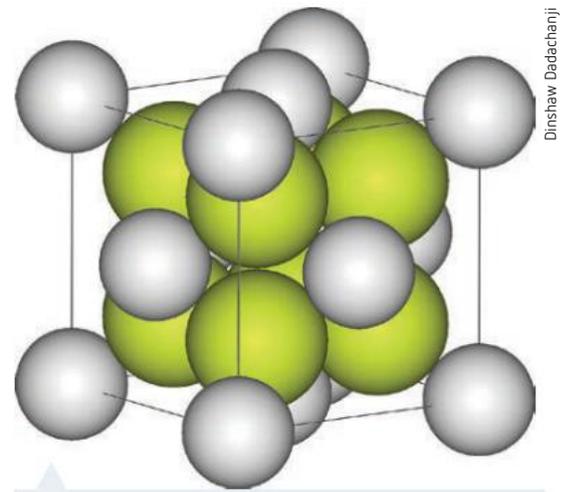
Minerals are the basic building blocks of the lithosphere. A **mineral** is a naturally occurring inorganic substance with a definite structure and composition. This definition identifies four properties of minerals. There are more than 5000 minerals recognised, with about 50 new minerals being described each year. While a particular mineral has a defined composition and structure, minor differences lead to a mineral having different varieties. For example, one of the most common minerals on Earth is quartz, but it has many varieties such as amethyst, smoky

quartz, citrine, rose quartz and rock crystal. You will learn more about the characteristics of minerals using fluorite as an example (Figure 3.2).

Fluorite is a naturally occurring substance found with some metal ore deposits and also in **igneous rocks**. It has a fairly constant chemical composition. It is composed mainly of the elements calcium and fluorine and has the chemical formula CaF_2 . Note in Figure 3.2 that each specimen has a different colour. Many of the colours of fluorite are due to tiny amounts of other metal atoms replacing

some of the calcium atoms. Green fluorite, for example can result from minor amounts of iron or copper in the mineral. However, the number of these other metal atoms that create the colours are so small that the overall chemical formula remains CaF_2 .

The atoms in a mineral are arranged in a highly ordered three-dimensional structure called a **crystal lattice**. As a mineral crystal grows, new atoms are systematically added to the surface of the crystal creating an ordered structure. Fluorite crystals exhibit a simple ordered structure. Each calcium is surrounded by eight fluorine atoms and each fluorine atom has four calcium atoms adjacent to it. Figure 3.3 shows how the calcium and fluorine atoms are arranged as if defining a cube. The calcium atoms are located on the corners and in the centre of each face of the cube, and fluorine atoms fill the spaces within the cube. This pattern repeats throughout a fluorite crystal and is referred to as a face-centred cubic lattice. Different minerals exhibit different types of crystal structures and later you will see how this feature can be used to identify minerals.



Dinshaw Dadachanji

FIGURE 3.3 The unit structure of fluorite. Calcium atoms are depicted as grey and fluorine atoms are green.

INVESTIGATION 3.1

Crystal formation

AIM

To investigate how temperature affects crystal formation

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Salol can cause skin irritations.	Wear a lab coat and safety glasses. Be careful not to get any salol on your skin. Wash your hands after the activity.



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

MATERIALS

- Ice cubes and hot water
- 2 microscope slides
- 3 small beakers and one large beaker
- Monocular microscope or hand lens
- Eye dropper
- Salol (phenyl salicylate)
- Digital camera

METHOD

- 1 Electronically record your experiment. Describe the individual steps and your observations as you proceed.
- 2 Put a microscope slide in a small beaker of hot water and another slide into a beaker of iced water.
- 3 In the third small beaker, put approximately 25 mL of salol.
- 4 If the salol is solid, then place the small beaker containing the salol into a warm water bath in the large beaker.
- 5 Remove the slide from the hot water and place it on the bench. Add a couple of drops of salol to the slide.
- 6 Repeat this with the slide from the cold beaker.
- 7 Wait for the salol to dry, and then look carefully at the two slides using your monocular microscope or hand lens.





RESULTS

Record your observations. Include labelled diagrams of what you see through the microscope or hand lens.

ANALYSIS OF RESULTS

- 1 What difference did you observe in how quickly the hot and cold slides cooled?
- 2 Describe the differences you observed when the salol was added to each slide.
- 3 Describe how the crystals grew.
- 4 Based on your observations, suggest a hypothesis that links temperature to crystal size.

CONCLUSION

Write a conclusion that addresses the aim of this investigation.

Like many minerals, fluorite finds a wide range of uses in industry. It is important in the production of ceramics, aluminium and iron. It is also used in the production of lenses for specialised microscopes and in the manufacturing of some integrated circuits. It is also the main source of fluorine, which has many uses in chemical industries.

Each mineral has its own properties and uses, making it unique. However, learning to identify the common minerals is straightforward if the physical properties they exhibit are used. Table 3.1 lists the properties of some common silicate minerals; it uses some technical terms that are explained later in the chapter.

TABLE 3.1 Common silicate minerals and their properties. Lustre is vitreous (glassy) unless otherwise stated.

MINERAL	COMPOSITION	CLEAVAGE PLANES	FRACTURE	HARDNESS (MOHS SCALE)	COLOUR	SPECIFIC GRAVITY	OTHER FEATURES	GROUP	
Olivine	(Mg,Fe) ₂ SiO ₄	none	conchoidal	6.5	green to brown	3.2–3.4	most often as rounded grains	Mafic	Silicate
Pyroxene (augite)	(Mg,Fe)SiO ₃	2 at 90°	uneven	5–6	green to black	3.2–3.6	often as crystals with regular cross-section. Streak light green to colourless		
Amphibole (hornblende)	Ca ₂ (Mg,Fe,Al) ₅ (Si,Al) ₈ O ₂₂ (OH) ₂	2 at 60° / 120°	uneven	5–6	black to dark green or brown	2.9–3.4	usually as platy or grainy crystals		
Biotite	K(Mg,Fe) ₃ AlSi ₃ O ₁₀ (OH) ₂	1	uneven	2.5–3	black to dark brown	2.8–3.4	lustre pearly	Felsic	
Plagioclase	CaAl ₂ Si ₂ O ₈ – NaAlSi ₃ O ₈	2 at 90°	uneven / conchoidal	6	white to grey	2.6–2.8	variable composition; often occurs as well-shaped crystals		
Muscovite	K(Mg,Fe) ₃ AlSi ₃ O ₁₀ (OH) ₂	1	uneven	2–2.5	colourless to light brown	2.7–3.0	lustre pearly		
K-feldspar (orthoclase)	KAlSi ₃ O ₈	2 at 90°	uneven / conchoidal	6	white, pink, light green, brown	2.6	one of the most common minerals		
Quartz	SiO ₂	none	conchoidal	7	variable	2.6–2.7	found in almost all environments		
Garnet (almandine)	(Fe,Mg,Mn) ₃ Al ₂ Si ₃ O ₁₂	none	uneven / conchoidal	7.5–8.5	brown to yellow-green	4.3	well-formed crystals		

Classification by composition

Every mineral has a characteristic composition. Fluorite has a simple composition (CaF_2), but other minerals can have compositions that vary within a certain range. Consider olivine, which has the formula $(\text{Mg,Fe})_2\text{SiO}_4$. The silicon (Si) and oxygen (O) mean that the mineral belongs to the group known as the **silicates**. The reason the magnesium (Mg) and iron (Fe) are in brackets is because the percentage of magnesium and iron can vary across a spectrum from $(\text{Mg})_2\text{SiO}_4$ to $(\text{Fe})_2\text{SiO}_4$.

Silicate minerals

Silicates such as olivine are the most common minerals in Earth's crust and upper mantle. This is not surprising, because silicon and oxygen are the most abundant elements in Earth's crust by weight. All silicates have a basic building block called the silica–oxygen **tetrahedron** (Figure 3.4). A silicon atom is surrounded by four oxygen atoms, which are arranged as if they are at the tips of a triangular-based pyramid – a **tetrahedron**. In silicates, the tetrahedra can be linked together in a variety of ways. A tetrahedron may link to other tetrahedra to make rods, sheets or networks. Tetrahedra can also be linked to each other via metal atoms that bind the tetrahedra together.

Silicate minerals can be divided into two major groups based on their composition: felsic and mafic minerals. The term **felsic** is composed of two parts: 'fel' referring to feldspar, and 'sic' referring to silica. Similarly, the term **mafic** is composed of the parts 'ma', referring to magnesium, and 'fic', which references iron. The terms felsic and mafic can also be applied to rocks. Basalt, for example, is referred to as a mafic rock and granite is referred to as a felsic rock.

Felsic minerals are rich in silicon and aluminium. They may also contain relatively high amounts of potassium. Felsic minerals tend to be light coloured and have densities generally less than 3gcm^{-3} . Common rock-forming felsic minerals include quartz, plagioclase, orthoclase (also known as K-feldspar because of the potassium it contains) and muscovite mica.

Mafic minerals differ from felsic minerals in important ways. Mafic minerals are rich in iron and magnesium. This causes them to appear dark, ranging in colour from green to black. Their densities are higher than felsic minerals and they generally crystallise at higher temperatures than felsic minerals. Examples of mafic minerals include olivine, pyroxene, amphibole and biotite mica.

Both felsic and mafic minerals can be found in a rock. Granite is predominantly composed of felsic minerals but mafic minerals such as biotite and hornblende are also present (Figure 3.5).

Non-silicate minerals

While silicate minerals account for most of the common rock-forming minerals, a range of other mineral types have economic importance. **Carbonate** minerals are widespread, particularly in sedimentary and some igneous rocks. Calcite is a carbonate mineral found in igneous, sedimentary and metamorphic rocks as well as being a **gangue** mineral in a range of ores. **Sulfide** minerals are composed of metals combined with sulfur.

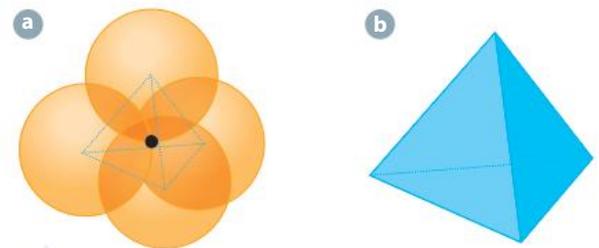


FIGURE 3.4 The silica–oxygen tetrahedron **a** atoms shown proportional to size **b** simplified representation



FIGURE 3.5 Felsic and mafic minerals in granite



Minerals

Research the characteristics of oxide, halide and phosphate minerals.

Properties used to identify minerals

Pyrite (FeS_2), chalcopyrite (CuFeS_2), sphalerite (ZnS) and galena (PbS) are four economically valuable sulfide minerals. Another common sulfur-containing mineral is gypsum. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is the most common mineral of the sulfate group. Note the presence of water in the formula. If water is absent the mineral is referred to as anhydrite. Some of the non-silicate minerals are included in Table 3.2.

TABLE 3.2 Some other common minerals

MINERAL	COMPOSITION	CLEAVAGE PLANES	FRACTURE	HARDNESS (MOH'S SCALE)	COLOUR	LUSTRE	SPECIFIC GRAVITY	OTHER FEATURES	GROUP
Calcite	CaCO_3	3 forms rhombus shapes	conchoidal but rarely seen	3	wide range of colours or colourless		2.7	bubbles when treated with acid	Carbonate
Pyrite	FeS_2	none	conchoidal	6–6.5	yellow-grey to grey	metallic	4.9–5.2	black streak with a slight green tinge	Sulfide
Galena	PbS	3 cubic	sub conchoidal	2.5–3.0	grey	metallic	7.4–7.6	most common mineral containing lead	
Chalcopyrite	CuFeS_2	none	uneven	3.5–4.0	brass yellow, sometimes brown or black	metallic	4.1–4.3	tarnishes to multicoloured red, purple and blue	
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	1 perfect, 2 poor	uneven	2	range of colours	vitreous-pearly	2.3–2.4	white streak commonly forms tabular crystals	Sulfate
Haematite	Fe_2O_3	none	uneven	5–6	black / grey to reddish brown		4.9–5.3	streak red to red-brown	Oxide
Ice	H_2O	none	conchoidal to uneven	1.5	colourless sometimes with a blue or blue-green tinge	vitreous	0.9	white streak	
Chlorite	$(\text{Mg,Fe,Li})_6\text{AlSi}_3\text{O}_{10}(\text{OH})_8$	1	uneven	2–2.5	light to dark green or black	vitreous, pearly or dull	2.6–3.3	common metamorphic mineral but also found in igneous rocks	Silicate
Kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	1	earthy	2–2.5	white to beige; may be coloured by iron oxides	dull	2.6	a clay mineral	
Goethite	$\text{FeO}(\text{OH})$	1	uneven	5–5.5	black to brown to yellow	submetallic, silky	3.3–4.3	streak brown-yellow to yellow	Hydroxide
Limonite	$\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$	none	uneven	4–4.5	yellow, brown to brownish black	most often dull	2.7–4.5	streak yellow to brown	
Fluorite	CaF_2	1	conchoidal	4	occurs in all colours		3.0–3.3	white streak	Halide
Halite	NaCl	3 cubic	conchoidal	2.0–2.5	varied colours or colourless	vitreous	2.1–2.6	natural form of salt	

Classification by physical properties

Scientists use a range of properties to identify minerals. The properties used are mainly physical properties related to composition and the crystal structure of the mineral.

Crystal form

Many minerals grow closely surrounded by other minerals and so fill the space available in an uneven way. If, however, a mineral has room to grow, its crystal structure generates crystal faces and sometimes a geometric shape known as a **crystal form**. Figure 3.6 shows the cubic crystal form of the mineral pyrite.



FIGURE 3.6 Pyrite crystals

Hardness

Hardness is the resistance a mineral has to scratching or abrasion. It reflects the strength of the bonds between atoms in the crystal lattice. Hardness is traditionally worked out using Moh's hardness scale (Table 3.3). This uses a set of common minerals that represent a range of hardness, from 1 (talc) to 10 (diamond). Hardness can also be determined using everyday items such as a fingernail, copper coin or piece of glass. The procedure of testing hardness is described in Investigation 3.2.



A mineral research scaffold

TABLE 3.3 Moh's scale

MOH'S SCALE OF HARDNESS		HARDNESS OF OTHER COMMON SUBSTANCES
Hardness number	Mineral	Substance and hardness
1	Talc	Skin
2	Gypsum	Fingernail 2.5
3	Calcite	Copper coin 3.0
4	Fluorite	
5	Apatite	Steel knife, nail, glass 5.5
6	Orthoclase	Hacksaw blade, streak plate 6.5
7	Quartz	
8	Topaz	
9	Corundum	
10	Diamond	

Cleavage and fracture

Many minerals contain zones of weak bonding in their crystal structure that cause the mineral to break or split along smooth surfaces. This is referred to as **cleavage**, and the smooth surfaces that result are called cleavage planes. Biotite is a silicate mineral that has one cleavage direction, so the mineral splits



FIGURE 3.7 One cleavage plane produces flat sheets in biotite mica

to form thin, flat sheets (Figure 3.7). Calcite and galena are minerals having three cleavage directions. **Fracture** is the property of breaking along an irregular surface.

Specific gravity

Specific gravity is the ratio of a mineral's density to that of water. Quartz has a density of approximately 2.7gcm^{-3} and water has a density of 1.0gcm^{-3} . The specific gravity of quartz is therefore 2.7. Metallic and metamorphic minerals generally have higher specific gravities than silicates such as quartz and feldspar.

Lustre

Lustre describes the appearance of light reflected off a mineral surface. Quartz reflects light like glass and it is said to have a vitreous lustre. The pyrite crystals in Figure 3.6 are described as having a metallic lustre. Some minerals do not reflect light strongly and are described as dull or earthy.

Colour and streak

Many minerals, such as fluorite or quartz, display a wide range of colours. For this reason colour is not the most diagnostic property of a mineral. However, colour in the form of a streak is useful in classifying some minerals. When a mineral is powdered by dragging it across a white tile, leaving a line called a **streak**, the colour is sometimes diagnostic, particularly for those with a metallic lustre. Pyrite has a black streak, sometimes with a tinge of green. Haematite is a mineral that has a characteristic red or reddish-brown streak.

Other properties

Other properties that can be used to identify minerals include magnetism (magnetite) or generation of bubbles when treated with acid (calcite). Bauxite, the mineral from which aluminium is refined, forms small spherical aggregates. In studying minerals in rocks, thin slices or sections are prepared and examined under a microscope using polarised light. The way the minerals affect polarised light generates characteristic colours, and this is a valuable diagnostic property. For example, olivine crystals appear a greenish yellow in normal light but in thin section the range of bright colours makes them easy to identify (Figure 3.8). Note the smaller crystals of the basalt in the top left of Figure 3.8.

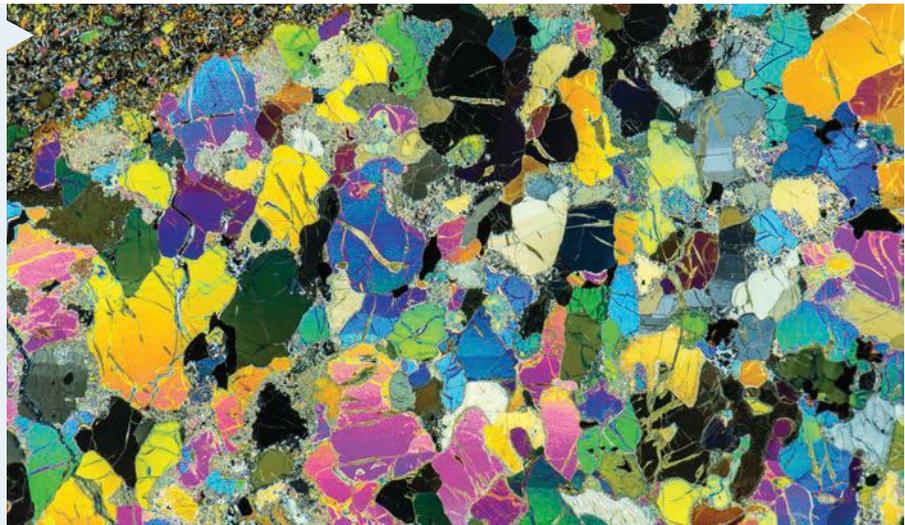


Rocks under the microscope

Contrast the minerals in a peridotite with those in a schist.

FIGURE 3.8

Olivine crystals in thin section under cross-polarised light



INVESTIGATION 3.2

The properties of minerals

INTRODUCTION

In this investigation you will examine a number of mineral specimens and identify some important properties that a geologist would use to classify minerals.

AIM

To learn the physical properties used to classify minerals

MATERIALS

- A collection of numbered mineral specimens
- Materials for testing hardness – a Moh's hardness set or pieces of glass, a hacksaw blade and copper coin
- Streak plate
- Hand lens

WHAT RISKS ARE THERE IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Some minerals contain toxic substances or fibres that are dangerous to breathe in.	Listen carefully to your teacher and follow their instructions. Carry samples on a tray or Petri dish. Do not handle the specimens too much. Wash your hands thoroughly after the investigation. Work in a well-ventilated room.



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

METHOD

- 1 Create a results table in your notebook before you begin.
- 2 As you proceed through this investigation, use your table to record observations and ideas that occur to you as you work.
- 3 As you follow the instructions below, think critically about each property in terms of how useful it is and how easy it is to use.

Part A: Colour

- 1 Describe the colour of the specimens indicated by your teacher. Be careful to use terms that apply only to the colour and not to the transparency of a mineral or the way it shines.
- 2 Record your results in a table indicating mineral name and its colour.

Part B: Lustre

Turn the specimens in the light until you can see the shine from the surface. Ignore colour or unevenness of the surface and think about the quality of the light being reflected.

The following terms are used to describe lustre.

- *Metallic* – reflects light like a metal such as cast iron or brass
- *Sub-metallic* – a feeble metallic reflection
- *Non-metallic* – reflects light like a substance that is not a metal, such as glass, silk, plastic. Non-metallic lustre can be further classified by comparing it to some commonly occurring substance:
 - *Vitreous* – reflects light like broken glass
 - *Pearly* – reflects light like a pearl
 - *Silky* – reflects light like silk or nylon
 - *Waxy* – reflects light like candle wax
 - *Resinous* – reflects light like resin
 - *Earthy* – dull, like soil.





- 3 Identify the type of lustre exhibited by the minerals provided. Record the mineral name and lustre in your results table.

Part C: Streak

To test streak, rub the mineral over a streak plate. The hard, rough surface of the plate breaks off minute grains and the colour can easily be seen against the white background.

- 4 Test the streak of the specimens provided. Describe the colour of the streak and compare it with the colour of the specimen. Record the mineral name, the colour of the mineral and the streak it produces in your results table.

Part D: Cleavage and fracture

Cleavage presents itself as flat surfaces of straight cracks in the surface of a mineral. It is described in terms of its direction and number of different planes. Be careful not to confuse cleavage with crystal faces.

To count the directions of cleavage:

- identify a cleavage face by its shine when you move it in the light. Hold the specimen so the cleavage plane is parallel to the top and bottom of the specimen.
- look for another cleavage plane. If you find one, arrange the specimen so that this second plane runs from back to front, forming the sides of the specimen. What angle do the planes appear to make with each other?
- look for a third cleavage face on the front and back of the specimen. If you find a third one, what angle does this cleavage plane make with the others?

Fracture is even, uneven or conchoidal (curved surfaces). Most of the mineral specimens are fragments of larger pieces. The flat surfaces produced by cleavage can be seen when the specimen is turned in the light. They reflect light in a single flash. Fracture surfaces are rough and do not reflect so perfectly.

- 5 Assess four samples for type of fracture and cleavage directions. Record your results in your table, detailing mineral name, cleavage number, estimated angle between cleavage planes and fracture type.

Part E: Hardness

Test hardness by rubbing a corner of the mineral being tested on the flat surface of another. If the mineral leaves a scratch it is harder; if it leaves a powder streak it is softer. Try to use an edge of the mineral being tested to reduce damage to the sample. For example, if a mineral has a hardness of 3.5 it will scratch calcite (H 3) but will not scratch fluorite (H 4). You would record the hardness as 3–4. Refer to Table 3.3 for Moh's scale of hardness.

- 6 Determine the hardness of the minerals indicated and record their names and hardness.

Part F: Specific gravity

Specific gravity (SG) is the mass of a mineral relative to the same volume of water. It is similar to density but uses water as a comparison. (Note that 1 mL of water has a mass of 1 g at 20°C.)

You can gain an idea of relative specific gravities of mineral specimens by weighing the specimen in one hand against a similar-sized specimen of quartz in your other hand. (Quartz has average SG of about 2.7.) With experience you can dispense with the quartz.

Specific gravity can be described relative to quartz as follows.

- *Light* – less than 2.5 (less than quartz)
 - *Average* – 2.5 to 3.2 (similar to quartz)
 - *Heavy* – 3.2 to 5.5 (heavier than quartz)
 - *Very heavy* – more than 5.5 (much heavier than quartz)
- 7 Estimate the specific gravity of the specimens provided. Record your results in your table, including the mineral name and the estimated specific gravity.

RESULTS

Record your results in the table you constructed at the start of this investigation. Include written observations, comments or questions that occurred to you as you worked.

DISCUSSION

- 1 How reliable is colour in identifying a mineral?
- 2 What does the hardness of a mineral tell you about the bonds in the crystal lattice?



- » 3 Cleavage is regarded by many geologists as one of the most important characteristics to use in identifying a mineral.
- a Why is cleavage always present in a particular mineral?
 - b Did you find it easy to identify the cleavage in the samples you studied?
- 4 How could the arrangement of atoms in a mineral be related to the mineral's specific gravity?
- 5 How could you find the specific gravity of a mineral specimen more accurately than by weighing it in your hand?

CONCLUSION

Outline the set of properties used to identify minerals.

INVESTIGATION 3.3

Creating a dichotomous key

INTRODUCTION

In this investigation you will work with a partner and use the properties of minerals to create a dichotomous key to classify minerals. A dichotomous key is one that separates things into two groups. In science, this separation is usually on the basis of whether an object has a property or not.



AIM

To create a dichotomous mineral key using physical properties that will accurately classify a new mineral specimen

MATERIALS

- Set of 10 minerals labelled with their names
- Materials for testing hardness – a set of Moh's hardness scale minerals, or pieces of glass, a hacksaw blade and copper coin
- Large sheet of paper or cardboard
- Streak plate
- Hand lens or dissecting microscope
- Numbered but unnamed specimens provided by your teacher

WHAT RISKS ARE THERE IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Some minerals may contain toxic substances.	Listen carefully to your teacher and follow their instructions. Carry samples on a tray or Petri dish. Do not handle the specimens too much. Wash your hands thoroughly after the investigation.



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

PROCEDURE

Part A: Creating a dichotomous key

- 1 Place the sheet of cardboard or paper on a desk and place the 10 specimens on it.
- 2 Choose one of the properties studied in Investigation 3.2 and use it to divide the minerals into two groups. Record above the groups the property used to define the group. For example, if you used cleavage as the property, one group might be labelled 'cleavage present' and the other 'no cleavage present'.



- » 3 Select another property from Investigation 3.2 and use it to again sub-divide one group into two parts.
- 4 Continue to use mineral properties from Investigation 3.2 to subdivide the specimens until all the specimens are separated out. Try to use at least five properties somewhere in your key.
- 5 Label each specimen with its name.
- 6 Ask your teacher to check your key. Revise it if necessary.
- 7 Make a chart of the sequence of classification decisions you used in your notes. This will be the key you use for the next part of the investigation.

Part B: Testing the key

- 8 Show your teacher your key. They will provide you with the numbered specimens.
- 9 Examine the specimens closely and identify their properties. Record the properties in a table.
- 10 Use your key to classify each specimen.
- 11 Have your teacher check your results.

RESULTS

Create a copy of the key you devised and a table of the test minerals and their properties.

DISCUSSION

- 1 Were any of your specimens harder to classify than others?
- 2 Which properties did you find most useful in classification?
- 3 Did you find non-silicate minerals easier to classify than silicates? If so, why?
- 4 Outline the importance of using a dichotomous key.
- 5 Would a key with three choices at each point work as well as a dichotomous key?

CONCLUSION

Assess how well you fulfilled the aim of this investigation.

KEY CONCEPTS

- A mineral is a naturally occurring inorganic solid with a definite structure and composition.
- Minerals differ in terms of their composition and crystal structure. Common compositional groups include silicates, carbonates, sulfates and sulfides, oxides and hydroxides.
- Minerals are composed of metal and non-metal atoms arranged in a crystal lattice.
- The composition and crystal structure of a mineral determines properties such as hardness, cleavage, density and crystal form.
- The physical properties of a mineral are used to classify it. These properties include hardness, cleavage, density, lustre, streak, colour and crystal form.
- Minerals are stable under certain conditions but can change if the environment they are in changes.
- Mafic minerals are silicate minerals common in igneous and metamorphic rocks. They contain relatively large amounts of iron and magnesium, have darker colours ranging from green to black, and relatively high densities.
- Felsic minerals are found in igneous, metamorphic and sedimentary rocks. They contain relatively large amounts of silicon and aluminium, are light coloured, and have lower densities than mafic rocks.

CHECK YOUR UNDERSTANDING

3.1

- 1 Distinguish between the following pairs of terms: crystal and mineral; mafic and felsic; silicate and non-silicate.
- 2 List the names of five silicate and five non-silicate minerals.
- 3 Using an example, describe the characteristic properties of a mineral.
- 4 Contrast cleavage and fracture as diagnostic properties of minerals.



- 5 Construct a table to compare the properties of the following minerals.
- Quartz
 - Plagioclase
 - Amphibole
 - Biotite
 - Olivine
- 6 Describe the arrangement of atoms in a mineral.
- 7 Outline the relationship between a mineral's crystal structure and its hardness, cleavage and density.
- 8 Why is colour alone not a reliable way to identify a mineral?
- 9 Compare the nature and origin of felsic and mafic minerals.

3.2 Nature of rocks

Rocks are solid natural substances composed of one or more minerals. They are classified using their composition and texture. Composition refers to the type of minerals present and the elements they contain. The minerals may be part of rock fragments, or crystals that have grown from liquids or other minerals. The term **texture** is used to describe the size, shape and arrangement of particles or mineral grains in a rock.

Scientists classify rocks into three groups: igneous, sedimentary and metamorphic. Classification of rocks uses both the types of minerals present and the way they are arranged to identify the origin of a rock.

Igneous rocks

Igneous rocks are formed when liquid rock, or **magma**, crystallises. In Chapter 9, you will learn how magmas form. To recognise and classify igneous rocks, geologists use the mineral composition and the texture of the rock. These characteristics and some examples of characteristic rock types are shown in Figure 3.9.

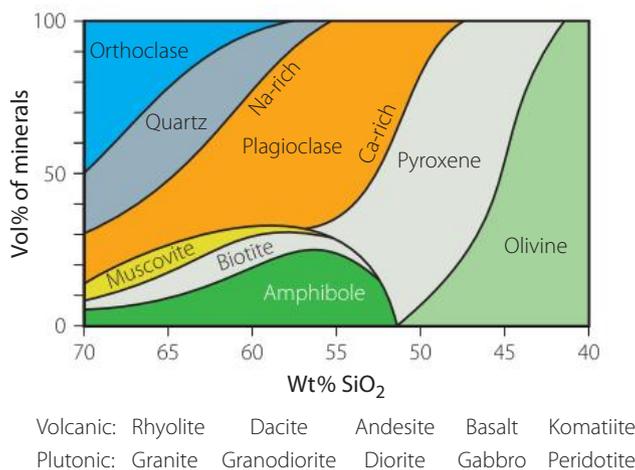


FIGURE 3.9
Characteristics of rock types

Igneous rock composition is reflected in the overall colour of the rock. Mafic rocks, such as basalt, are very dark; felsic rocks, such as granite, are a light colour, and intermediate rocks such as andesite tend to have a grey colour. The colour of a rock also reflects the amount of **silica** (SiO_2) the rock contains. Mafic rocks have 45–52% silica, intermediate rocks contain 52–63% silica, and felsic rocks contain 63–80% silica. Some rocks consisting of only olivine and pyroxene have only 30–45% silica. These are termed ultramafic rocks.

Igneous rock textures are based on the size or presence of mineral crystals. A coarse-grained igneous rock is one in which you can see the mineral crystals without the aid of a hand lens. Such rocks have cooled slowly inside Earth and are referred to as plutonic. A fine-grained rock is one where the mineral crystals are too small to see. Vesicular rocks have pores, or holes, in them due to rapid surface cooling and the release of gas. A pyroclastic rock is formed when escaping gas shatters the rock as it forms and the fragments are then bonded together. If **lava** cools extremely quickly, no crystals grow and a glass is formed. Fine-grained rocks, vesicular rocks and **pyroclastics** all show rapid cooling and are referred to as volcanic.

Sedimentary rocks

Sedimentary rocks are formed from the products of weathering: particles, clay, salts and organic material. Rocks at the surface of Earth are broken down into sediments. Regardless of where they form, rocks may become exposed to the atmosphere and hydrosphere due to uplift and erosion. Oxygen, water and living things are powerful agents of change. When exposed at the surface, rock minerals are changed by chemical and physical breakdown processes called **weathering**. **Erosion** refers to gradual removal of the weathered material. The products of weathering are compacted and cemented together to form sedimentary rocks.

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FIGURE 3.10 A sample of conglomerate. Note the different rock types cemented together to form this rock.

Sedimentary rocks can be classified into three groups according to the sediments that make them up. **Clastic** rocks are formed from clast, or fragments of rock or minerals. The fragments may be large, such as the pebbles making up conglomerate (Figure 3.10), or small, such as the clay making up a shale. The size of sediment reflects the energy of the material that transported the sediment. Small clay particles settle from almost still water or from wind, but only pebbles are heavy enough to be deposited in fast-flowing rivers. **Chemical** rocks are those formed by chemical precipitation. Limestone (when precipitated from warm water), chert, gypsum and rock salt are

examples of chemical rocks. **Organic rocks** are composed of material formed by biological processes. Coal (formed from plants) and limestone (when formed from coral skeletons) are examples. Sometimes rocks may be a mixture of these components. Oil shale is a good example. It contains a great deal of clay, like a clastic rock, but also contains oil derived from organic material.

Metamorphic rocks

Metamorphic rocks are those in which minerals change and grow due to a changed physical or chemical environment. For example, a shale close to a body of magma experiences a great deal of heating. Minerals in the shale recrystallise and new minerals may form. The result is a hard, dark rock called hornfels with some new metamorphic minerals.

Metamorphic rocks mainly form due to increased temperature and pressure. Temperatures range from those at which sedimentary rocks form in Earth through to the temperature where rocks melt. Pressure results from deep burial and directed pressure. The pressure at plate boundaries acts over large areas, **folding** rocks and setting up conditions for metamorphism. Heat and pressure cause new minerals to grow in a rock. Pressure controls the direction the crystals grow. If pressure is directed, crystals grow at right angles to the direction of pressure and this causes the crystals to be aligned. The layered textures that form are referred to as **foliation** (Figure 3.11).



FIGURE 3.11 A garnet schist. Note the large garnets and the surrounding foliation due to mica and other minerals.

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Indigenous rock classification

For tens of thousand of years before Europeans created the framework of mineral and rock classification used by scientists today, Aboriginal and Torres Strait Islander peoples had been selecting, mining, trading and using stone and minerals. Some of these materials were highly prized and laws controlled access to the resources and how they could be used. High-quality materials were selected for specific purposes, and to do this Aboriginal and Torres Strait Islander peoples used a classification system based on what the rock or mineral was used for.

The guiding principle for classification was not the composition of the material but its properties and how well they suited specific uses. For example, it seems likely that Aboriginal people developed the technology of creating ground-edge axes soon after they colonised Australia. Researchers from Sydney University have found evidence of axe production in northern Australia between 44 000 and 49 000 years ago. Such axes were valuable tools, and the best material for their manufacture is fine-grained igneous rock. This rock is hard, not brittle, and it is capable of having the cutting edge ground and sharpened. Australia, being geologically ancient, does not have much fresh basalt, and such rock was highly prized. In some areas, the fine-grained rock used was more brittle, such as silcrete, quartzite and flint. These did not last so well.

Another use of rock materials is the manufacture of sharp blades. Cutting and scraping required tools made of materials with different characteristics to those of a good axe. Here, the silcrete, quartzite and flint were prized because flaking techniques applied to them produced extremely sharp edges. The shaping of such edges is called **knapping** and skill in knapping requires both practice and a keen understanding of the properties of the material being used (page 110). Ochre, used for ceremonies, was also classified according to its practical features. Good **ochre** is not only brightly coloured but also fine grained, and it does not cause itching. If it contains mica flakes to glisten, this is an added bonus. Again, the material is classified in terms of how its properties suit a particular use, not in terms of the material's properties alone.

Aboriginal and
Torres Strait
Islander histories
and cultures

You will
learn more
of Aboriginal
quarrying and
mining in
Chapter 5.

INVESTIGATION 3.4

Classifying rocks using a scientific dichotomous key



Critical and creative thinking



Work and enterprise

INTRODUCTION

Keys are valuable tools in classifying different objects. In this investigation you will use a key to identify 10 common rocks of different types. You will also assess the effectiveness of the key and its suitability for the area in which you live.

AIM

To work in a group of 2–3 students to successfully use and assess a key to identify a range of rocks

MATERIALS

- Set of 8–10 unnamed rock specimens
- Hand lens or dissecting microscope
- Dropper bottle of 1 M hydrochloric acid
- Petri dish
- Safety glasses



WHAT RISKS ARE THERE IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Some rocks and minerals contain potentially toxic substances.	Listen carefully to your teacher and follow their instructions. Do not handle the specimens too much. Wash your hands thoroughly after the investigation.
Small droplets of acid may be ejected by bursting bubbles of gas.	Wear safety glasses.

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

TABLE 3.4 A rock classification key to 25 common rock types

1 Is the rock composed of rock or mineral fragments or clay?	Yes	Go to 2.
	No	Go to 8.
2 Are the fragments greater than 3 mm in diameter on average?	Yes	Go to 3.
	No	Go to 4.
3 Are the clast rounded like pebbles?	Yes	conglomerate
	No	breccia
4 Does the rock produce bubbles when treated with acid?	Yes	limestone
	No	Go to 5.
5 Are the individual grains large enough to be seen with the eye alone?	Yes	Go to 6.
	No	Go to 7.
6 Are the grains mainly quartz, without rock fragments?	Yes	quartz sandstone
	No	lithic sandstone
7 Are fine layers present?	Yes	shale
	No	mudstone





8 Does the rock resemble a glass?	Yes	obsidian
	No	Go to 9.
9 Is the rock light weight, containing many pores?	Yes	pumice
	No	Go to 10.
10 Is the rock coarse grained? (Can you see individual grains?)	Yes	Go to 11.
	No	Go to 21.
11 Do the minerals exist as large crystals in a fine-grained matrix?	Yes	porphyry
	No	Go to 12.
12 Are the mineral grains larger than 6 mm in diameter?	Yes	pegmatite
	No	Go to 13.
13 Is the rock foliated? (Do grains form flat sheets or layers?)	Yes	Go to 14.
	No	Go to 15.
14 Does the rock lack banding and appear to consist of visible mica grains?	Yes	schist
	No	gneiss
15 Is the rock hard and consist mainly of quartz?	Yes	quartzite
	No	Go to 16.
16 Does the rock produce bubbles when treated with acid?	Yes	marble
	No	Go to 17.
17 Does the rock contain more than 20% quartz grains?	Yes	Go to 18.
	No	Go to 20.
18 Is the amount of plagioclase feldspar greater than or equal to the amount of orthoclase feldspar?	Yes	Go to 19.
	No	Go to 20.
19 Is the amount of orthoclase greater than the amount of plagioclase?	Yes	granite
	No	granodiorite
20 Is quartz or biotite present?	Yes	diorite
	No	gabbro
21 Does the rock have good cleavage (break into sheets)?	Yes	slate
	No	Go to 22.
22 Is the rock extremely fine grained and exhibit a conchoidal fracture?	Yes	chert
	No	Go to 23.
23 Does the rock contain feldspar and mica in a grey matrix?	Yes	andesite
	No	Go to 24.
24 Is the rock dark and fine grained?	Yes	basalt
	No	dolerite (dibase)





METHOD

- 1 Use the key in Table 3.4 to identify the rocks supplied. For some steps it may be useful to refer back to Table 3.1.
- 2 For each rock, record the steps you used in reaching your decision. Record your results in a suitable table.
- 3 Have your teacher check your results. Reclassify the specimens you did not identify correctly and highlight where you made the wrong decision in your original classification.

RESULTS

Create a table that includes the number of the specimen, the characteristics you identified for the specimen, and the name of the rock you determined using the key.

ANALYSIS OF RESULTS

- 1 Which type of rock (igneous, sedimentary or metamorphic) was easiest to identify? Explain why.
- 2 For each rock type, identify the two most important features needed to classify rocks of that group.
- 3 Which rock specimen did you find hardest to classify? Explain why.
- 4 There are many rocks absent from the key. If you were asked to add coal to the key, where would you place it? Explain your decision.

DISCUSSION

- 1 What benefits are there in using a dichotomous key for classification?
- 2 Are technical terms an asset or a problem in using a key?
- 3 Are keys easy to modify when new items need to be added to them?
- 4 What would be the benefit of using this key in the field?

CONCLUSION

Assess your success in using the key and the benefits of such keys in classifying rocks.

EXTENSION

Use the key in Table 3.4 to extract a key classifying only igneous rocks.

INVESTIGATION 3.5

Aboriginal and Torres Strait Islander methods of rock classification



Aboriginal and Torres Strait Islander histories and cultures



Information and communication technology capability

INTRODUCTION

Three types of stone tools that were once regularly created by Aboriginal and Torres Strait Islander peoples were ground-edge axes, cutting blades and grindstones. In this investigation you will identify the characteristics of rocks valued for making tools. Using this information, you will infer how those properties made the rocks suitable for the various tools.

AIM

To investigate methods of classifying rocks and minerals in ways used by Aboriginal and Torres Strait Islander peoples

PROCEDURE

- 1 Use the Internet to research the origin and characteristics of each of the rocks basalt, sandstone, chert, quartzite and silcrete. Identify their origin, grain size, hardness and how they fracture.



- » 2 Consider the three tools identified in the introduction. For each one, list three characteristics you would expect each tool to have to be effective for its purpose. For example, does the tool need to be hard, sharp, tough or rough? You may find it useful to find images of these tools on the Internet to help you understand their form and functions.

ANALYSIS OF RESULTS

Correlate the rock properties with the tool features. You might do this in the form of a two-way table with rock properties as column headings and tool properties labelling the rows. Tick the cells of the table where the rock and tool properties coincide.

DISCUSSION

- 1 a What properties do silcrete, chert and quartzite have in common?
b How does the way these minerals fracture make them suitable for creating cutting blades?
- 2 Contrast the features of basalt and sandstone as suitable materials for making a ground-edge axe.
- 3 When Europeans introduced glass to northern Australia, Aboriginal peoples used the glass to make edged tools called Kimberley points. Previously these tools were made from quartzite. What reasons might the Aboriginal peoples have had for making the change?

CONCLUSION

In what ways is the classification of a material in terms of its potential use as a tool different from the way scientists classify rocks and minerals?

Rock cycle

The atmosphere, biosphere and hydrosphere all cause weathering of rocks exposed as outcrops on the surface. The products of weathering, transported and deposited, then become sedimentary rock over time as the sediment is compacted and cemented together. In the lithosphere, heat and pressure cause rocks to change. They may even melt. All these processes of change and the rocks that result are summarised in a model called the **rock cycle** (Figure 3.12).

The processes of the rock cycle take a long time to occur. Changes in the rock cycle are driven by gravity and **heat energy** in Earth. Water plays a critical role in weathering, erosion, metamorphism and the melting of rocks in subduction zones. Each stage can take hundreds of thousands to millions of years to occur. James Hutton, in the 19th century, recognised how slowly outcrops weather and from this realised how ancient Earth must be.

You will learn more of water and its roles in Chapters 9 and 10.



Related rocks

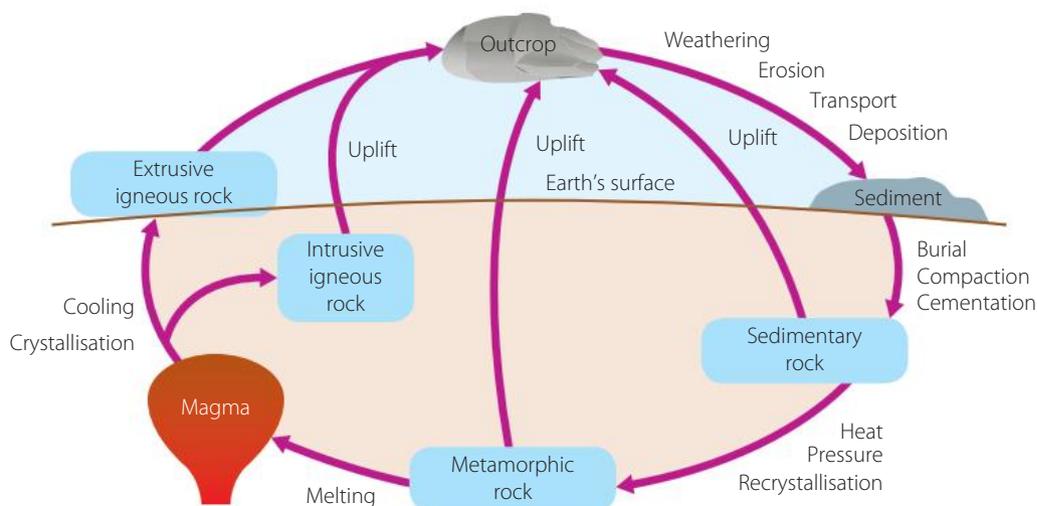


FIGURE 3.12
The rock cycle summarises the processes that form rocks.

- Rocks are composed of minerals intergrown or cemented together.
- Rocks are classified by geologists as igneous, sedimentary or metamorphic in terms of their origin.
- Igneous rocks are formed from magma.
- Sedimentary rocks are composed of the products of weathering. The products of weathering are compacted and cemented together to form sedimentary rocks.
- Metamorphic rocks are formed when rocks experience new conditions, such as heat, pressure or the presence of hot mineral-rich fluids.
- Scientists classify rocks and minerals based on their composition and physical characteristics.
- Aboriginal and Torres Strait Islander peoples traditionally classify rocks in terms of their uses and required physical properties.
- Changes in a rock's environment can lead to changes to a rock and its components becoming part of new rocks. This process of change is described by a model called the rock cycle.

CHECK YOUR UNDERSTANDING

3.2

- 1 Distinguish between a mineral and a rock.
- 2 Outline the origin and features of the three types of rocks.
- 3 Describe, using an example, the properties of a rock that Aboriginal and Torres Strait Islander peoples would use to classify it.
- 4 Explain how a sedimentary rock can be identified.
- 5 Both igneous rocks and metamorphic rocks contain mineral crystals. How can these types of rocks be distinguished?
- 6 Explain how you would use a dichotomous key to identify and name an unknown rock.
- 7 Draw a simplified version of the rock cycle to identify the processes involved in an igneous rock becoming a metamorphic rock.
- 8 Select an igneous, a sedimentary and a metamorphic rock you have studied. Create a table to contrast their properties.

3.3 Nature and origin of soil

The rock cycle shows that changes occur to rocks at Earth's surface. The area between unaltered rock and the atmosphere is referred to as the **regolith**. The regolith is the place where the hydrosphere, atmosphere,

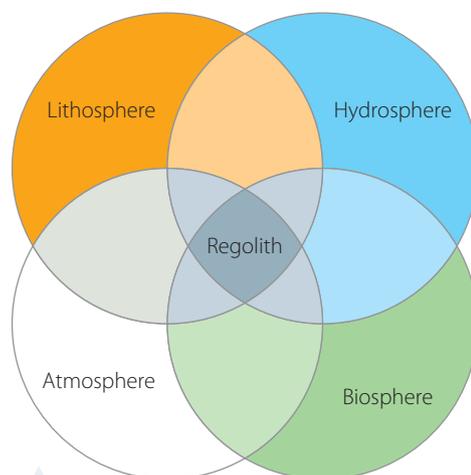


FIGURE 3.13 At the regolith, the biosphere interacts with Earth's three physical spheres.

lithosphere and biosphere all interact (Figure 3.13). The **biosphere** is the sum of all the living things on Earth. One of the key products of this interaction is soil. **Soil** is a complex system consisting of **abiotic** (non-living) and **biotic** (living) components. Humans and terrestrial ecosystems depend on soils; they provide us with food and renewable resources. Pastures grown in soil provide food for livestock and crops provide food and fibres for people. Natural ecosystems rely on soils for nutrients to support plant growth. The soil itself also hosts rich ecosystems of micro-organisms and invertebrates. Ecosystems are shaped by the soils they grow on and influence the way a soil develops.

Soil is a system comprising minerals, water, air and organic material. The approximate proportions of these components under normal conditions are

shown in Figure 3.14. The mineral material is derived from the rocks or sediments on which a soil develops. The parent material may be a rock such as basalt or a sediment such as sand and silt deposited on a flood plain. Spaces between the mineral grains, called **pore spaces**, are where air and water are located. The size of pores is affected by the size of mineral particles. Large particles provide more pore space than small mineral particles such as clay. The water forms a thin film on the surface of the mineral grains. If the pore spaces are filled with water the soil is said to be waterlogged. This means plant root cells cannot obtain sufficient oxygen to carry out cellular respiration and the plants may die. Micro-organisms grow in the pore spaces, binding particles together and providing surfaces that bind mineral nutrients so they are not easily lost.

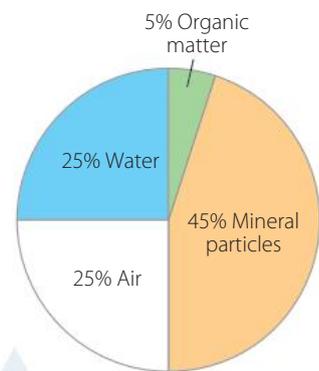


FIGURE 3.14 The components of a soil

Physical properties of soils

Soil components establish a soil's physical properties, such as texture, structure and porosity. **Porosity** is the amount of pore space in a soil. It ranges from 10% to 70% of a soil and determines how well water drains through a soil. Texture refers to the relative amount of clay, silt and sand-sized particles in a soil (Figure 3.15). The relative amounts of each size affect how well a soil drains, how it binds nutrients and how easy it is to cultivate. Structure refers to the way mineral particles are bound together to form clumps called **peds** (Figure 3.16). Cracks and spaces between the peds provide soil micro-organisms and fauna with places to live and allow water and air to penetrate the soil. The peds are partly the result of organic materials formed by bacteria and fungi binding mineral fragments together. In some heavy clay soils, structure is absent or massive.

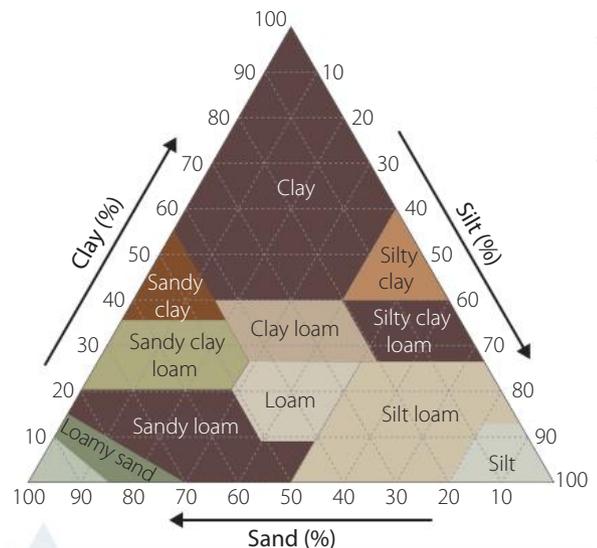


FIGURE 3.15 Textural classification of sediment

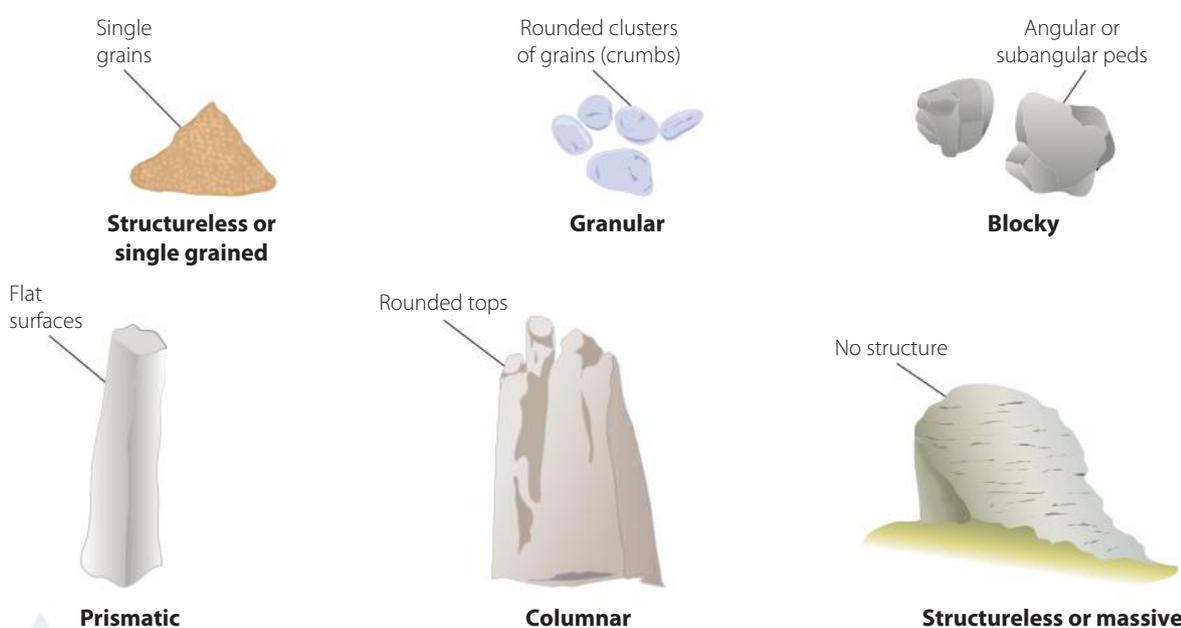


FIGURE 3.16 Structures found in soils

Imlay Gillespie, & Huxley, C. (2002) Earth and Environmental Science The Preliminary Course Cambridge University Press. © Cambridge University Press 2002. Reproduced with permission of the Licensor through PLSclear

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Chemical properties of soils

A soil's chemical properties depend on the rock material from which the soil forms and the combined actions of the hydrosphere, biosphere and atmosphere. Colour in soils reflects both the parent material and the processes that have produced the soil. A basalt may weather to provide iron, which reacts with oxygen from the air to create yellow, orange or red colours in a soil. If the soil becomes waterlogged the soil may take on a mottled colour due to reactions between the water and minerals present.

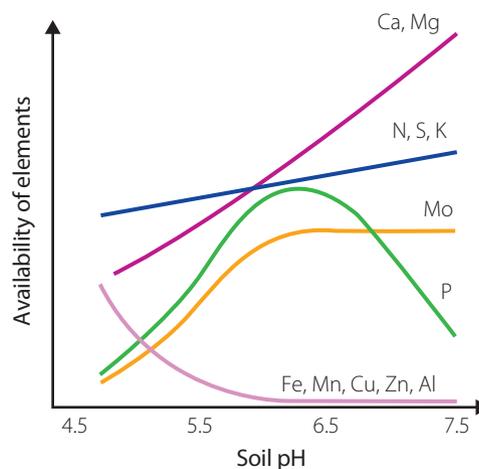
A key feature of soils is **pH**. This is a measure of the acidity or alkalinity of a soil. The pH of a soil is influenced by how chemicals are moved through the soil by water, a process called leaching. It is also affected by the amount of organic material present and the addition of fertilisers. The pH of a soil affects the availability of essential elements for plants (Figure 3.17). Plants are adapted to the pH conditions of the soils they grow in naturally. Changes to pH can restrict access to mineral nutrients or sometimes release elements that are toxic to plants.



Acid soils

Identify three consequences of acid soils using this resource.

FIGURE 3.17
Nutrient availability and pH



Symbol	Element
Ca	calcium
Mg	magnesium
N	nitrogen
S	sulfur
K	potassium
Mo	molybdenum
P	phosphorus
Fe	iron
Mn	manganese
Cu	copper
Zn	zinc
Al	aluminium

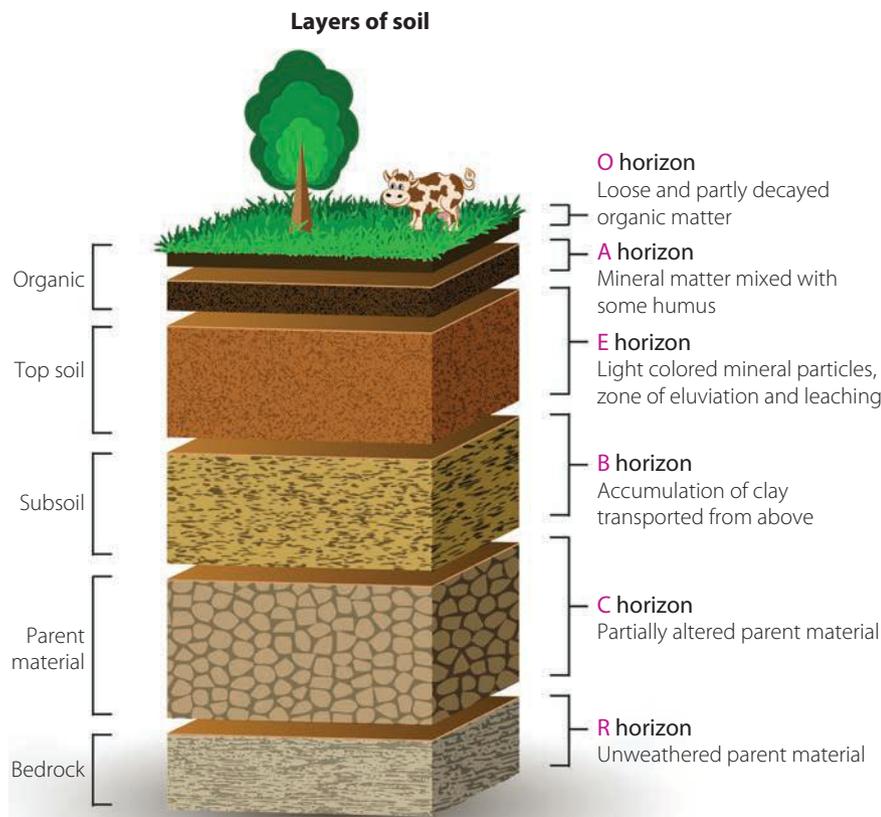
Gazey, C. Davies, S. and Master, R. (2014), Soil acidity : a guide for WA farmers and consultants. Department of Agriculture and Food, Western Australia, Perth. Bulletin 4858. <https://researchlibrary.agric.wa.gov.au/bulletins/223/> © State of Western Australia (Department of Primary Industries and Regional Development, WA)

Organic matter influences the chemistry of the soil. Organic material makes soil colours darker, and it also stores nutrients used by plants and the soil micro-organisms. Nitrogen, sulfur and phosphorus are all important nutrients for plant growth. These nutrients are bound up with organic matter. A consequence of hot bushfires is the removal of organic material from the upper layers of a soil, leading to a rapid loss of nutrients and making the soil more vulnerable to erosion.

The analysis of physical and chemical properties of a soil provides scientists with information needed to manage that soil. On many New South Wales soils, heavy machinery or livestock cause compaction of the soil. This reduces pore spaces, water infiltration, root growth and seed germination. A range of solutions to compaction are available but which one is most effective depends very much on the nature of the soil.

Soil profiles

Soil structure is the product of weathering, water movement and biological action. Soils display layers at different depths in an overall arrangement referred to as a **soil profile** (Figures 3.18 and 3.19). Each layer is referred to as a **horizon**. Traditionally, the uppermost horizon containing mineral material is called the **A horizon**. It is rich in organic material, making it dark, and contains nutrients easily accessible to plants. The layer called the E horizon is sometimes present below the A horizon. This layer is paler due to the removal of minerals such as clay minerals and iron and aluminium salts. The **B horizon** is different from the A horizon both in composition and structure. It is a zone of accumulation where quartz, clay, organic material, iron, aluminium and carbonate compounds may be found. They are moved by water from the layers above and below the horizon. The **C horizon** is a zone of weathered material. Remnants of the rock



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FIGURE 3.18 A soil profile

from which the soil formed may be present and the material shows weathering but it does not show evidence of the soil-making processes seen in the layers above. Below the C horizon is the unweathered rock from which the soil has formed.

Two key sets of processes generate a soil profile: mixing and vertical movements. In the A horizon, mixing of organic material occurs as living things burrow or grow through the material. Minerals may be concentrated and mixed when the movement of water is impeded. Water moving through a soil carries dissolved minerals and small clay particles downwards. This eluviation contributes to the concentration of materials found in the B horizon. In warm climates, **evaporation** of water at the surface may cause water to move upward through the soil, carrying material with it. This can cause the movement and concentration of iron and aluminium oxides, forming soils called **laterites**.



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FIGURE 3.19 A podzol soil profile. Can you identify the horizons present?

Factors affecting soil formation

The depth, fertility and the nature of a soil are determined by time, living things, climate and topography. Living things and climate play a key role in the process of weathering.

Components of the lithosphere, hydrosphere, atmosphere and biosphere all determine the nature of weathering. Weathering can be caused by ice, salts, acids, water, plants, animals, wind, changes in temperature and the removal of pressure from a rock body. These components and processes are referred to as agents of weathering, and where they act is partly a function of geography and climate.

Soils in your area

To find out more about soils in your area of New South Wales, explore the eSpade application from the New South Wales Office of Environment and Heritage.

Weathering processes are classified according to whether they chemically change the minerals in a rock or soil. When daily changes in temperature, or the growth of ice in a rock, causes a rock to break into smaller pieces, the weathering is called **physical weathering**. Physical weathering is a characteristic of mountains, deserts and polar areas. If the nature of the minerals in a rock changes through chemical reactions with water, acids or oxygen, the weathering is referred to as **chemical weathering**. Chemical weathering is a feature of areas near the equator where it is warm and rainfall is relatively high. Components of the biosphere can generate both physical and chemical weathering.

The minerals in a rock or sediment also determine how weathering occurs. Mafic minerals such as olivine and pyroxene break down rapidly in the presence of water and oxygen. Felsic minerals are much more resistant. This is why quartz and feldspar are more common in sands than the mafic minerals. The longer that the soil-making processes occur, the deeper the soil may become. In Western Australia, weathering as deep as 30 metres has been revealed in some open-pit mines.

Topography affects the rate at which soils form. Slope is important because weathered material tends to move down slope. Soils in valleys are generally deeper than soils on ridge crests. Aspect is important. In the southern hemisphere, north-facing slopes receive more sunlight and heating, which affects plant growth and water evaporation. Areas prone to periodic erosion, such as flood plains, may have soil-making processes interrupted by the abundance of water increasing the rate of weathering.

INVESTIGATION 3.6

Mapping a soil profile



Information and communication technology capability



Work and enterprise

INTRODUCTION

An important stage in understanding a soil and its history is systematically describing its properties. Your teacher will identify a safe, readily accessible soil profile for this exercise or you will obtain information about the profile using a soil auger.

AIM

To compile data on a soil profile and identify the soil using a key

MATERIALS

- Spade
- Soil auger
- Measuring tape
- 10 plastic bags
- Marking pen
- Inclinator
- Compass



WHAT RISKS ARE THERE IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Pit or cutting collapse	Follow the directions of your teacher. Do not work near a high surface that is unstable.
Working with sharp tools in a confined space	Ensure that only one person works with a sharp tool on the profile at any time.
Dust and spore inhalation	Spray water on surfaces if there is a great deal of dust. Avoid inhaling any dust from the work area or wear a face mask. Wash hands well after collecting samples.

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



» METHOD

- 1 Prepare a site chart sheet using the example table in the Results section.
- 2 First, assess the area. Describe the slope (angle) and the direction the slope faces (aspect). Briefly describe the type of vegetation growing near the profile and identify the way the land is being used (e.g. native vegetation, cropping, grazing). Does the area look as if it drains well? Record your observations in the top of your site chart.
- 3 Dig a small pit to a depth of 50 cm so a vertical face is exposed. Alternatively, use the soil auger to obtain samples initially to a depth of 50 cm.
- 4 Observe the profile and identify the horizons or layers within the soil.
- 5 For each horizon, measure and record the depth from the surface to the top of the horizon and its thickness.
- 6 Collect a sample of material from each horizon and assess colour, texture, moisture and structure. Note, you may need to collect samples for use in Investigation 3.7. If so, label a plastic bag with the date and soil horizon before placing a sample in it.
- 7 Carry out a pH test and record the pH. (See Investigation 3.7 for details.)

RESULTS

Create a table similar to the one below.

LOCATION:							DATE:		
SOIL CLASSIFICATION:							SLOPE, ASPECT AND DRAINAGE:		
UNDERLYING ROCK OR PARENT MATERIAL:									
VEGETATION / LAND USE:									
ADDITIONAL NOTES:									
Soil profile data									
Horizon	Depth to horizon (cm)	Thickness of horizon (cm)	Colour	Moisture estimate	Texture	Structure	pH	Amount of organic matter	Other features

ANALYSIS OF RESULTS

- 1 Use the weblink to access the soil classification key.
- 2 Follow the key to identify the classification of the soil you have recorded. Use the glossary to understand the meanings of the technical terms in the table.
- 3 Record the soil classification on the site chart.

DISCUSSION

- 1 How distinct were the horizons in the soil profile?
- 2 What were the possible reasons for the differences between the horizons?
- 3 In what ways have the slope and aspect affected the development of the soil profile?
- 4 What aspect of the soil description did you find hardest to carry out? Why?

CONCLUSION

Write a conclusion to address the aim of the investigation.

EXTENSION

Use the eSpade website (page 75) to identify the soil landscape of your soil. How does your data compare with that recorded there?



The Australian Soil Classification

INVESTIGATION 3.7

Examining the components of a soil

INTRODUCTION

This investigation will give you experience in assessing some soil properties. Think about how these properties relate to the overall nature of the soil the samples come from.

AIM

To measure six properties of top soil and subsoil samples and relate them to soil features

MATERIALS

- 2 soil samples (top soil horizon and a subsoil horizon)
- Spatula or small trowel
- 30 cm ruler
- 2 large test tubes with stoppers
- 2 Petri dishes
- 2 evaporating basins
- Dropper bottle containing dilute hydrochloric acid
- Universal indicator in dropper bottle
- Universal indicator colour key
- Shaker containing barium sulfate
- White tile
- Electronic balance



WHAT RISKS ARE THERE IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Weak acid can burn skin and eyes.	Ensure eye protection is worn.
Universal indicator will stain.	Avoid contact with skin or clothes. Wear a lab coat if possible.
Dust and spore inhalation	Ensure you work in a well-ventilated area. Wash hands well after collecting samples.
Chemical and micro-organisms in soil samples	Handle samples with spatula or trowel. Wash hands and clean bench after the investigation.

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

PROCEDURE

Carry out the tests described below for the top soil and a subsoil sample from your soil profile.

Part A: Texture

Texture is a measure of the relative amounts of sand, silt and clay in the sample.

- 1 Collect enough soil sample so it will fit comfortably in the palm of your hand.
- 2 Remove any gravel or large organic pieces.
- 3 If the sample is dry, add just enough water so that you can shape the sample into a ball (**bolus**). Note how it feels.
- 4 Using the bolus, see how long a ribbon you can form between your thumb and finger.
- 5 Use Table 3.5 to assess the texture of the bolus and record the name and features observed. 

» **TABLE 3.5** Field determination of soil texture

BOLUS CHARACTERISTICS	RIBBON LENGTH	APPEARANCE UNDER A HAND LENS	TEXTURE TYPE	APPROXIMATE CLAY CONTENT (%)
Does not form a ball. Feels very gritty. A loamy sand leaves a film of clay on fingers.	Cannot form a ribbon	Mostly sand-sized particles	Sand or loamy sand	0–10
Only just forms a ball.	1–2 cm long between your thumb and finger	Sand grains obvious	Sandy loam	10–20
Forms a ball that feels slightly spongy.	About 2.5 cm long	Similar amounts of sand, silt and clay	Loam	25
Forms a good ball. It feels spongy and silky.	About 2.5 cm long	Some sand grains but mostly silt	Silty loam or silt	25
Forms a good ball Slightly gritty feel. Feels like soap when moist.	3–5 cm long	A few sand grains present	Silty clay loam, clay loam, sandy clay loam	20–35
Forms a smooth, sticky ball that is easy to shape.	More than 5 cm long	Sand grains rare or absent	Clay or silty clay	more than 40

More detail on soil texture properties can be found at the Soil quality weblink.

Part B: Structure

Structure refers to the way mineral particles and organic matter hold together to form clods or peds.

- Use Figure 3.16 as a guide and describe the structures found in your sample.

Part C: pH

pH is an indication of the acidity of the soil.

- Place enough soil to cover the size of a \$1 coin on a white tile.
- Add 3 drops of universal indicator to the sample.
- Shake barium sulfate onto the soil sample until a white surface is made.
- Wait 1 minute and then use the colour guide and the colour of the barium sulfate to determine the pH.
- Record the colour and the pH.

Part D: Carbonate content

Carbonate affects water penetration and the acidity of a soil.

- Place a small sample of the soil in a Petri dish.
- Add 3–5 drops of dilute acid to the sample.
- If bubbles of gas are formed, then carbonate is present.
- Record your observations.

Part E: Organic matter and fine fraction estimation

This method gives a qualitative indication of organic material and the clay content as these components settle in a water column.

- Half-fill a large test tube with the soil sample.
- Add water until the test tube is two-thirds full.
- Add a stopper to the test tube and shake well.
- Leave the test tube to stand overnight.
- Assess the proportion of dark organic material and the fine clay layer that forms on top of the sample. Record your observations or measurements.

Part F: Water field capacity

Field capacity is the maximum amount of water the soil can hold. For this test, try to use a soil sample that has not been broken up too much during collection.

- Measure the mass of an evaporating basin.
- Quarter-fill the evaporating basin with soil.
- Measure the mass of the evaporating basin and soil.
- Now, calculate the original mass of the soil by subtracting the mass of the evaporating basin.
- Add water to the basin and make sure the soil is well saturated.





- 26 Carefully pour off any excess water.
- 27 Measure the mass of the evaporating basin and saturated soil.
- 28 Dry the sample by leaving it uncovered in a warm place for 48 hours. Do not heat it.
- 29 Measure the mass of the evaporating basin and saturated soil again.
- 30 Calculate the final mass of the soil by subtracting the mass of the basin.
- 31 Calculate the field capacity by dividing the mass change (due to water loss) by the dry mass of the soil (final mass – original mass). Your units will be gram/gram of dry soil.

RESULTS

Record any calculations you make during the investigation.

Create a table to record the results of each test for each of the two horizon samples.

ANALYSIS OF RESULTS

- 1 Compare the results for the two samples. In what ways were they similar?
- 2 In what ways were the properties of the two horizons different?
- 3 Comment on the distribution of carbon and clay in the samples. What processes might account for the differences?
- 4 Relate the features you have measured to the following soil characteristics:
 - a water movement or retention in a soil
 - b soil fertility
 - c soil compaction.

CONCLUSION

- 1 Compare and contrast the features you measured for the two soil samples.
- 2 Summarise two features of the soil related to the properties you assessed.

EXTENSION

Research other methods for assessing organic content and bulk density. Why are these features of a soil important for understanding the agricultural productivity of a soil?

KEY CONCEPTS

- Humans and terrestrial ecosystems depend on soils.
- Soil is a system comprising minerals, water, air and organic material.
- Soil components determine a soil's physical properties such as texture, structure and porosity.
- A soil's chemical properties depend on the rock material from which the soil forms and the actions of the hydrosphere, biosphere and atmosphere.
- The analysis of physical and chemical properties of a soil provides scientists with information needed to manage that soil.
- Soil structure is the product of weathering, water movement and biological action.
- Depth, fertility and the nature of a soil are determined by time, living things, climate and topography.

CHECK YOUR UNDERSTANDING

3.3

- 1 Define a soil.
- 2 Outline the processes that break down a rock during weathering.
- 3 Describe the processes that operate to form horizons in a soil.
- 4 Create a table to contrast physical and chemical properties of a soil.
- 5 Make a labelled diagram of a soil profile.
- 6 Describe the nature of the A, B and C horizons in a soil profile.
- 7 Describe the factors that influence the way a soil develops.

3 CHAPTER SUMMARY

- ▶ A mineral is a naturally occurring inorganic solid with a definite structure and composition.
- ▶ Minerals differ in terms of their composition and crystal structure. Common compositional groups include silicates, carbonates, sulfates and sulfides, oxides and hydroxides.
- ▶ Minerals are composed of metal and non-metal atoms arranged in a crystal lattice.
- ▶ The composition and crystal structure of a mineral determines properties such as hardness, cleavage, density and crystal form.
- ▶ The physical properties of a mineral are used to classify it. These properties include hardness, cleavage, density, lustre, streak, colour and crystal form.
- ▶ Minerals are stable under certain conditions but can change if the environment they are in changes.
- ▶ Mafic minerals are silicate minerals common in igneous and metamorphic rocks. They contain relatively large amounts of iron and magnesium, have darker colours ranging from green to black, and relatively high densities.
- ▶ Felsic minerals are found in igneous, metamorphic and sedimentary rocks. They contain relatively large amounts of silicon and aluminium, are light coloured, and have lower densities than mafic rocks.
- ▶ Rocks are composed of minerals intergrown or cemented together. They are classified according to their mineral composition and texture.
- ▶ Rocks are classified by geologists as igneous, sedimentary or metamorphic in terms of their origin.
- ▶ Igneous rocks are formed from magma.
- ▶ Sedimentary rocks are composed of the products of weathering.
- ▶ Metamorphic rocks are formed when rocks experience new conditions such as heat, pressure or the presence of hot mineral-rich fluids.
- ▶ Scientists classify rocks and minerals based on their composition and physical characteristics.
- ▶ Aboriginal and Torres Strait Islander peoples traditionally classify rocks in terms of their uses and required physical properties.
- ▶ Changes in a rock's environment can lead to a rock changing and its components becoming part of new rocks. This process of change is described by a model called the rock cycle.
- ▶ Humans and terrestrial ecosystems depend on soils.
- ▶ Soil is a system comprising minerals, water, air and organic material.
- ▶ Soil components determine a soil's physical properties, such as texture, structure and porosity.
- ▶ A soil's chemical properties depend on the rock material from which the soil forms and the actions of the hydrosphere, biosphere and atmosphere.
- ▶ The analysis of physical and chemical properties of a soil provides scientists with information needed to manage that soil.
- ▶ Soil structure is the product of weathering, water movement and biological action.
- ▶ Depth, fertility and the nature of a soil are determined by time, living things, climate and topography.

3 CHAPTER REVIEW QUESTIONS



- 1 What properties make galena (lead sulfide) a mineral but coal not a mineral?
- 2 **a** Contrast the properties cleavage and hardness.
b Explain why both cleavage and hardness are a product of a mineral's crystal structure.
- 3 Figure 3.20 shows a representation of a silicate mineral called pyroxene.



FIGURE 3.20

- a Why is pyroxene classified as a mafic mineral?
 - b The metal atoms are bonded weakly to the double chains of silica. Explain how this leads to the formation of cleavage planes in the mineral.
 - c Orthoclase feldspar is a felsic mineral. Contrast its properties with those of pyroxene.
- 4 A certain mineral has the formula $\text{Ca}_2\text{Mg}_3\text{Fe}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$.
- a Use a periodic table to name the elements present in this mineral.
 - b To which compositional group does this mineral belong?
 - c Predict the colour of the mineral and explain your prediction.
- 5
- a Use information in Table 3.1 to create a dichotomous key for olivine, biotite mica and K-feldspar.
 - b Outline how you would determine the hardness of biotite.
 - c Evaluate the most valuable property for distinguishing between the three minerals.
- 6 A Petri dish contains a mineral crystal of biotite mica resting on a wet piece of filter paper. After a week the crystal displays a dull surface and there is a red–yellow stain on the paper around the crystal. You are told by another student that this is an example of chemical weathering caused by the presence of water on the mineral.
- a Design an experiment using a control to test the other student’s explanation.
 - b Would you have expected a similar result if a feldspar crystal had been used?
- 7 Three metamorphic minerals – andalusite, kyanite and sillimanite – all have the same chemical formula: Al_2SiO_5 . The pressure and temperature conditions in which each mineral forms have been experimentally determined and the data is shown in Figure 3.21. (1 bar = 100 kPa)

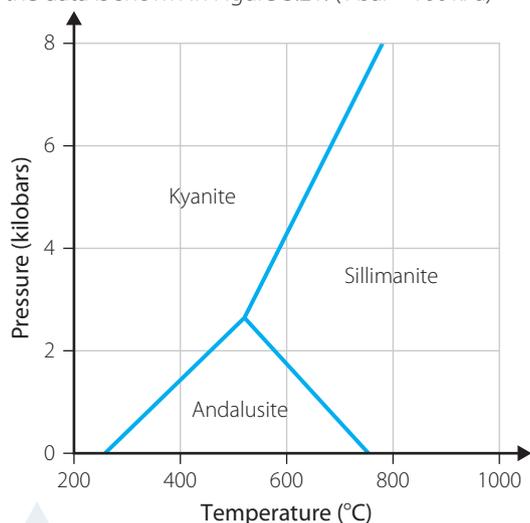


FIGURE 3.21

- a Which mineral would you expect to form in a sedimentary rock close to Earth’s surface that is heated by a nearby igneous intrusion?
 - b Why might kyanite be found in a foliated metamorphic rock such as schist?
 - c Explain how three different minerals can all have the same composition but different properties.
 - d Predict which of the three minerals has the highest density and justify your prediction.
- 8 Figure 3.22 shows the arrangement of minerals in a rock.

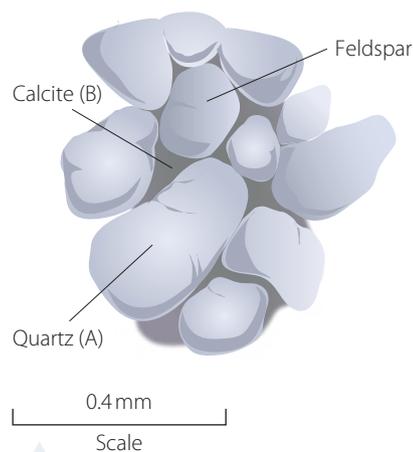


FIGURE 3.22

- a What type of rock is this most likely to be?
 - b Explain the origin of the minerals labelled A and B.
- 9 In Western Australia, mineral grains called zircons have been dated as being 4.4 billion years old. The rock that contain them is a metamorphic rock that was originally a sedimentary conglomerate. The rock has been dated as being approximately 3.0 billion years old.
- a Describe the features of a conglomerate.
 - b Using the rock cycle (Figure 3.12), explain how a rock can contain minerals older than the rock itself.
 - c What conditions could have caused the conglomerate to become a metamorphic rock?
 - d What evidence would you look for in the rock to confirm your answer to part c?
- 10 Figure 3.23 shows a specimen of an igneous rock.
- a Outline three properties you would use to identify the minerals in the rock.
 - b Assess whether this rock is mafic or felsic.
 - c The average crystal size of the rock is 3 mm. Explain why the coarse texture reflects an origin for the rock deep in Earth.



FIGURE 3.23

Shutterstock.com / fosmandarin

- 11 Contrast the texture of igneous rocks formed at Earth's surface with those that form deep in Earth.
- 12 Assess the importance of sediment burial in the creation of sedimentary and metamorphic rocks.
- 13 Use the rock cycle to explain how sedimentary rocks are produced by the formation of mountains.
- 14 Consider the description of a soil profile below.

TOPSOIL	Brownish black sandy loam; poorly formed peds; pH 6.5; to 15 cm depth
SUBSOIL	Very dark brown light sandy clay loam; poorly formed peds; pH 6.5; to 55 cm depth
C HORIZON	Weathered intermediate to mafic volcanic rock

- a Suggest a reason for the darker colour of the topsoil.
- b Explain why the subsoil is richer in clay and iron oxides than the topsoil.
- c Assess how well-draining the soil is likely to be.

- 15 How might a soil forming on a basalt lava flow be different from a soil forming on a quartz sand?
- 16 Soils from four areas on a farm were analysed using two methods. The number of living microbes in 1 mm^3 of soil from each area was counted using a microscope. Samples of each soil were then dried and 500 g of each soil was heated to 500°C for 30 minutes to remove any organic matter. The results are presented in the table below.

AREA	ORGANIC MATTER (%)	LIVING CELLS PER mm^3 (1000)
1	9.2	4.2
2	4.4	1.1
3	7.3	2.9
4	21.2	10.1

- a Describe how the percentage of organic matter was calculated.
 - b Construct a graph of organic matter versus number of living things per mm^3 .
 - c Describe the relationship shown in the graph.
 - d Assess which area contained the most nutrient-rich soil.
- 17 Evaluate the importance of parent material, topography and climate in the formation of a deep, nutrient-rich soil.
 - 18 Three samples of different horizons of a soil profile were obtained and analysed but their layers were incorrectly recorded.
 - a Order the layers from shallowest to deepest.
 - b Justify why Layer 2 is most likely to be the A horizon.
 - c How does the pH change with depth?
 - d Assess the likelihood that this soil comes from a flood plain rather than a hill slope.

	LAYER 1	LAYER 2	LAYER 3
COLOUR	brownish black	dull yellow brown	yellowish grey
TEXTURE	medium-heavy clay with angular blocky peds	light clay loam with little ped structure	medium clay with angular blocky peds
FIELD pH	7.5	6.0	7.0
% CLAY	42	53	51
LAYER THICKNESS (cm)	greater than 40	10	40
% ORGANIC CARBON	0.37	4.59	1.03
COARSE FRAGMENTS	none	none	none

- 19** The table below details information about climate factors, elevation and soil depth for two soils labelled A and B.

LOCATION	SOIL A	SOIL B
ELEVATION (m)	40	60
SOIL DEPTH (m)	40	0.8
AVERAGE TEMPERATURE (°C)	26	9
AVERAGE RAINFALL (mm YEAR ⁻¹)	2000	40
EVAPORATION RATE (mm YEAR ⁻¹)	1100	80

- a** Describe two possible reasons why Soil A is deeper than Soil B.
 - b** Assess whether Soil A or Soil B is most likely to come from a tropical environment.
 - c** Soil B has a salt layer close to the surface. Explain the movement of salt in terms of the rainfall and evaporation rates.
- 20** Discuss how low relief, the age of soils and long periods of leaching contribute to the low fertility of many Australian soils.

4 Geological time

OUTCOMES

In this chapter you will learn about:

- absolute and relative methods used to date Earth materials
- how secondary-sourced data is used to determine the age of geological materials using relative and absolute dating methods. [ICT N](#)





We use clocks, calendars, smartphones and tablets to measure time in the familiar units of seconds, minutes, hours, days, years, decades and centuries. Human history is recorded in written documents and stone tablets going back many thousands of years.

Geologists are historians who determine the sequence of natural events that have formed and changed Earth and its environments. The units of time that geologists work with are much longer than those used to measure human history. Rather, geological time is measured in spans of tens of thousands of years through to billions of years (Figure 4.1).

Dr Tom Hubble



FIGURE 4.1 Headwaters of the Grose River Valley eroded over time into the shales and sandstones of the Sydney Basin rock sequence

Geological time is long and our planet is old – over four billion years old. Earth's rocks record a lot of stories – the collisions of the plates, formation of the continents, the opening of oceans, the evolution of life, 'Snowball Earth', the extinction of the dinosaurs and many other catastrophes. Understanding the history of Earth requires knowledge of when each geological event happened. We use geological clocks to measure this.

4.1 Relative dating

By the mid-19th century, the consensus among scientists was that Earth had a long geological history. The idea that Earth is very ancient was proposed when naturalists made two important discoveries. First, they determined that geological structures, and the materials rocks are made from, record how and when the rocks formed. Second, they documented a progressive sequence of the way that fossils appear in the geological record.

The Grand Canyon is a good example of how rocks record geological history (Figure 4.2). The walls of the canyon are formed of flat layers of sedimentary rock that have buried much older folded and faulted granites and schists. Water in the Colorado River flowing through the canyon eroded the rocks and carved out the canyon walls. This has exposed all the different layers that we see today. Geologists have determined a history for the Grand Canyon by examining the rocks in these layers and the spatial relationships of the layers to each other.

The granites and schists found at the bottom of the canyon are between one and two billion years old. An ancient landscape separates these old, metamorphosed, folded rocks from the younger, flat layers of sediment. This ancient landscape was eroded into the granites and schists before the sedimentary rock layers were deposited.

The oldest of the flat sedimentary rock layers are about 550 million years old. These layers of sediment are stacked on top of each other, each layer younger than the one found underneath it (**law of superposition**). The youngest layers are located at the top of the stack and were formed about 200 million years ago.

Close inspection of the sedimentary rock layers shows that they contain **fossils** – the preserved traces of living things – in this instance mainly marine life (Figure 4.3). It is possible to date these fossils by looking at the position of the layer of rock in which they are found. This **relative dating** is based on the law of superposition, which in turn relies on observations of how sediment is deposited and our understanding of how sedimentary rocks are formed.

Sedimentary rock is composed of products of weathering, such as sands that have been transported by water and deposited in river beds, flood plains, beaches and on the sea floor. Sediment transportation and deposition is an ongoing process; it has been continuously occurring on Earth for billions of years and can still be observed today.

Over time, these deposited sediments form defined layers that form sequences of sedimentary rock. The layers are called **strata**, and the process of depositing a sequence of layers is called **stratification**. A drawing or a cross-section showing successive layers of sedimentary deposition is called a **stratigraphic section** or a **stratigraphic column**.

Assuming natural processes such as a plate tectonic collision have not completely deformed or inverted the layers, the law of superposition allows palaeontologists to assign relative ages to fossils based on the strata in which they are found. While this technique does not give an age in years, the sequence of the strata can be used to estimate the relative ages of the rocks.

Leonardo da Vinci (1452–1519) was one of the first people on record to think about fossils in the way that we do today. He examined and sketched the molluscs and gastropods that occur in the sedimentary rock layers of the mountains around Parma in western Italy. One of his sketches is shown in Figure 4.4.

In ancient Greece, Aristotle (384–322 BCE) proposed that shells had formed in rocks spontaneously. Da Vinci did not agree and instead proposed that the shells had been buried by sediment while they had been part of a living organism on the sea floor.

The area around Parma is now mountainous, but it was obvious to da Vinci that the rocks had formed from mud and sand layers deposited on the sea floor. He identified several different



FIGURE 4.2 Rocks in the Grand Canyon in the United States show clearly that they were laid down in layers with the oldest layers at the bottom and the youngest layers at the top.



FIGURE 4.3 Brachiopod shell found in a layer of limestone in the Grand Canyon

Plate tectonics is discussed in detail in chapters 6 and 7.



FIGURE 4.4 Sketches from Parma made by Leonardo da Vinci some time between 1496 and 1506, where he discovered mollusc and gastropod fossils in sedimentary rock layers and proposed the inland area had once been the sea floor.



FIGURE 4.5 A megalodon tooth (left) compared to that of a great white shark (right)

layers of seashell-bearing rock stacked on top of each other, and from this he argued that for a very long time the sea must have covered the area. Therefore the sea floor must have risen to become mountains (uplift) and the sea must have receded. River valleys had then been eroded into the landscape. The uplift and erosion had exposed the layers of rock in the sides of the valley and the erosion had also exposed ancient fossilised animals that had once lived on the sea floor.

Nicolas Steno (the latinised name of Niels Stensen) (1638–1686) explored and expanded on Leonardo's ideas. Steno demonstrated that the remains of animals and plants present in rocks really were fossils. He did this by comparing the shape and internal structure of teeth of present-day great white sharks to the much larger megalodon teeth commonly found in Tertiary age marine rocks of northern Europe (Figure 4.5). He compared their internal structures by dissecting large fossil teeth and small teeth taken from a dead shark. The only difference between the teeth that Steno found was their size.

The laws of stratigraphy

Steno devised the four geometric laws of stratigraphy – original horizontality, lateral continuity, superposition and inclusions – and probably also **cross-cutting** relationships. These laws, illustrated in Figure 4.6, now form a basic toolkit to enable us to determine the relative ages of rock layers and the sequence of events that generated the rock layers. They allow a group of geological events to be sorted into a time-ordered sequence by examining the stacking relationships of the layers of rock and the shape of the contact surfaces that separate the layers of rock.



The laws of stratigraphy and ordering geological events

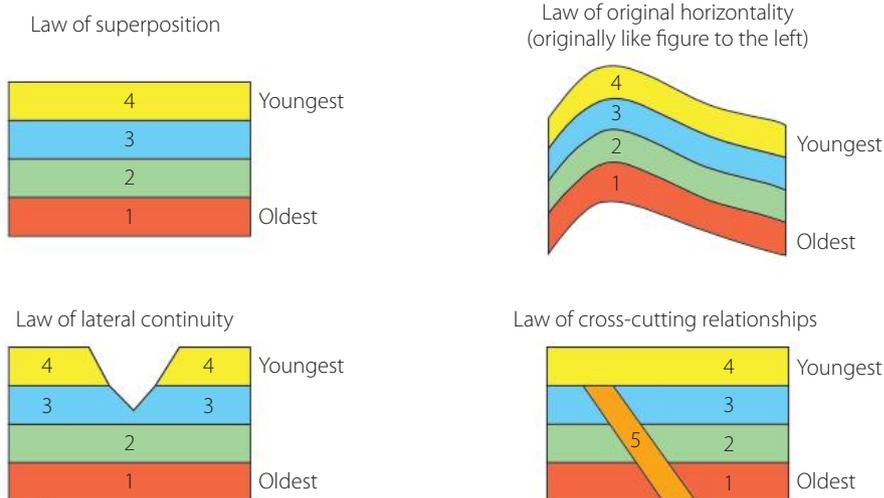


FIGURE 4.6 The four laws of stratigraphy

Law of superposition

The law of superposition states that in an undisturbed, stacked set of sediment layers, the oldest layer is located at the bottom of the stack and the youngest layer is located at the top of the stack. Figure 4.7 shows an example of stacked sedimentary layers. A common analogy for this idea is the construction of a layered sponge cake. A starting layer of sponge is placed first, then a second layer of jam is placed on top of the first sponge layer, then a third layer of whipped cream, and then finally a fourth layer of sponge cake.

Law of original horizontality

The **law of original horizontality** states that, when it is first deposited, sediment is always laid down in extensive horizontal layers. Figure 4.7 is an example of these horizontal layers. These flat sheets of mud, sand and gravel can then be tilted or bent into **folds** by subsequent geological activity and events. The lower boundary surface of a bed is usually called the base or bottom of the bed, while the upper boundary surface is simply called the top of the bed.

Law of lateral continuity

The **law of lateral continuity** states that layers of sediment are deposited as continuous layers that extend laterally (sideways) until either they meet a boundary or the layer gradually thins away to nothing and peters out. This is illustrated in Figure 4.8.

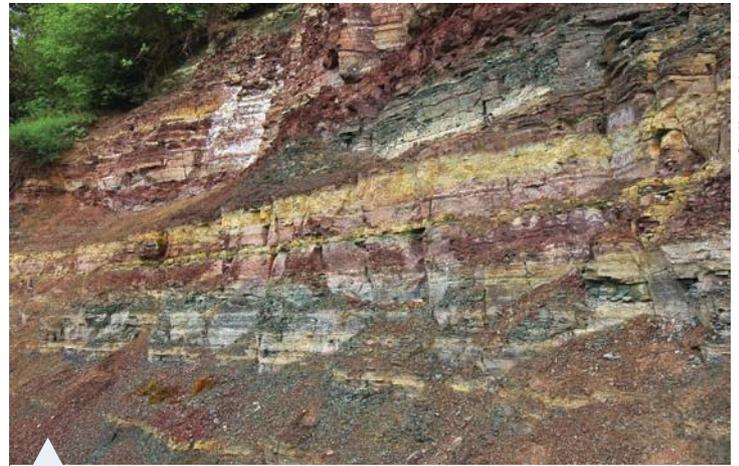


FIGURE 4.7 The laws of superposition and original horizontality. The layer at the bottom was laid down first, followed by each successive layer. The top layer is the youngest layer. All the rock layers were deposited as flat horizontal sheets of sediment.

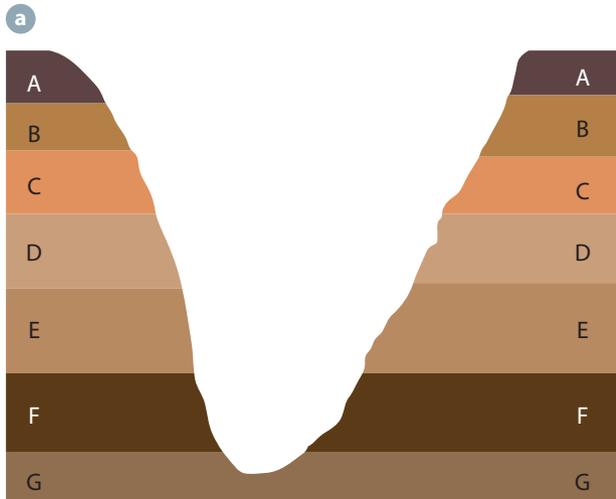
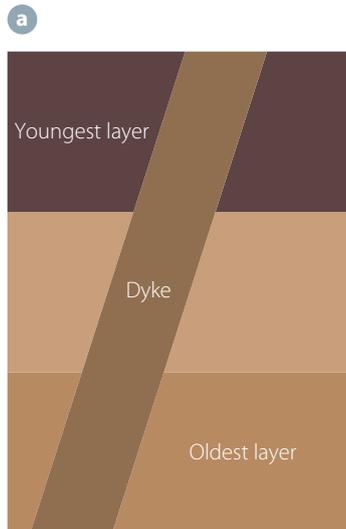


FIGURE 4.8 **a** The law of lateral continuity **b** Layers of sediment exposed in the walls of the Bungle Bungle Ranges in the Purnululu National Park are an example of the law of lateral continuity. The way the different coloured layers are stacked on top of each other also demonstrates the law of superposition.

Law of cross-cutting relationships

The **law of cross-cutting relationships** states that any continuous geological structure that cuts across another geological structure is the younger structure. This idea can be simply expressed with the phrase 'the unbroken surface is younger'. We can use this principle to work out the sequence of geological events in a geological cross-section. Rock formations, such as the one shown in Figure 4.9, illustrate this law.

FIGURE 4.9
a The law of cross-cutting relationships
b The cross-cutting dyke is younger than the rocks it has intruded. The dyke has cut through and separated the layers of rock that surround it.



Science Photo Library/Marill Miller, Visuals Unlimited

Law of inclusions

The **law of inclusions** is sometimes linked with the law of cross-cutting relationships and sometimes is stated as a separate, fifth, law. It states that a large piece of a material included within a layer of rock is older than the rock layer in which the piece of material is found. The piece of material is called an **inclusion** or an included fragment. The inclusion must have existed before the layer of rock was formed. Sometimes this law is called the law of included fragments. An included fragment is illustrated in Figure 4.10.



Dr Tom Hubble

FIGURE 4.10 The large piece of granodiorite formed long before it became an included fragment within the younger brown rhyolite lava flow.

INVESTIGATION 4.1

Modelling the four laws of stratigraphy

AIM

To use modelling clay to model the four laws of stratigraphy

MATERIALS

- 2 sticks each of four different coloured modelling clays
- Metal probe
- Plastic knife
- Rolling pin
- Wooden board
- 60cm baking paper
- Digital camera

METHOD

- 1 Place two sticks of one colour clay on the baking paper and roll them into a flat sheet approximately 10cm×10cm.
- 2 Place this sheet of clay on the wooden board.
- 3 Roll out another colour of clay.
- 4 Place the different coloured sheet on top of the original one.
- 5 Continue to do this until all four sheets are in place.
- 6 Photograph your model.
- 7 Gently push the sheets inwards from both sides.
- 8 Photograph your model.
- 9 Insert the probe vertically through the four layers of clay.
- 10 Photograph your model.
- 11 Using the knife, cut a V-shaped incision through the top three layers of your model.
- 12 Photograph your model.

RESULTS

Label each photograph with the law that it represents.

ANALYSIS OF RESULTS

- 1 Identify which coloured sheet was laid down first.
- 2 In which orientation were the four sheets laid down?
- 3 Describe what happened when you pushed the sheets in from both sides.
- 4 List in sequential order the events that occurred to arrive at step 9 in the method. Which event was the most recent?
- 5 In step 11 of the method, provide one piece of evidence to suggest that the top three layers were once continuous even though they are no longer continuous.

CONCLUSION

Comment on how accurately your model represents the true situation. How could the model be improved to illustrate the four laws of stratigraphy more accurately?

By examining the relationships between structures present in a geological cross-section, it is possible to determine the order of geological events that formed that part of Earth's crust. We use **cross-cuts** to determine the order in which layered rock sequences were modified by faults, intrusions and

unconformities (breaks in the geological record). This method enables geologists to order the events that generated a rock sequence from oldest to youngest.

KEY CONCEPTS

- Relative dating is based on the assumption that rocks are laid down in layered sequences with the older rocks at the bottom and the younger rocks at the top.
- Relative dating cannot give an age in years but dates the sequence of layers relative to each other.
- Fossils are the preserved traces of once-living life forms.
- The laws of stratigraphy are superposition, original horizontality, lateral continuity and cross-cutting relationships and inclusions.

CHECK YOUR UNDERSTANDING

4.1

- 1 Define:
 - a relative dating
 - b fossil
 - c strata.
- 2 What evidence did Leonardo da Vinci provide to support his theory that the mountains near Parma had been submerged beneath the sea?
- 3 State the four laws of stratigraphy. Draw a sketch to illustrate each one.
- 4 Refer to Figure 4.11.
 - a State the laws of stratigraphy that you can see in this profile.
 - b Which rock is the youngest? Which law is governing this?
 - c Which rock is the oldest? Which law is governing this?
- 5 Place the following list of events in your life in their relative order of occurrence. You might need a friend or relative to help you.

– Last athletics carnival you attended	– First steps
– Starting secondary school	– First film or video you watched
– Starting kindergarten or daycare	– First swimming carnival you attended
– Starting primary school	– First swimming lesson
– First athletics carnival you attended	– Last competitive team you joined
– First competitive team you joined	– Last school concert you attended
– First school exam you attempted	– Last swimming carnival you attended
– First words spoken	– First school concert
– Last school exam you attempted	
- 6 Provide evidence to show that knowledge of geological events has been built upon by different people over many years.

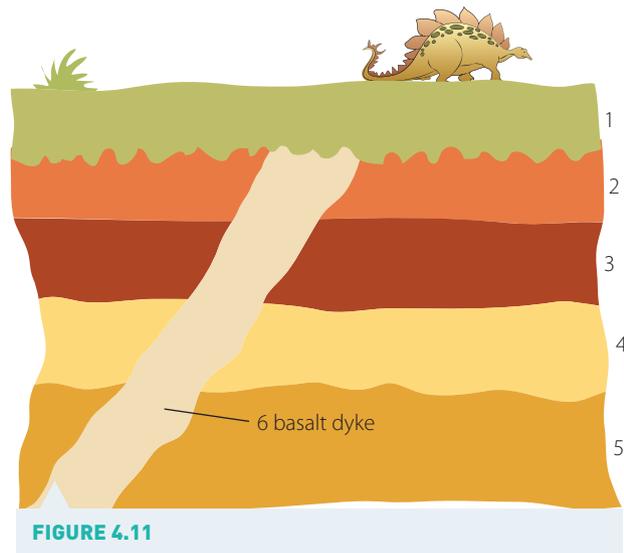


FIGURE 4.11

4.2 Absolute dating

Absolute dating or **age dating** is the name given to a number of techniques that are used to measure the chronological or actual age of geological materials, as opposed to relative age. Chronological age is stated as a number of years. For example, the Taupo rhyolites from New Zealand are 1200 ± 86 years old. The \pm sign indicates the **accuracy** and **precision** of the measurement and gives you a sense of the quality of the measurement.

Refer to page 19 for a discussion on accuracy and precision.

During the 20th century, scientists steadily improved the methods used to determine absolute ages for Earth materials, fossils, animal bones, seashells and archaeological objects. Many materials are now able to be dated accurately because physicists and chemists discovered the process of decay of **radioactive isotopes**. These are atoms with unstable nuclei that emit energy in the form of radiation and transform into other types of atoms at predictable rates.

Radioactive decay

The radioactive decay process, called **fission**, occurs spontaneously in radioactive isotopes of particular elements. The nucleus of a radioactive isotope ejects electrons, protons, neutrons or other subatomic particles. This process changes the number of protons present in the nucleus and converts the starting, or parent, element into another 'daughter' isotope. For example, a **parent nucleus** of uranium-238 has 92 protons and 146 neutrons ($92 + 146 = 238$). In one form of decay it ejects a particle consisting of two protons and two neutrons, which is the makeup of a helium nucleus, also called an α -particle. The resulting **daughter nucleus** has 90 protons and 144 neutrons ($90 + 144 = 234$) and so it is a thorium-234 atom (Figure 4.12).

By this means, isotopes of one element are converted into isotopes of another element. The predictable rate at which this process occurs is called the **half-life** ($t_{1/2}$). This is the period of time in which the initial number of atoms in a sample is reduced by half.

Some common isotopic transformations that are used to determine absolute ages for ancient Earth materials are listed in Table 4.1. These radioactive isotopes of particular elements present in a rock or mineral decay at known rates (half-life). If there is no **product element** present in the rock or mineral when the rock was first formed, then it is possible to determine the age of the rock or mineral by measuring the amount of the parent element and the amount of the product element that has accumulated in the rock or mineral since its formation. The exception is carbon-14, which is discussed separately below.

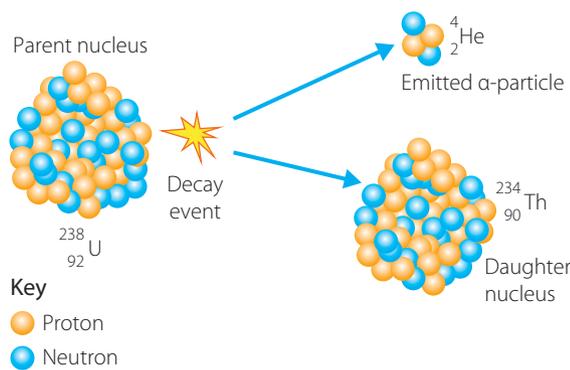


FIGURE 4.12 Radioactive decay of uranium-238 to thorium-234 with a helium atom (α -particle) ejected

TABLE 4.1 Radiometric clocks used for dating Earth materials

PARENT \rightarrow PRODUCT	HALF-LIFE (YEARS)	MINERALS THAT CONTAIN THE PARENT ISOTOPE AND USUALLY RETAIN THE PRODUCT ISOTOPE
$^{235}\text{U} \rightarrow ^{207}\text{Pb}$ uranium-235 decays to lead-207	713 million years	zircon, apatite, uraninite
$^{40}\text{K} \rightarrow ^{40}\text{Ar}$ potassium-40 decays to argon-40	1300 million years	muscovite, biotite, orthoclase feldspar, hornblende, volcanic glass (Metamorphism usually resets this geological clock to zero because the ^{40}Ar escapes easily from the mineral grains if they are heated above their closure temperature.)
$^{238}\text{U} \rightarrow ^{206}\text{Pb}$ uranium-238 decays to lead-206	4500 million years	zircon, apatite, uraninite
$^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$ rubidium-87 decays to strontium-87	48 800 million years	muscovite, biotite, orthoclase feldspar, hornblende
$^{147}\text{Sm} \rightarrow ^{143}\text{Nd}$ samarium-147 decays to neodymium-143	48 800 million years	garnet, muscovite, biotite

This technique works best in igneous and metamorphic rocks, such as the granite shown in Figure 4.13. This is because some of their minerals contain only the parent element and none of the product element when the rock is formed. For example, the mineral zircon will have some uranium in it but no lead when it forms. Feldspars will have some potassium in them but no argon when the rock is formed. This sets these radiometric clocks to zero when igneous and metamorphic rocks form.

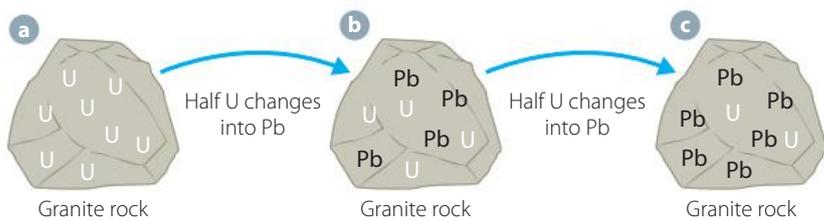


FIGURE 4.13 **a** The parent granite rock contains only uranium-235. **b** After 710 million years half of the uranium in the daughter rock has decayed to lead-207. **c** After another 710 million years, half of the remaining uranium-235 has decayed to lead-207. Hence the age of the rock can be calculated.

Sedimentary rocks are usually made up of fragments of a number of different rocks and grains of many different minerals. These radiometric clocks have already been running for some time when the sediments are deposited. This means that these clocks cannot be used to determine an accurate date for the time of sediment deposition. This is like forgetting to reset a stopwatch at the end of each foot race in school sports. An accurate time for running each race would not be recorded if the stopwatch was kept running.

INVESTIGATION 4.2

Modelling half-life and decay



Numeracy

AIM

To model half-life and decay of a radioactive isotope

MATERIALS

- 1 paper bag or cup
- 100 M&Ms or similar with a distinct difference between the two sides (e.g. an M&M mark on one side but nothing on the other)
- Baking paper to cover work space



RISK

ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?

Some M&Ms may contain peanuts, which could trigger an allergic reaction in some students.

HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

Alert your teacher to any allergies.
Do not use M&Ms that contain peanuts.

What other risks are associated with your investigation, and how can you manage them?

METHOD

- 1 As a class, decide which side of the M&Ms represents decay and which side represents no decay.
- 2 Put all the M&Ms into the bag or cup. Shake the bag and pour them out onto the baking paper.
- 3 Remove all the M&Ms that have decayed; according to the rule established in step 1.
- 4 Count the number of M&Ms remaining and place these back into the bag or cup.
- 5 Draw a suitably formatted table to record the results from each count.
- 6 Repeat the process until there is one or no M&Ms remaining.

RESULTS

Combine the results from the whole class into a single data table. Use this data to plot a graph of the number of M&Ms remaining versus the number of trials.

ANALYSIS OF RESULTS

From the graph, determine the half-life of the M&Ms.

CONCLUSION

How did this model assist you in understanding radioactive decay and half-life? Did the model have any limitations? How could the model have been improved?

Carbon dating

Cosmic rays from space and the Sun increase the energy of neutrons in the atmosphere. If one of these high-energy neutrons collides with a nitrogen atom (7 protons + 7 neutrons), the nitrogen atom can absorb the neutron and eject a proton to become carbon-14 (6 protons + 8 neutrons). The rate of carbon-14 formation can vary slightly so scientists calibrate their carbon-14 clock against data from tree rings.

Most of the carbon on Earth is carbon-12 (6 protons + 6 neutrons), which exists along with a very small known amount of carbon-14. Plants incorporate both these isotopes of carbon into their tissues through **photosynthesis**. Animals eat the plants, transferring the carbon content to their own living tissues. Once an organism dies, it no longer takes in carbon and so the carbon-12 content of the dead organism does not change. This sequence is illustrated in Figure 4.14.

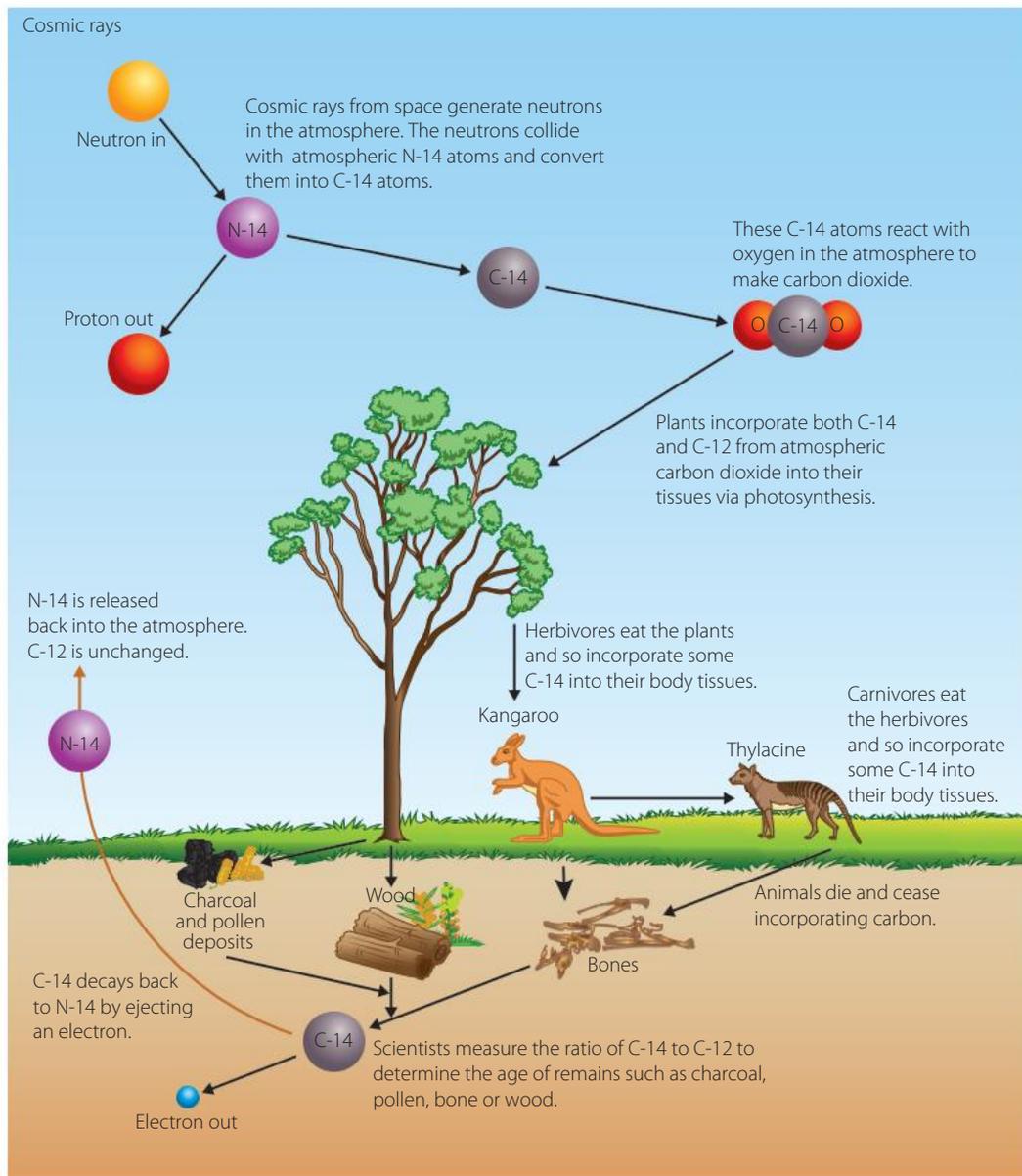


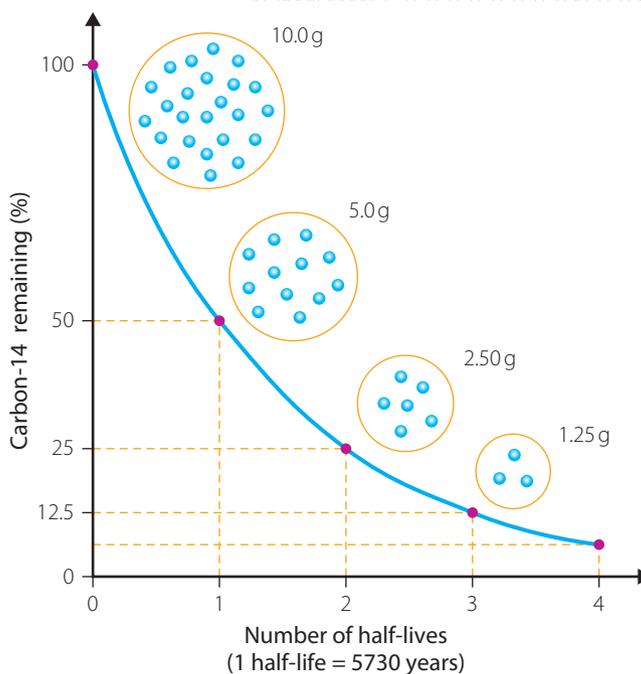
FIGURE 4.14
Carbon-14 incorporated into living organisms allows their remains to be dated.
N-14 = nitrogen-14
C-12 = carbon-12
C-14 = carbon-14

Carbon dating is the best known of the radioactive dating methods and is a commonly used technique. Carbon-14 is radioactive and it decays with a half-life of 5730 years. This decay is relatively quick in comparison to some of the other commonly used isotopes. Hence, carbon-14 is used for dating archaeological discoveries and relatively recent geological materials. It is a technique that is particularly good at determining the age of organic material, which, by its very nature, is rich in carbon. So, carbon-14 dating is commonly the technique of first choice for bone and other plant and animal remains that we find in materials deposited during the last ice age. The decay product of carbon-14 is nitrogen-14, much of which is lost to the environment. Instead of measuring the amount of nitrogen-14 in a sample, scientists measure the ratio of carbon-12 to carbon-14.

After about 50000 years, almost all the original carbon-14 atoms will have decayed (Figure 4.15). The normal limit for carbon-14 dating is, therefore, about 50000 years. With expensive equipment, ultra-clean preparation techniques and a large starting sample, this technique can be pushed to 60000 and even 75000 years, but no further.

FIGURE 4.15

The half-life of carbon-14 is 5730 years, decaying of 10 g of carbon-14. After 5730 years 5 g remains, after another 5730 years there will be 2.5 g and after another 5730 years only 1.25 g remains.



Radiometric clocks for dating Earth materials

To date Earth materials older than 50000 years, an **isotopic clock** with a much longer half-life is needed. Isotopic clocks are also called radiometric clocks. Some of the more important examples are listed in Table 4.1 (page 93). The first reliable method of dating Earth materials measured the transformation of two uranium isotopes into two lead isotopes ($^{235}\text{U} \rightarrow ^{207}\text{Pb}$ and $^{238}\text{U} \rightarrow ^{206}\text{Pb}$) and was called the uranium-lead method.

Early methods of isotopic dating were difficult because they required complicated chemical extractions and special laboratories to isolate the parent uranium isotopes from the lead product. Today **mass spectrometers** are used to measure isotopic ratios directly. This analytical approach gives far more accurate results (Figure 4.16).

Accurate and precise isotopic dating requires that the crystal or rock is fresh and that there has been no parent or product isotope removed over time. If there is a loss of the parent isotope, the analysed age will be older than the actual age. Reheating of the rock by metamorphism can reset an isotopic clock. Weathering can remove material from rocks or crystals and change the ratio between the parent and product isotopes, thereby altering the measured age. This is a bit like a clock that is

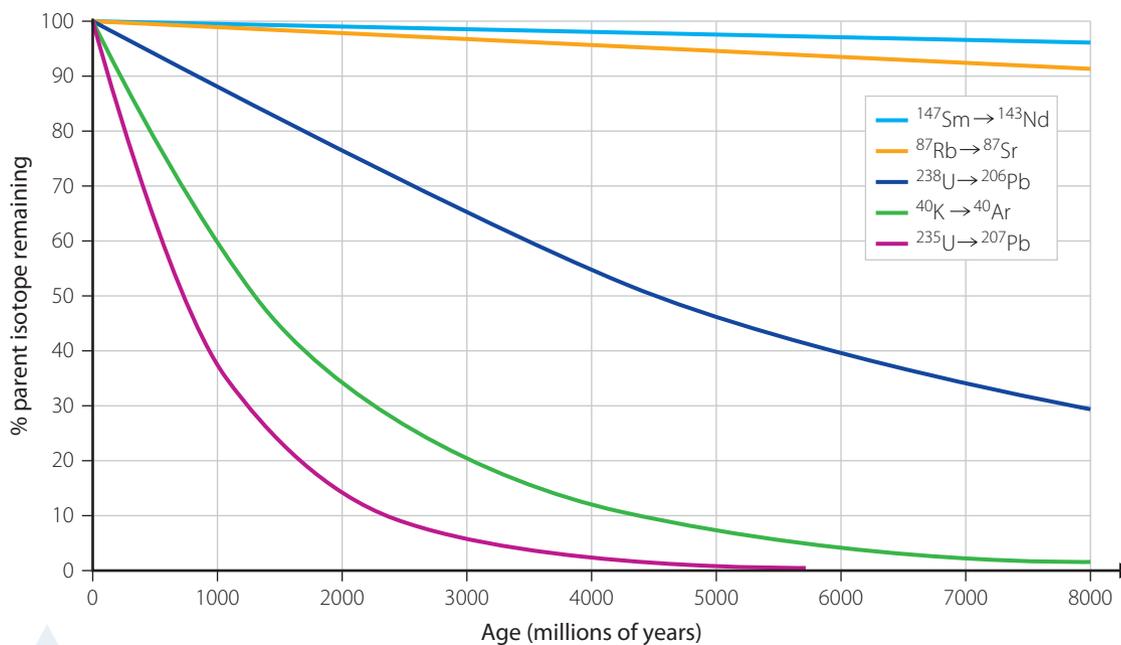


FIGURE 4.16 Isotope half-life curves used for dating rocks and minerals

running fast or slow. Losing parent material from the crystal or rock is like a clock that is running fast.

Zircon is the oldest terrestrial material found so far, with some crystals estimated to be as much as 4.4 billion years old. These zircons were discovered in a three-billion-year-old conglomerate at a site near Jack Hills in Western Australia. Zircon crystals are very stable and always incorporate a little uranium but no lead when they form. They are very hard minerals that are resistant to both chemical weathering and physical abrasion. Zircon has a very high melting temperature and retains its uranium and lead within the crystal when it is reheated. As a result, zircon crystals are almost perfect isotopic clocks and provide unique insights into Earth's early history (Figure 4.17).

Mass spectrometers use a high voltage, commonly in excess of 10000 volts, to accelerate charged ions from the sample to be analysed. The charged ions pass through a strong magnetic field that causes their path to curve, with the degree of curvature depending on their mass. Heavy ions are deflected less than lighter ions. By varying the accelerating voltage and the strength of the magnetic field, it is possible to tune the spectroscope to select the charge and mass of the ions that are able to pass through the length of the tube. The end of the tube contains a detector that generates an electrical signal when the ions collide with it (Figure 4.18). In this way, the isotopes in the sample are sorted by mass and their relative amounts can be measured.

Standards of known isotopic composition are measured in the mass spectrometer at the same time as the samples to be analysed. This use of a control ensures that the ratios of the isotopes in the sample are measured reliably and the age of the crystals or rock is determined accurately and precisely.

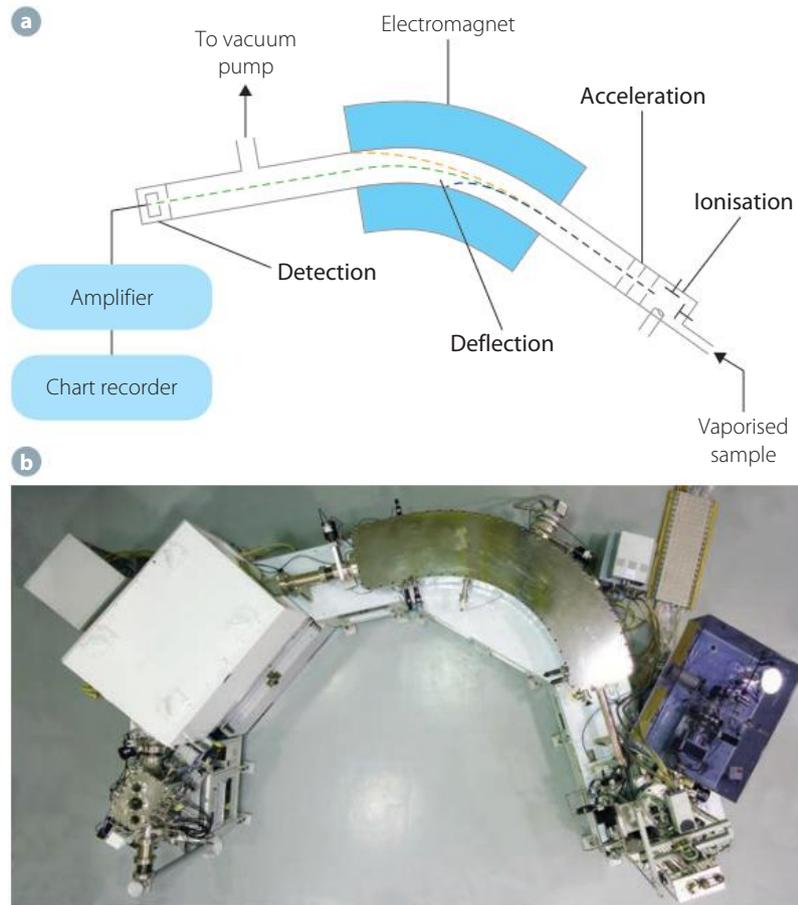


FIGURE 4.17 Zircon crystals are almost perfect isotopic clocks.

Zircons, the oldest fragments of Earth

FIGURE 4.18

a Schematic diagram of a mass spectrometer
b SHRIMP II ion probe and mass spectrometer designed at the Research School of Earth Sciences, Australian National University



Australian National University



Geological time

KEY CONCEPTS

- Absolute dating is the measurement of the chronological age of geological materials by comparing the ratio of an original parent isotope to its decayed daughter product.
- The half-life of an isotope is the amount of time it takes for half the amount of the isotope to decay and produce a different isotope.
- Carbon-14 dating is used to measure the age of biological materials under 50 000 years old.
- Isotopes with longer half-lives, such as uranium, potassium and rubidium, are used to date older materials.
- Zircon crystals are ideal isotopic clocks.
- Mass spectrometers are machines that measure isotopic ratios accurately.

CHECK YOUR UNDERSTANDING

4.2

- 1 Explain the relationship between each of the terms in the following pairs.
 - a absolute dating and years
 - b half-life and fission
 - c parent isotope and product isotope
- 2 Go back to your answer for Check your understanding 4.1, question 5. Assign absolute dates for each of the important events. If you cannot provide an absolute date, estimate a possible date and suggest an error range for the date; for example, 1 May 2014 \pm 10 days.
- 3 Explain why radiometric dating works well for rocks that contain zircon crystals.



- ▶ 4 When uranium-238 decays to thorium-234, a positively charged particle called an α -particle is ejected. The α -particle is identical to the nucleus of a certain element. What is the name of that element?
- 5 Refer to Figure 4.15, which shows three half-lives of carbon-14. Using this figure, calculate how much carbon-14 would remain after another two half-lives have passed.
- 6 Explain why carbon-14 dating is ideal for dating biological material less than 50 000 years old.
- 7 Refer to Table 4.1 on page 93. Decide which isotopic clock (or clocks) would be best used to provide an absolute date for an Earth material:
- approximately 3640 million years old
 - approximately 3 million years old
 - 10 000 years old.
- 8 Explain what would happen if there is a loss of product isotope from the material being dated.

4.3 Dating geological materials

It is possible to determine numerical ages for particular events in the geological past if material that can be dated using isotopic methods is found at the same stratigraphic level. A good example is the way geologists are able to identify and date volcanic tuff horizons just below and just above the layer of sediment that marks the major change from Palaeozoic faunas to Mesozoic faunas.

This change in the fauna is known as the **Permian–Triassic mass extinction** and is recognised as the largest of the big five extinction events in Earth's history. It represents a catastrophic collapse of the Permian ecosystems. Half of all genera **extant** at the time died out and became **extinct** in a very short period of time – probably less than 500 000 years, and maybe in less than 100 000 years. These organisms disappeared completely from the geological record at this stratigraphic level. They were gradually replaced by new Triassic genera and ecosystems over the next 20 million years. The abrupt change in the types of fossils is used to determine relative ages for rocks. This event is an example of Smith's **law of faunal succession**, discussed below.

Dating this important event was the result of intensive effort by a large team of geologists and palaeontologists. They dated 550 individual zircon grains using the SHRIMP II instrument (Figure 4.18b) at the Australian National University. These zircons were extracted from different layers of volcanic ash that were erupted just before, and just after, the time when the Permian extinction occurred. The zircons formed in the magma chamber that supplied the volcanic ash eruptions. They contain radiogenic uranium isotopes ^{238}U and ^{235}U and these isotopic clocks act like stopwatches that were started when the crystal formed.

Zircon, mica, feldspar, amphibole and some other minerals present in volcanic rocks can be dated relatively easily because they contain uranium or potassium that decays into isotopes that are trapped within the crystals. Zircon, mica, feldspar and amphibole minerals also occur in other igneous and metamorphic rocks. These minerals can be used to date when the igneous rock crystallised from its magma or when a schist or gneiss was metamorphosed.

These dates are often used to date the igneous or metamorphic rock directly and can be useful in determining the age of particular geological events. Volcanic lavas and volcanic ash layers are often deposited between layers of sedimentary rocks. Determining absolute isotopic ages for these volcanic materials is relatively easy and can be used to determine the age of the rock layers or geological surfaces

Eon	Eras of time	Period	Age	Millions of years ago	Major biological events	
Phanerozoic	Cenozoic	Quaternary	Age of mammals	0	Humans expand in range Major ice ages and extinction of large animals in the northern hemisphere	
		Neogene		2.6	Extensive radiation of flowering plants and mammals	
		Paleogene		23		
	Mesozoic	Cretaceous	Age of reptiles	146	First flowering plants Extinction of ammonites and marine and aerial reptiles	
		Jurassic			202	Cycads, conifers, ginkgoes, dinosaurs dominant First birds, flying reptiles, marine reptiles
		Triassic			251	Dominance of mammal-like reptiles Dominance of ammonites
	Palaeozoic	Permian	Age of amphibians	299	Extinction of trilobites and many invertebrates Reptiles more abundant as amphibians decline	
		Carboniferous			359	Coal swamp forests Amphibians on land First reptiles Algal sponge reefs Echinoderms and bryozoans dominant
		Devonian	Age of fishes	416	Oldest land vertebrates Radiation of fishes and land plants Corals, brachiopods and echinoderms	
		Silurian			444	Oldest life on land: plants, scorpions First jawed fishes
		Ordovician	Age of invertebrates	488	Diverse marine communities: brachiopods, bryozoans, corals, graptolites, nautiloids First jawless fishes	
		Cambrian			542	Evolution of invertebrates with hard skeletons Dominance of trilobites
		Proterozoic	Precambrian	Ediacaran fauna Organisms	2500	First marine plants appear, red algae Cyanobacteria drive the Great Oxygenation Event
	Archaean	Eukaryotes appear				
Hadean	Stromatolites abundant Prokaryotes appear					
	Bombardment of planetessimals Earth forms	4000		First organisms appear 3800 million years ago		
			4500			

FIGURE 4.19 Simplified stratigraphic column and major evolutionary events in Earth's history. Dates from International Commission on Stratigraphy, 2009

located above and below them. This method works best when rocks that can be dated occur just above and just below the layer that is to be dated. According to the law of superposition, the dated rocks above are a little younger and the rocks below are a little older than the event in question. For example, if a fossilised dinosaur bone is found in a sedimentary rock layer in between two ash layers, it is possible to date the ash layers and infer that the dinosaur lived somewhere between these two dates.

The closer these two ages are to each other, the more accurate the age determined for the geological event. If the layer below our dinosaur fossil is dated at 220 million years ago and the layer above is dated at 210 million years ago, you could infer that the dinosaur lived in between these two dates – about 215 million years ago.

This is how the absolute age of the boundaries between the major geological periods has been determined. Absolute ages have been used to calibrate the stratigraphic column and the relative dating based on fossils and conventional stratigraphy (Figure 4.19).

The law of faunal succession

William ‘Strata’ Smith is credited with proposing the law of faunal succession in 1815. He developed the law while constructing canals, tunnels and bridges for the system of canals once used to transport agricultural produce and industrial products between the major English cities.

Smith developed a detailed knowledge of the distribution of England’s rock layers during his work as a construction engineer. Repeating patterns of fossils became evident to him while he was working in the field. He observed that the same order of fossil groups occurred from the bottom to top of sedimentary sequences no matter where the rock sequence was located. He reasoned that this ordering of fossils and fossil groups was probably constant. The constancy meant that you could compare and relate sequences of the rocks of one area to rocks in another area. The presence of the same fossils within rocks found at two different locations meant that the two sets of rocks had been deposited at the same point in geologic time. Figure 4.20 illustrates this concept.

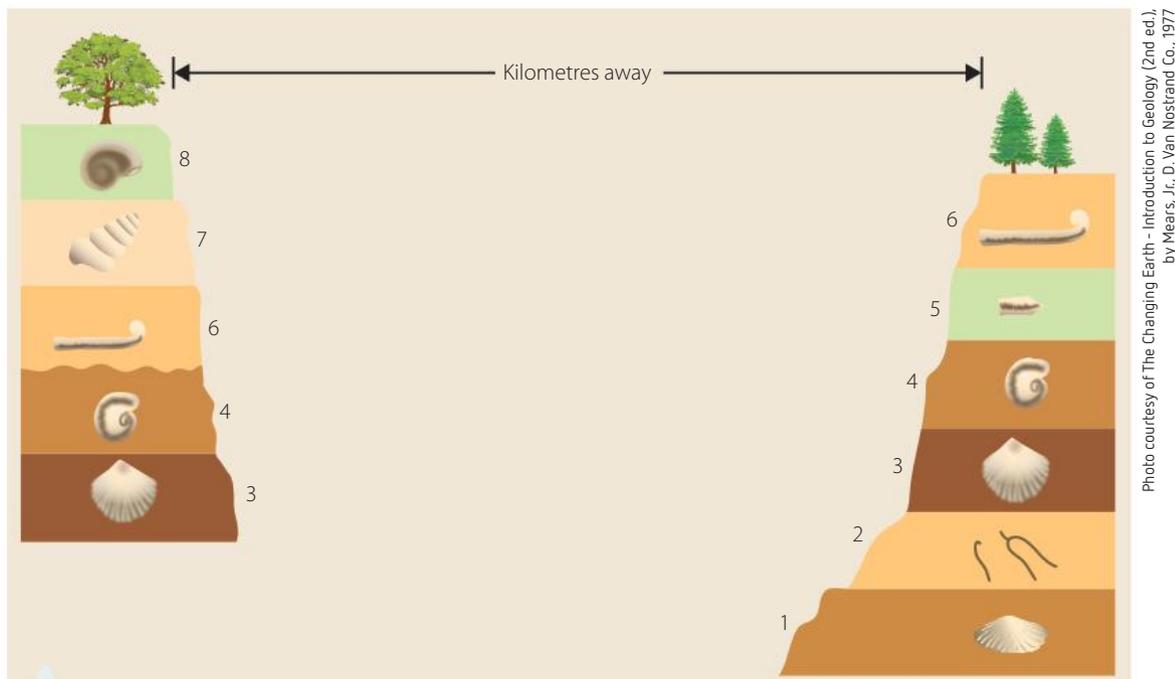


FIGURE 4.20 The law of faunal succession suggests that specific rock layers containing the same fossils could be correlated across different places.

Photo courtesy of The Changing Earth - Introduction to Geology (2nd ed.), by Mears, Jr., D. Van Nostrand Co., 1977

This meant that sets of rocks could be directly related to each other, or correlated in time, if they contained the same fossils. Smith devised a stratigraphic method for the temporal (time-based) correlation of sedimentary rock layers based on the consistent succession of fossil fauna (Figure 4.21.)

The law of faunal succession can be thought of as a refinement of Steno's law of superposition. Fossils provide a way of ordering the sediment layers, either bottom to top or oldest to youngest. The fossils occur in the sediment layers in a specific order.

Steno's principle of superposition stated that fossils incorporated within a higher layer of sediment were deposited later than those contained in a lower layer of sediment. Sets of rock layers contained different sets of fossils. Lower sets of layers contained older fossils. Upper sets of layers contained younger fossils.

The law of faunal succession takes superposition a step further or *to the next level* because it states that fossils occur in a specific historical order or time sequence. It also enables us to infer that rocks containing the same fossils were deposited at the same point in time. It is thus a multi-component law, and can be summarised as follows.

- 1 Fossils succeed each other vertically in a specific and predictable order.
- 2 Fossils appear at a particular level in a sequence and can be identified over large horizontal distances.
- 3 Fossils disappear at a particular level in a sequence above the level where they appeared; the disappearance level can also be identified over large horizontal distances.
- 4 Once a fossil disappears from a sequence, it never reappears.

This fourth point was a really important one. For Smith, it was true because that was what he always observed. This is what we call an empirical deduction, and it is a good example of an evidence-based deduction. Smith wasn't all that concerned about the implications of his observation. He left that to the naturalists. His law came to be widely accepted and it enabled many subsequent breakthroughs in the understanding of Earth history.

Information and communication technology capability

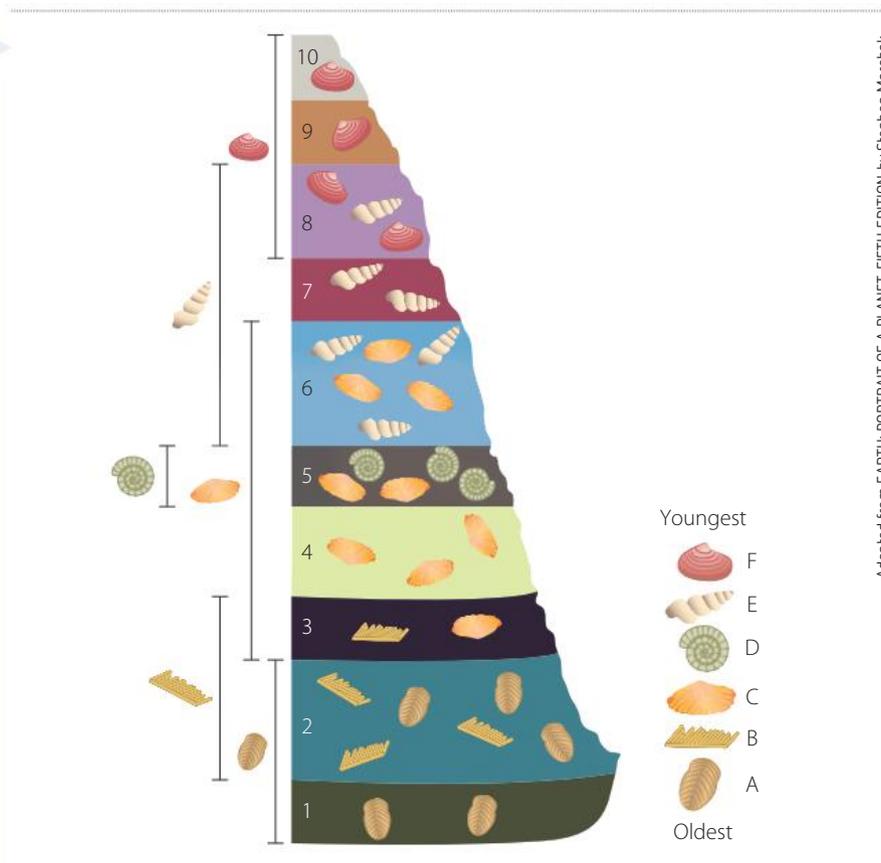


Layers of time

See if you can work out the correct order of strata

FIGURE 4.21

Smith's law of faunal succession illustrated by the ranges of five hypothetical species. Species A is the oldest and so is found in the lowest layers. Going forward in time and ascending the stratigraphic column, species A dies out to be replaced by species B and C. When B and C die out and become extinct, species D, E and F replace them.



Adapted from EARTH: PORTRAIT OF A PLANET, FIFTH EDITION by Stephen Marshak. Copyright © 2015, 2012, 2008, 2005, 2001 by W.W. Norton & Company, Inc. Used by permission of W. W. Norton & Company, Inc.

INVESTIGATION 4.3

Determining the age of geological materials

INTRODUCTION

While fossils may occasionally contain isotopes such as carbon-14 that can be used for absolute dating, carbon-14 has a relatively short half-life and cannot be used reliably to date events more than 50 000 years old.



To find the age of older fossils, relative dating is combined with absolute dating. Geologists date the layers above and below fossil-containing sedimentary rock layers. They can use this information to determine an absolute age for specific fossil-containing layers. They use these dated layers as time-markers within a relatively dated sequence. This has been done many, many times and has meant that absolute dates can be assigned to the many relatively dated units of geological time.

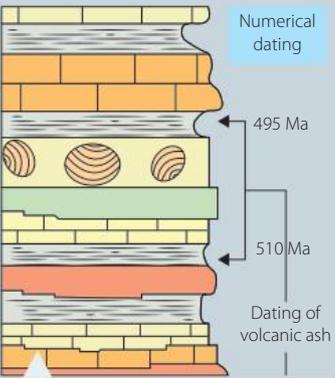
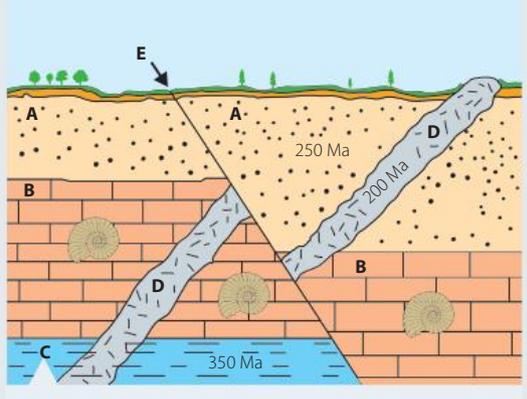
AIM

To use absolute and relative dating techniques to estimate the age of fossils in a stratigraphic column.

METHOD

Complete the table for each of the diagrams in Figure 4.22 below. (Ma = millions of years)

RESULTS

STRATIGRAPHIC SEQUENCE	ESTIMATED AGE OF FOSSILS	PROVIDE JUSTIFICATION FOR YOUR ESTIMATION
<p>1</p>  <p>FIGURE 4.22a</p>		
<p>2 Examine Figure 4.22b and rank layers A to E in order from youngest to oldest. How old are the rocks from layer B?</p>  <p>FIGURE 4.22b</p>		





STRATIGRAPHIC SEQUENCE	ESTIMATED AGE OF FOSSILS	PROVIDE JUSTIFICATION FOR YOUR ESTIMATION
3 Estimate the age of the fossils in Figure 4.22c.		

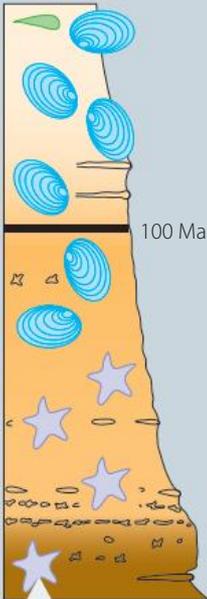
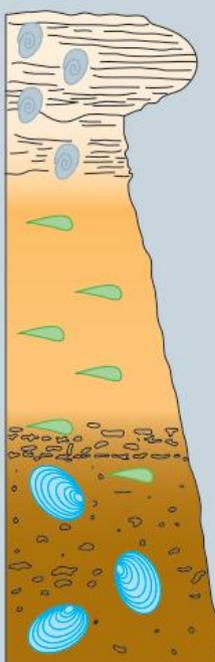
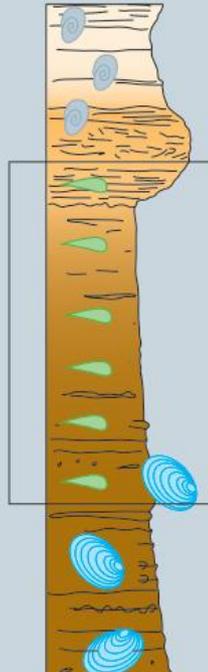
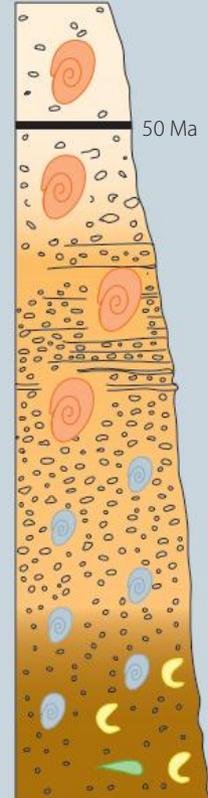
<p>Adapted with permission of Jeffrey Martz</p> <p>Area C</p>  <p>100 Ma</p>	<p>Area A</p> 	<p>Area B</p> 	<p>Area D</p>  <p>50 Ma</p>
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FIGURE 4.22c

CONCLUSION

How useful was it to use both relative and absolute dating techniques to reconstruct the order of events?

KEY CONCEPTS

- It is possible to use both relative and absolute dating techniques together to find the age of Earth materials.
- The law of faunal succession states that:
 - fossils succeed each other vertically in a specific, reliable order
 - fossils appear at a particular level in a sequence and can be identified over large horizontal distances
 - fossils disappear at a particular level in a sequence above the level where they appeared; the disappearance level can also be identified over large horizontal distances
 - once a fossil disappears from a sequence it never reappears.

- 1 What is the law of faunal succession? What are its four components?
- 2 How is the law of faunal succession similar to the law of superposition?
- 3 Why are tuffs containing zircon grains useful for determining the absolute age of geological boundaries such as the one that separates the Permian and Triassic periods?
- 4 Refer to Figure 4.23.
 - a Give absolute dates for the fossils shown. Explain how you calculated those dates.
 - b Explain why the ash layers rather than the layers containing the fossils have been dated using radiometric techniques.
 - c Infer why each of the different types of fossils shown is found in only one layer.

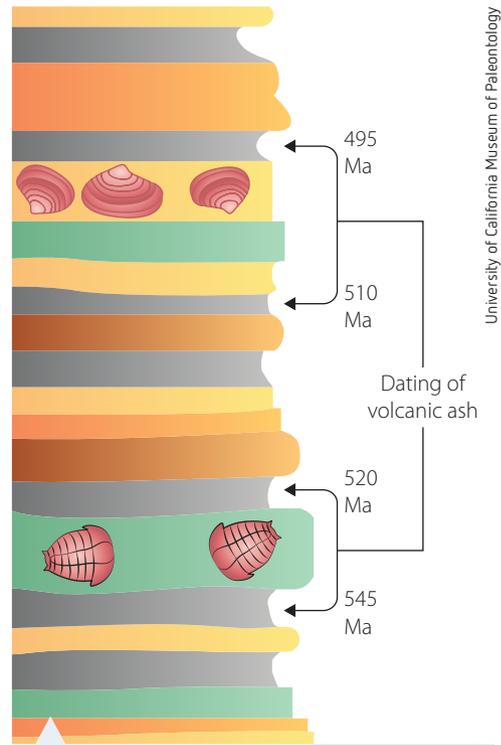


FIGURE 4.23

4 CHAPTER SUMMARY

- ▶ Relative dating is based on the assumption that sedimentary rocks are laid down as stacked sequences of laterally continuous horizontal layers, with the oldest rocks at the bottom and the youngest rock layers at the top.
- ▶ The four laws of stratigraphy are the law of original horizontality, the law of lateral continuity, the law of superposition, and the law of cross-cutting relationships and inclusions.
- ▶ Relative dating does not determine an age in years for a geological event but assigns that geological event a place in a chronological list of geological events.
- ▶ Fossils are the preserved traces of once-living life forms.
- ▶ Absolute dating is the technique of measuring the chronological age of geological materials by determining the ratio of parent isotopes to daughter or product isotopes.
- ▶ The half-life of an isotope is the time it takes for half the starting amount of an isotope to decay by fission into its product isotope.
- ▶ Carbon-14 or ^{14}C dating is used to measure the age of biological materials under 50 000 years old.
- ▶ Radiogenic isotopes with longer half-lives, such as uranium, potassium and rubidium, are used to measure the age of geological materials that are millions or billions of years old.
- ▶ Mass spectrometers are analytical machines that are used to measure isotopic ratios.
- ▶ It is possible to use both relative and absolute dating techniques together to find the age of Earth materials.
- ▶ The law of faunal succession states that:
 - fossils succeed each other vertically in a specific, reliable order
 - fossils appear at a particular level in a sequence and can be identified over large horizontal distances
 - fossils disappear at a particular level in a sequence above the level where they appeared; the disappearance level can also be identified over large horizontal distances
 - once a fossil disappears from a sequence it never reappears.

4 CHAPTER REVIEW QUESTIONS



Review quiz

- 1 Distinguish between relative and absolute dating.
- 2 Explain how knowing the relative order of events is different from knowing the time when each of the events took place.
- 3 Examine the geological timescale in Figure 4.19 (page 100).
 - a How old is Earth?
 - b Name an extinct fossil group typical of the Palaeozoic, Mesozoic and Cenozoic eras.
 - c When did fish first become numerous in the oceans?
 - d When did amphibians, reptiles and mammals first become dominant groups of land animals?
- 4 What is a fossil?
- 5 Refer to Figure 4.24.
 - a Which layer is the oldest?
 - b Which layer is the youngest?
 - c Column 1 was discovered in the mountains of Italy, 80 km from the sea. Explain the geological processes that could have occurred to locate this layer there.

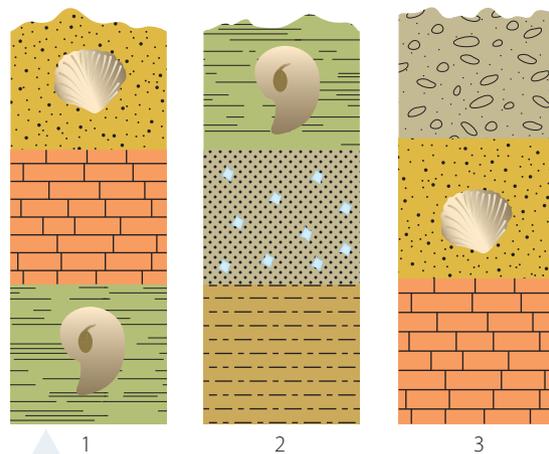


FIGURE 4.24

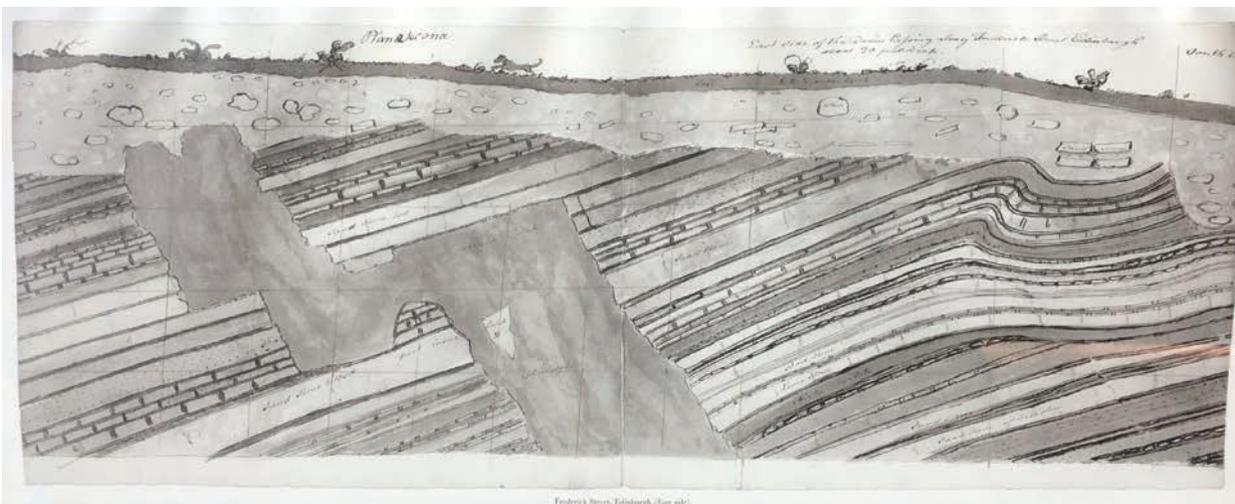


FIGURE 4.25

- 6 The sketch shown in Figure 4.25 is the unconformity at Frederick Street in Edinburgh. The sketch was drawn around 1795.
 - a Identify an example of each of the six principles of stratigraphy in this sketch.
 - b Produce a geological history for the Frederick Street unconformity using relative dating by using a numbered list that places the sequence of geological events evident in Figure 4.25 in correct relative time order.
- 7 Explain how Smith's principle of faunal succession was used to correlate rocks deposited on different continents at the same point in geological time.
- 8 How were fossils used to divide geological time into a set of relatively dated stratigraphic units?
- 9 What are the half-lives of ^{14}C , ^{40}K , ^{87}Sm and ^{238}U ? What elements are produced when each of these radioactive isotopes decays?
- 10 What is the SHRIMP and how is it used to enable geologists to determine the age of rocks?
- 11 Are zircon crystals used to determine absolute or relative ages for geological events? Justify your response.
- 12 Explain why geologists consider layers of volcanic ash to be very useful in absolute dating studies.
- 13 Refer to Table 4.1 on page 93 and use it to determine the age indicated by the following radiometric clocks.
 - a 60% of ^{238}U remaining in a sample
 - b 40% of ^{40}K remaining in a sample
 - c 20% of ^{235}U remaining in a sample
- 14 Explain why we can't use the ^{14}C method to determine the timing of geological events that occurred during the Cretaceous period.

- 15 Copy and complete the following table. Determine which isotopic clock is best suited to determine the age of the geological or biological material. Use Figure 4.15 (page 96) and Table 4.1 (page 93) to determine the age of the geological material from the percentage of parent isotope remaining in the sample analysed.

GEOLOGICAL OR BIOLOGICAL MATERIAL	SUITABLE PARENT → PRODUCT DECAY PROCESS HALF-LIFE OF DECAY PROCESS	PERCENTAGE OF PARENT ISOTOPE REMAINING	AGE OF SAMPLE
Potassium feldspars separated from a granite	$^{40}\text{K} \rightarrow ^{40}\text{Ar}$; 1300 million years	40	1650 million years
Zircon crystals in a granodiorite slide		10	
Zircon crystals separated from volcanic ash		42	
Volcanic glass sample		65	
Garnet in a gneiss		98	
Animal bones and wood		12.5	

- 16 Explain how geologists determined when the Permian–Triassic mass extinction occurred.
- 17 What is the difference between a mass extinction and the extinction of a single species?
- 18 How do geologists determine ages for the beginning and ends of the periods listed in the stratigraphic column?
- 19 Dinosaurs became extinct during a mass extinction that occurred at the end of the Cretaceous period. Investigate how the age of this event was determined and write a short summary of this mass extinction. You should:
 - a explain why it is a good example of Smith's law of faunal succession
 - b outline how the absolute age of this event was determined.

- 20 Refer to Figure 4.26. Complete the table below by writing in the correct letter(s) beside each law.

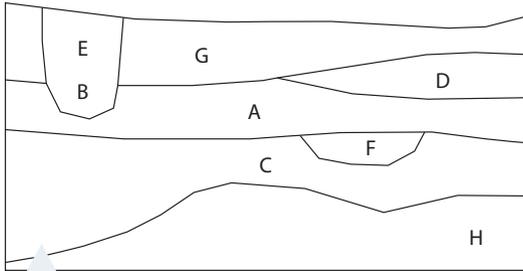


FIGURE 4.26

LAW	LETTER(S) EXAMPLE
Superposition	
Original horizontality	
Lateral continuity	
Cross-cutting relationships	
Inclusions	

- 21 Geology relies on the laws of stratigraphy to describe how geologic layers were deposited. There is some debate among geologists about the number of laws: are there four, five or six? Give at least two reasons to explain why geologists cannot agree on the number of laws of stratigraphy.

5 Geological resources

OUTCOMES

In this chapter you will learn about:

- the quarrying and mining methods that Aboriginal peoples used to access non-renewable resources [ATSIHC](#)
- the location of different non-renewable resources [ICT WE](#)
- how important non-renewable resources are to Australia's economy [CCT ICT N WE](#)
- the appropriate techniques used in locating non-renewable resources [CCT ICT](#)
- the methods of extracting non-renewable resources from their locations. [CCT ICT N WE](#)





Science Photo Library/JOHN READER



FIGURE 5.1 Stone tools found at the archaeological site of Blombos, South Africa

Human history has been classified by the use of available natural resources that humans have obtained from the Earth. Names such as the Palaeolithic, Neolithic, Bronze Age, Iron Age and Industrial Age have been used by historians to describe various periods of human history that can be defined by the types of earth materials being used. The Stone Age (Palaeolithic) is characterised by hunter-gatherer peoples who used tools fashioned from stones to cut up and skin their hunted animals (Figure 5.1).

The best mineral to produce a sharp cutting edge or piercing point

was quartz. Two-million-year-old quartz stone tools with traces of blood, bone marrow, muscle and fat have been found in the Sterkfontein caves near Johannesburg, South Africa.

5.1

Aboriginal methods of quarrying and mining

Australian Aboriginal peoples are the descendants of humans who migrated from the eastern savannas of Africa. These migrations from Africa occurred in waves thought to have begun around 120 000 years ago with humans spreading to Europe, Asia, Australia and beyond. There is evidence that humans began arriving on the northern shores of Australia sometime around 80 000 years ago.

Aboriginal peoples relied on stone tools to assist them to hunt, gather and process their foods and medicines.

There is evidence of early Aboriginal quarry sites across Australia, such as the one shown in Figure 5.2. Here stones such as ironstone, granite, greenstone, silcrete, quartz, basalt and chert were quarried to make stone tools. Quarry sites were chosen according to the type of stone available and the ease of removing it from the earth. Usually a rocky outcrop with rocks exposed by erosion was best.

Stones were also trimmed at the quarry site. When a suitable piece of rock was found, it was hit with another rock or **hammer stone** to produce both a worked core tool and flake tools that could be further manipulated to produce the shape required. **Core tools** are items such as hand axes, while **flake tools** are items such as spear tips, arrow tips and stone knives.

Once the flake had been removed from the original rock, it could be further fashioned using a piece of bone or even the end of a small stick. If the tool lost its cutting edge, the flake could be reworked to produce a sharp cutting surface. This was usually done away from the quarry site, and in New South Wales evidence of 'finishing' sites have been found at Emu Plains (west of Sydney), Long Bay and Maroubra Bay (south of Sydney) and near Dubbo.

There is also evidence that rocks were dug from below ground. Quarry sites have been found that show signs of trenches where the earth was dug to remove rocks. This practice produced unweathered rocks that could be used for grinding stones.



Finding evidence of early Aboriginal habitation

Watch the video about archaeological finds in Kakadu National Park.



Aboriginal and Torres Strait Islander histories and cultures



Narcoonowie ancient grindstone quarry



FIGURE 5.2
Evidence of an
Aboriginal ochre pit
at West MacDonnell
National Park, NT.

INVESTIGATION 5.1

Learning the ancient technology of knapping

INTRODUCTION

Knapping is the technique that Aboriginal and Torres Strait Islander peoples used to make sharp edges on their stone tools. They were so successful with this technique that they were able to produce stone tools for different purposes, such as knives, spears and arrowheads. In this investigation students will use different types of rock and compare the results to find out which rock is best for making stone tools.

AIM

To compare the suitability of different types of rock for knapping

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Pieces of stone can fly off and hit you in the face or eye.	Always wear safety glasses and strike the stone downwards and away from you and other people.
Your fingers can get hit by the stones as you strike them together.	Always wear thick protective gloves and take care to keep your fingers away from the hit site.



What other risks are associated with your investigation, and how can you manage them?

MATERIALS

- Thick gloves (such as leather gardening gloves) and safety glasses
- Large piece (about the size of a large potato) of flint, obsidian or chert
- Hard round pebble
- Apple

METHOD

- 1 Devise a list of criteria to compare your stone tool to the stone tools that others in your class will make.
- 2 Hold the piece of flint, obsidian or chert in your hand.



- » 3 Use the smaller pebble to hit downwards on the larger rock to split it in half.
- 4 With the flat face of the rock facing upwards, use the pebble to hit at the edge to split off a small bladelet. (Figure 5.3.)

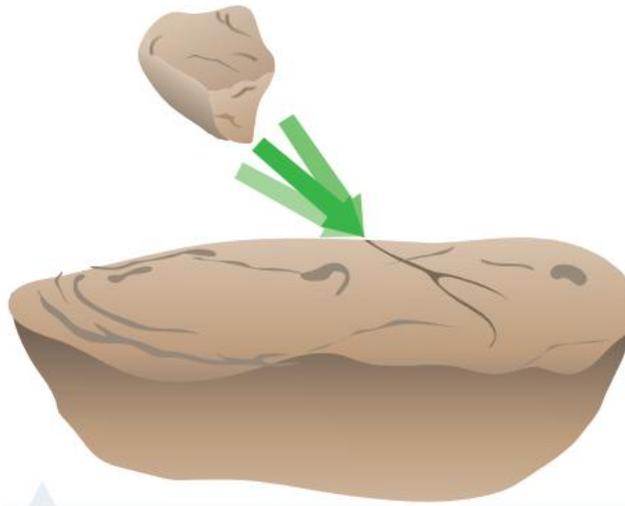


FIGURE 5.3

- 5 Turn the larger rock and repeat step 3. Keep doing this until you have produced a number of small bladelets.
- 6 Choose one bladelet and use it to cut a slice from the apple.

RESULTS

Photograph your stone tool.

ANALYSIS OF RESULTS

Using the criteria that you have devised, decide which stone was the best to use to make a stone tool.



Producing pigments
from natural materials

Alamy Stock Photo / John Robinson



FIGURE 5.4 Wilgie Mia ochre mine

Ochre was extensively mined by Aboriginal peoples across Australia. **Ochre** is an iron oxide ranging in colour from yellow through to red and brown. When mixed with water or animal fat it can be used as ceremonial body paint. Wilgie Mia ochre mine in the Weld Ranges of Western Australia is the largest traditional ochre mine in Australia (Figure 5.4). The area was mined by the Wajarri people and the ochre was used as body paint, for paintings, or traded for shields and spears with groups as far away as Queensland. The red ochre from this mine is believed to be the blood of *marlu*, the red kangaroo. It is particularly prized for its pink hue, silver sheen and glow-in-the-dark properties, giving it a potency of sacred value.

There are two large chambers at this mine, with a number of tunnels. The tunnels show evidence of pole scaffolding with wooden

platforms. This would have enabled the many miners to work at different levels to follow the prized ochre seams. Stone mauls and wooden wedges were used to pry out the ochre from the earth.

The ochre mine near Mount Rowland in Tasmania was mostly worked by Aboriginal women. They squeezed through narrow crevices and used stones as hammers and pointed sticks as chisels to remove the ochre from the earth. Kangaroo skin bags were used to carry the ochre away from the mine.

Mining at most of the Aboriginal mining sites continued up until about 50 years ago. Deposits of ochre are still being mined for use in traditional Aboriginal painting. In eastern Australia, there are currently 416 recorded Aboriginal mining sites or locations that indicate mining has occurred.

KEY CONCEPTS

- Aboriginal peoples quarried stone to fashion into stone tools.
- Quarry sites show evidence of above- and below-ground stone removal.
- Ochre is used for ceremonial body paint, art and for trade.
- There is evidence of the use of wooden scaffolding and platforms in mining for ochre.
- Stone and wooden tools were used to remove ochre from the earth.

- 1 List the types of rock that were quarried by Aboriginal peoples.
- 2 What criteria did Aboriginal peoples use to decide upon a quarry site?
- 3 Distinguish between core tools and flake tools. Where were each produced?
- 4 Describe how stones were removed from the earth at the quarry site.
- 5 List five items that quarried stones were used to make.
- 6 What is ochre? What did the Aboriginal peoples use ochre for?
- 7 How did the Aboriginal peoples remove the ochre from the earth?
- 8 What evidence is there to suggest that the Aboriginal peoples used sophisticated techniques to remove the ochre from the earth?

CHECK YOUR UNDERSTANDING

5.1

5.2

Non-renewable resources and where to find them

Non-renewable resources are those materials that cannot be renewed by natural processes in the short to medium term.

Minerals

A **mineral** occurs as a solid on Earth's surface. It is a non-organic, naturally occurring material with a distinctive chemical composition and an ordered crystalline structure. The International Mineralogical Association recognises 5312 different minerals. The great majority of these minerals are rare, with many found only at a single location. The most common minerals in Earth's crust are the various feldspar minerals (as a group) and quartz. The most common mineral in the whole Earth is bridgmanite, a form of perovskite (Figure 5.5). It is found only where there is high temperature and pressure, such as in the middle and lower mantle.

A location where there is a concentration of minerals of one type or another is known as a **mineral deposit**. The locations of economically viable mineral deposits, called **ores**, can be seen in Figure 5.6. Aluminium



FIGURE 5.5 Crystals of perovskite (calcium titanium oxide)

Dreamstime.com/Vvoevale

is the most abundant metallic element found in Earth's crust but it is never found as aluminium metal. Instead, it is usually found associated with oxygen as bauxite and is referred to as bauxite ore if in high concentrations. Australia and Guinea have large deposits of bauxite and 24% of the world's aluminium is produced in Australia.

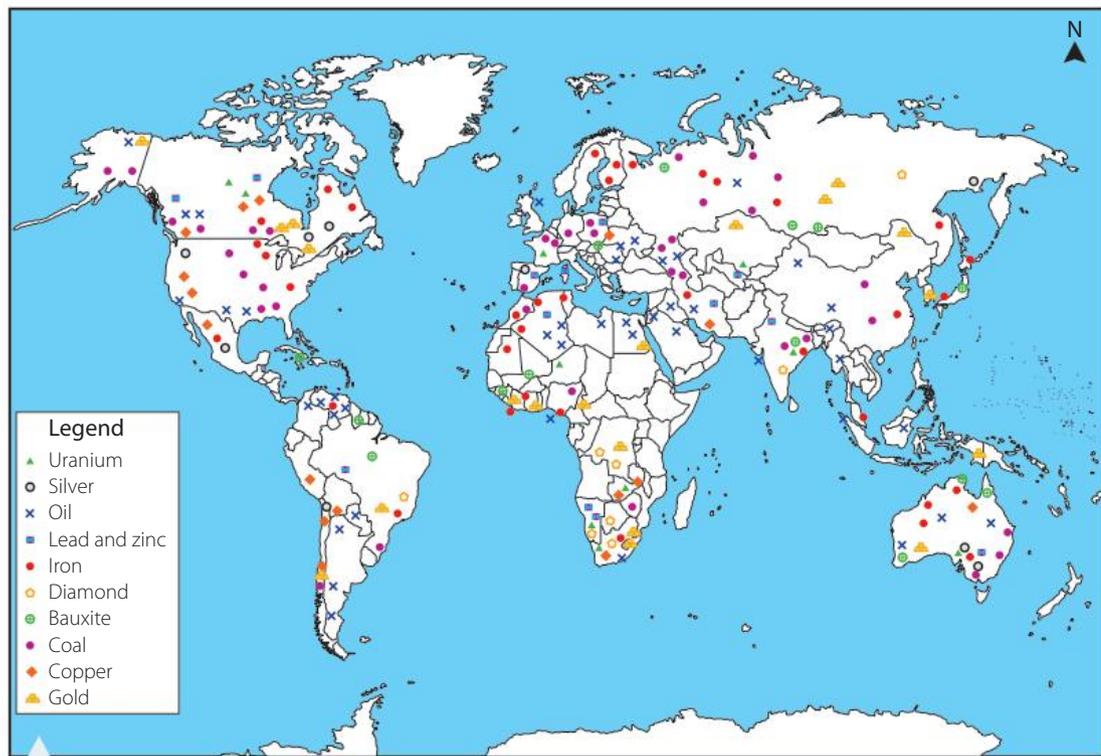


FIGURE 5.6 Mineral resources map showing where significant deposits of each mineral are found

INVESTIGATION 5.2

Minerals – where and why?

Minerals are found across the world. When there are large deposits of minerals that are useful to humans, then it can be economically feasible to mine them. Figure 5.6 shows where these deposits are located. Why do large deposits of minerals occur in some places and not others? To answer this question, use Figure 5.6 and the Internet (e.g. Minerals database weblink) to fill in Table 5.1 for 16 of the world's most mined minerals. The first row has been done for you. If you cannot find the information you require on the Minerals database website, go to other websites to find the answer. Add three minerals of your own choice.

RESULTS

TABLE 5.1

MINERAL	WHERE IS IT FOUND?	IN WHAT FORM IS IT FOUND?	HOW WAS IT FORMED?	WHAT IS IT USED FOR?
Aluminium	Brazil, Jamaica, Africa, Russia, India, Europe and Australia	Bauxite ore	Silica in aluminium-bearing rocks is leached, so occurs in tropical (or once tropical) climates	Transportation, packaging, building, electrical applications



Minerals database

Find out more about specific minerals



Information and communication technology capability



MINERAL	WHERE IS IT FOUND?	IN WHAT FORM IS IT FOUND?	HOW WAS IT FORMED?	WHAT IS IT USED FOR?
Uranium				
Silver				
Lead and zinc				
Iron				
Diamond				
Copper				
Gold				

Fossil fuels

Fossil fuels are materials that have formed as a result of past biological and geological processes. Humans make use of these materials to produce energy, usually in the form of heat.

Coal

Coal is a fossil fuel of sedimentary origin that has formed by conversion of large thicknesses of vegetation over many millions of years. Locations where coal is formed are large sedimentary basins, often near the coast, where water flowing into the basin carries sediment that promotes growth of vegetation. Examples of this type of environment are the Florida Everglades and cypress swamps along the coast of Louisiana in the United States. The Sydney–Bowen Basin (incorporating the Gunnedah Basin between them) was formed during the Permian period due to stretching of the crust on the then eastern edge of Gondwana by a subducting oceanic plate approaching from the east.

The process of converting vegetation into coal occurs over millions of years. Heat and pressure drive off much of the water and, in doing so, increase the carbon content in the material through a process known as **coalification**. Increasing the level of coalification of the vegetation is known as increasing the ‘rank’ of the coal. Black coal consists of anthracite (highest rank, with the lowest water and highest carbon content), bituminous and sub-bituminous. Australia does not have viable sources of anthracite but does have extensive deposits of bituminous and sub-bituminous coal. The lower rank brown coal, lignite (lowest rank, with the highest water and lowest carbon content), is usually much younger in age than the black coals (Figure 5.7). The only major deposits of brown coal in Australia occur in Victoria and are of Palaeogene age (30 to 50 million years).

Coal is primarily used as a fuel to generate electricity and in Australia it is used to produce about 80% of the nation’s electricity requirements. High-quality bituminous coal is the rank of coal used to produce

Stephen Greb, Kentucky Geological Survey

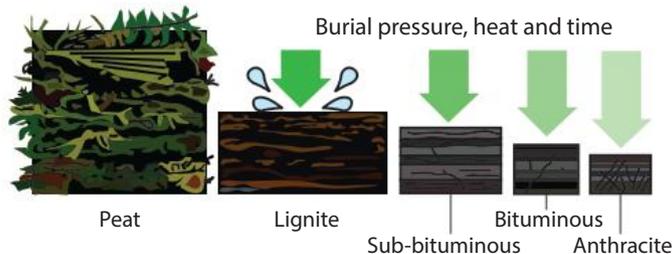


FIGURE 5.7

Steps showing the conversion of vegetation into the various types (ranks) of coal

coke, the source of carbon in steel-making. Coke is made by heating bituminous coal in a vacuum to drive off any volatile substances. The by-products of coke-making include coal gas (methane), tar, some oils and ammonia gas.

Australia has approximately 6% of the world's black coal and has the sixth-highest black coal reserves in the world. The United States, Russia, China, India and South Africa are the other nations with extensive black coal reserves. Australia has about 25% of the world's known brown coal reserves (Figure 5.8).

Australia's operating black and brown coal mines as at December 2012, from Australia's Mineral Resource Assessment 2013, © Commonwealth of Australia (Geoscience Australia) 2019

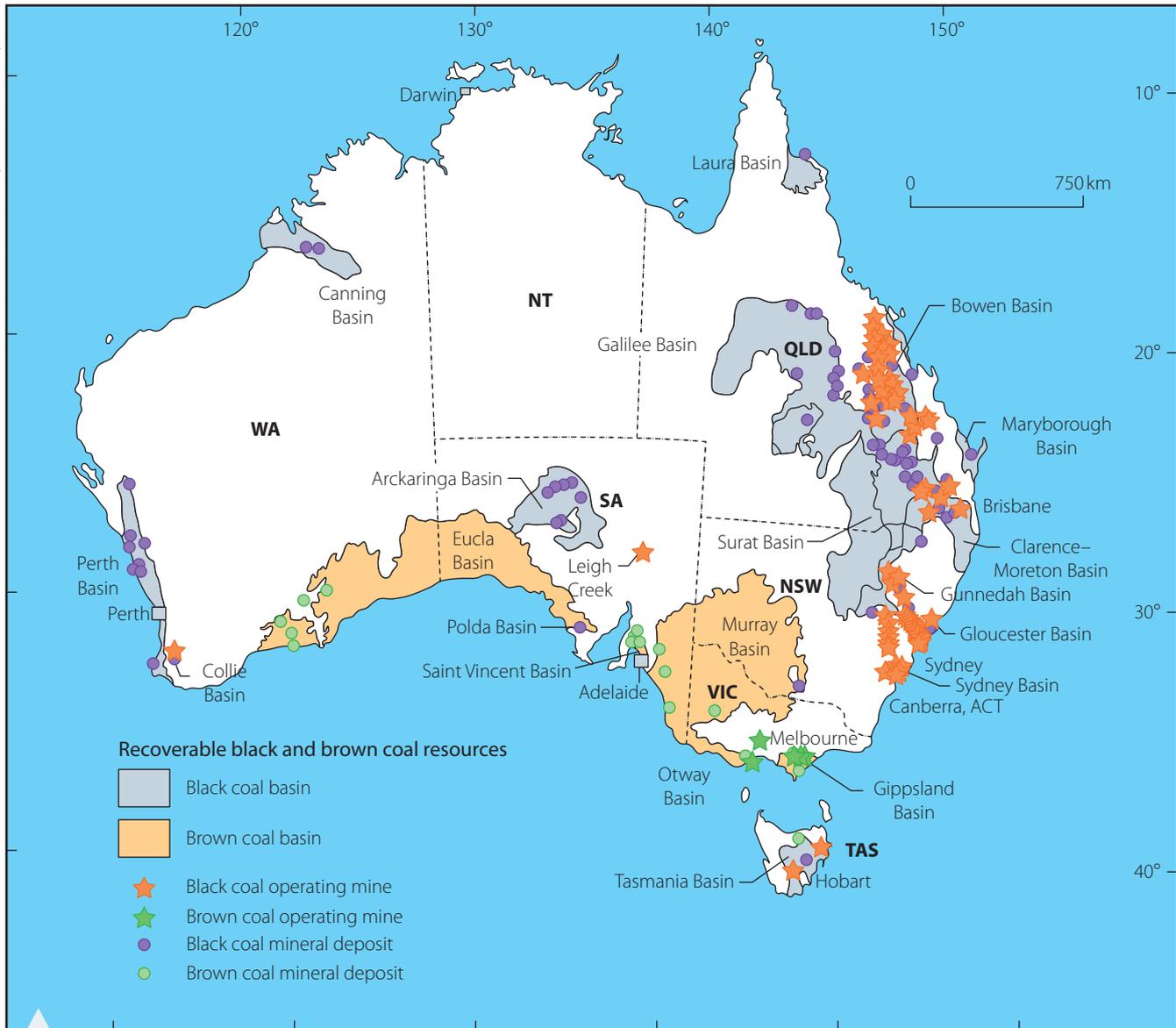


FIGURE 5.8 Map of the distribution of coal in Australia

Petroleum

Petroleum encompasses a wide range of liquid hydrocarbons (crude oil and condensate). Petroleum is a naturally occurring liquid consisting of hydrocarbons that have been formed by the chemical and heat alteration of buried marine organic matter in marine sedimentary basins. It is formed as these marine sediments are covered by further sedimentation and heated, either by nearby igneous intrusions or by the steady release of heat from the mantle, over geological time. Most of the world's petroleum reserves are found in marine sedimentary basins of Mesozoic age.

Marine sedimentary basins of the appropriate age are found between the mainland and Tasmania, along most of the coastline and offshore in Western Australia, and in a wide band across the centre of the continent. These areas were covered by shallow seas during the Mesozoic era due to the high sea levels that existed at that time.

Australia has a very limited amount of the world's petroleum reserves, about 0.3% of the world supply. Most of the country's known remaining oil resources are associated with the giant offshore gas fields in the Bonaparte, Carnarvon and Browse Basins off the north-west coast of Western Australia (Figure 5.9).

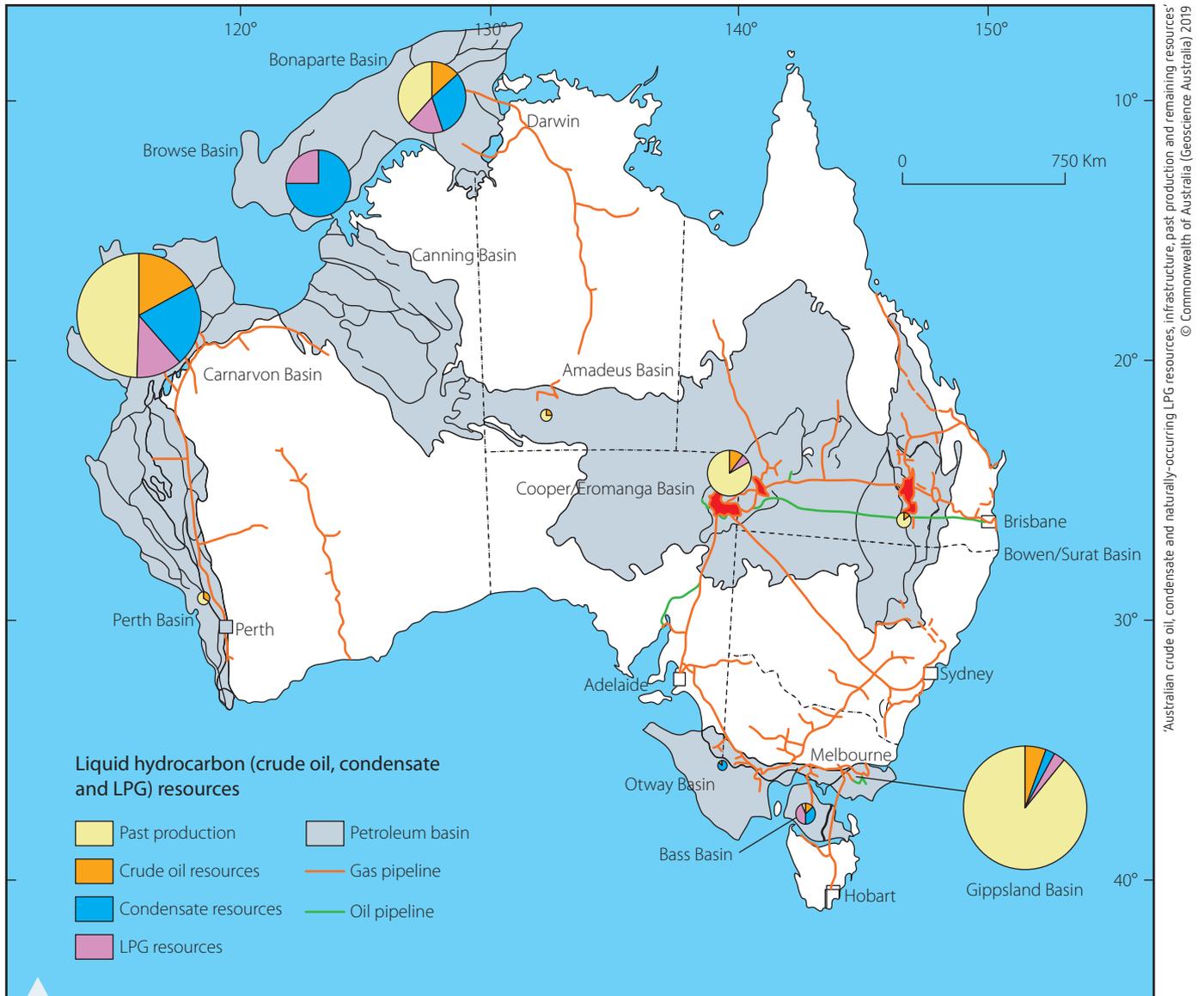


FIGURE 5.9 Oil and gas basins of Australia

Natural gas

Natural gas is a combustible mixture of hydrocarbon gases. It consists mainly of methane, but often contains varying levels of longer-chain hydrocarbons such as ethane, propane and butane, along with other gases such as hydrogen and carbon dioxide. There is a close association between natural gas and petroleum, with regions of higher **geothermal gradient** tending to produce natural gas from the same source material. The marine basins across central Australia and the offshore basins to the north-west of Western Australia are the main sources of natural gas in the country.

Liquefied natural gas (LNG) is composed of two short-chain hydrocarbons: methane and ethane. This mixture is a gas at surface conditions (1 atm of pressure and 25°C) and is cooled and compressed to a liquid for ease of transport in large LNG tankers. (LNG is transported at around –160°C and 100 atm of pressure.)

Australia possesses large gas resources. Natural gas is Australia's third largest energy resource behind coal and uranium. Gas resources are widespread in onshore basins such as the Surat and Galilee basins, but most of the exportable resource is off the north-west coast in the Bonaparte, Carnarvon and Browse Basins. This is one of the largest reserves of natural gas and is the location of a major resource development project.

INVESTIGATION 5.3

Fossil fuels



Information and communication technology capability



Work and enterprise



Numeracy



Energy update report

Fossil fuels are a significant source of energy production and a major export commodity for Australia. Your task is to locate the economic information for fossil fuels and present that information in an appropriate format. A weblink is provided (Energy update report) to assist you, but you will need to locate your own information as well.

Work in pairs for this task. Divide the task so you can complete it in the required time.

Information to find out:

- 1 What types of fossil fuels are produced in Australia?
- 2 Where in Australia are these fossil fuels produced? Locate these areas on a map.
- 3 In 2015–2016, how much of each type of fossil fuel was used locally? How much was exported?
- 4 Which industries were the major energy consumers?
- 5 Find the information referred to in question 3 for the current financial year. Calculate the percentage change from 2015–2016 financial year.

Economically significant ores

When an ore occurs in a particular area in large amounts or with a high concentration, it may be economically viable to mine it for export or for use locally. Ore deposits can be of a number of different types and can occur in a wide variety of geological environments. Mineral deposits are often divided into those that contain metals and those that contain non-metallic materials. Geologists do not consider coal, petroleum and natural gas to be mineral deposits but rather group them together under the term of fossil fuels. The main types of geological ore deposits can then be divided into metallic deposits and non-metallic deposits.

Geologists and mining companies are always searching for new ore deposits to meet ongoing demand because each deposit has a limited life span. Finding new economically viable deposits has become increasingly difficult over time because easily accessible ore deposits at or near Earth's surface have been exploited by humans in the past. Surface mining of copper deposits on the island of Cyprus are estimated to have begun about 6000 years ago. Complex techniques have been developed over the last 100 years or so to locate new ore deposits. Better and more efficient processing techniques mean that mining companies can exploit ore deposits that were previously considered uneconomic. As well, new technologies may allow mining companies to reprocess material at closed mine sites.

Many factors control the economic viability of an ore deposit but the most important are:

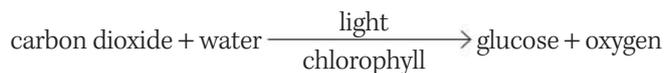
- grade (amount of metal or commodity per tonne of rock)
- the size of the deposit (tonnage)
- easy access to infrastructure such as roads, rail and ports for transportation
- the current and projected price for the commodity (based on estimates for future demand)
- demand, both local and international.

Metallic deposits

Metallic deposits of ore are those that contain metals such as iron, gold, silver and aluminium.

Pilbara iron ore deposits

About 4200 million years ago, the Pilbara region was covered by ocean. The sea floor was made of basalt rock, much as it is today. The early oceans are thought to have been acidic because there were high levels of carbon dioxide gas in the early atmosphere. Carbon dioxide dissolves in water to produce the weakly acidic solution, carbonic acid. Over many millions of years, this acid mix in the oceans accelerated the weathering of the sea-floor basalts. As a result, the oceans became highly enriched in soluble iron. Around 3200 million years ago, cyanobacteria evolved in the ocean. They used the process of **photosynthesis** to gain their food according to the equation below.



Oxygen gas was released into the water as a waste product. There it reacted with the soluble iron ions to form insoluble iron oxide. This insoluble material sank to the ocean floor where, over time, it accumulated to large thicknesses. It took approximately 1400 million years for all of the dissolved iron in the oceans to be removed in this way. These deposits of iron are known as **banded iron formations (BIFs)** due to their distinctive banding. The largest deposits are in the Hammersley range in the Pilbara district of Western Australia (Figure 5.10). They are also known to occur in Archaean marine sedimentary basins within the ancient 'shield' regions of North America, Africa and Siberia.



FIGURE 5.10 The distinctive red rocks of the Pilbara area indicating iron ore

Archaean gold deposits

Late in the Archaean and the early Proterozoic, **fold belts** developed around the pre-existing shield regions of the early Earth's crust. These fold belts wrapped around the **shield areas** and extended from the eastern half of Western Australia to border regions of New South Wales, Victoria and Queensland. The fold belts were intruded by granites during their formation and the heat from the intrusions mobilised fluids in the rocks. These fluids were able to scavenge metals such as gold and transport them towards the surface, where they were deposited in the rocks. The fold belts developed into very large **mountain** ranges that have been progressively eroded over time to the relatively flat central plateau region that covers most of central Australia. Mining locations such as Kalgoorlie and Roxby Downs are located within this central region.

Volcanogenic massive sulfide deposits

Volcanogenic massive sulfide deposits are deposits of copper, lead, zinc and silver that formed as a result of volcanism. Late in the Proterozoic, subduction processes intensified along the eastern coastline of Gondwana. This led to the development of a series of **island arc** systems that ran parallel to the coast of what was then eastern Australia. Compression of these island arcs joined them to

the Australian land mass in a series of mountain-building events characterised by volcanism and metamorphism. Intense folding of the mix of marine and terrestrial sediments led to the generation of granite bodies deep within the crust. The upward movement of the granites provided the heat necessary to mobilise fluids within the crust. These fluids scavenged and then concentrated the metals, mostly in marine volcanic sediments of the fold belts. Mineral deposits of this kind are found at Mt Isa and Cloncurry in Queensland, at Broken Hill and Cobar in New South Wales, and at Queenstown and Rosebery in Tasmania.

Aluminium deposits of north Queensland

Aluminium is mined in tropical north Queensland, and is most commonly associated with the town of Weipa on the Gulf of Carpentaria. The aluminium deposits are located within heavily weathered tropical soil profiles in regions where there is extensive weathering of granite and associated rocks. Under tropical conditions, the aluminium ore, along with a significant percentage of iron, is stable as an insoluble oxide compound. The ore is usually mined using large earth-moving equipment such as bulldozers, because it exists as pea-sized spheres. The ore is loaded onto bulk carriers for transport to locations with abundant electricity supplies, such as Gladstone in Queensland or Tomago in New South Wales. The ore is first converted into alumina (AlO_3) in a smelter and is then electrolytically refined to produce aluminium metal. Australia is one of the world's largest exporters of aluminium metal and alumina.

Non-metal deposits

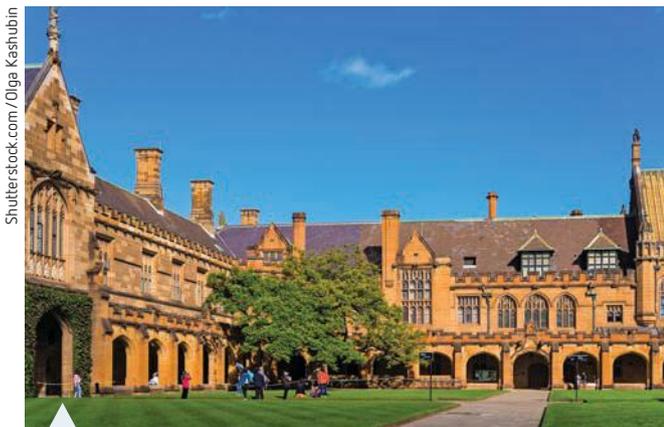
Non-metal deposits are those that do not contain metal. These include coal, petroleum, natural gas and limestone for cement manufacturing and materials used in the building industry.

Limestone

Limestone is formed by the action of reef-forming corals and these are often found within the eastern third of all the states along the eastern side of Australia. Marulan, near Goulburn, is the largest limestone quarry and supplies most of the limestone needed for cement manufacture in the eastern states.

Sandstone

Sandstone has been quarried extensively in the Sydney region, where there are extensive sandstone deposits. The older buildings in the central city and many suburbs, particularly older churches, are made of sandstone (Figure 5.11). The most common sandstone layer to have been quarried is Hawkesbury sandstone, which forms many of the cliffs around Sydney Harbour. It has been used since the early 19th century as building stone, with more than 20 quarry sites within greater Sydney. All these quarries have now closed because of building around them.



Shutterstock.com/Olga Kashubin

FIGURE 5.11 Sandstone building, University of Sydney

Other non-metal materials

Mining of other non-metal materials, such as sand for concrete or crushed basalts for railway sidings, is generally small in scale and is carried out to meet specific markets. One major mine that produces non-metallic material is the Argyle diamond mine in the Kimberley region. Diamonds are found only in regions of very thick crust of Archaean age and so the exploration for diamonds is restricted to areas like the Kimberley.

- Non-renewable resources are those materials that cannot be renewed by natural processes in the short to medium term.
- A mineral:
 - occurs as a solid on Earth's surface
 - is non-organic
 - occurs naturally
 - possesses a distinctive chemical composition
 - has an ordered crystalline structure.
- Fossil fuels are formed from biological and geological processes occurring over long periods of time.
- Examples of fossil fuels are coal, petroleum and natural gas.
- Economically significant metallic ores include iron ore, gold, sulfide and aluminium.
- Economically significant non-metallic ores include limestone, sandstone and diamonds.
- There is a strong relationship between the geological setting and the type of material extracted.

- 1 Define non-renewable resource, mineral, mineral deposit, ore.
- 2 Name the most common mineral on Earth. Where is it found?
- 3 Explain how fossil fuels are formed.
- 4 Correlate the conditions required for fossil-fuel formation and where large deposits of fossil fuel are located.
- 5 Use the data in Table 5.2 to calculate the percentage change in export earnings from coal for the years 2014–2015, 2015–2016 and 2016–2017.
- 6 State the two main types of economically significant ores and provide two examples of each.
- 7 Choose one ore of economic significance. Locate where this occurs in viable amounts and explain why it formed there.

TABLE 5.2 Export earnings of coal

YEAR	EXPORT EARNINGS (BILLION DOLLARS)
2014	38.0
2015	37.0
2016	42.3
2017	56.5

Based on data from Department of Foreign Affairs and Trade website; www.dfat.gov.au

CHECK YOUR UNDERSTANDING

5.2



5.3

How economically important are Australia's non-renewable resources?

Mining provides Australia with a valuable commodity both in terms of material to be exported and as a source of employment for its citizens.

Exports

There has been a steady increase in the tonnages of commodities mined and exported over the last 25 years (Table 5.3). Mining exports make up over 50% of Australia's total export earnings. The effect of the **mining boom** on exports between 2000 and 2010 meant that the value of exports from mining rose by more than 120%, from \$63 billion to \$139 billion during the decade.

TABLE 5.3 Change in the exported tonnages of selected commodities between 1989–1990 and 2016–2017

COMMODITY	1989–1990 TONNAGES	2016–2017 TONNAGES
Aluminium	940 000	1 329 000
Copper	206 000	920 000
Zinc	686 000	1 008 000
Gold	192	334
Coal	105 000 000	379 000 000
Liquefied natural gas	2 000 000	52 000 000
Uranium	4 812	7 081
Iron ore	99 000 000	818 000 000

ABS (2018) International Trade in Goods and Services, 5368.0; Department of Industry, Innovation and Science (2018)

In 2018, Australia’s earth resources exports (processed and unprocessed minerals, metals and petroleum) set a new record value of \$248 billion and accounted for 72% of Australia’s total goods and services export earnings. Mining resources export earnings in 2018 were more than double the value of services exports and four times the value of rural goods exported (Source: Minerals Council of Australia, February 2018). Mining generates more export revenue for Australia than all other industries combined.

According to the Australian Bureau of Statistics and the Department of Industry and Science, earnings from minerals and energy exports are expected to reach \$264 billion by end of 2018–19. Figure 5.12 shows

that iron ore and coal dominate export earnings, followed by gold and base metals (copper, lead and zinc), but liquefied natural gas (LNG) will make a dramatic increase once the LNG plants in northern Western Australia come online completely.

Between the 2005–2006 financial year and the 2015–2016 financial year, the mining sector contributed \$185 billion in federal taxes and royalties as well as royalties to various state governments (Source: *Sydney Morning Herald*, January 2018).

Resources and Energy Quarterly - March 2019, © Department of Industry, Innovation and Science, <https://publications.industry.gov.au/publications/resourcesandenergyquarterlymarch2019/index.html>

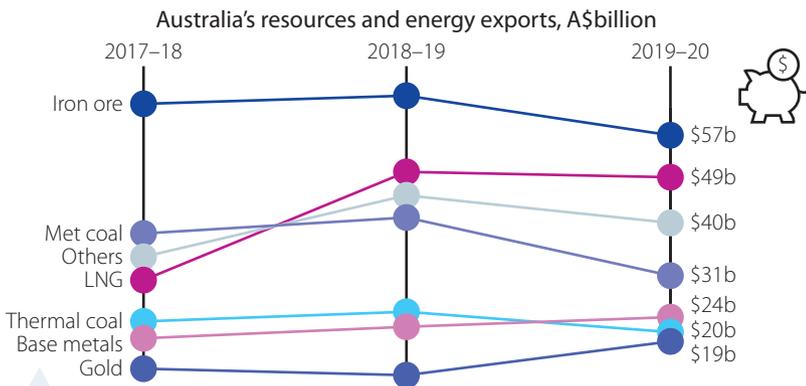


FIGURE 5.12 Contribution of the various mineral products to export earnings

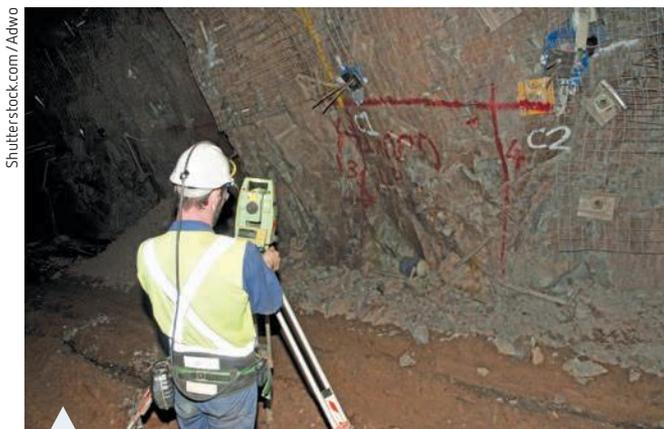


FIGURE 5.13 A surveyor working in an underground mine

Employment

In 2018, Australian mining employed approximately 251 700 people in full-time and part-time jobs. This was around 2.0% of the total Australian workforce (Department of Jobs and Small Business, February 2019).

However, this figure greatly underestimates the downstream impact of the mining sector. Mines need to be supplied with equipment, tools and workwear. Mined material needs to be processed, trucked and shipped. Miners need to be fed and housed. If this downstream component were to be included, then the mining sector would be an even more important driver of the Australian economy.

INVESTIGATION 5.4

The changing face of mining

There has been increased mechanisation and use of computer control systems to increase productivity in the mining sector. In large open cut mines, economies of scale have an increased effect on production and, therefore, profit.

- 1 Using the data in Table 5.3, calculate the percentage increase for each of the commodities listed between 1989–1990 and 2016–2017.
- 2 Predict the tonnages for each of the commodities in 25 years if the same percentage increase was maintained.

In many deep underground mines, the danger to miners is increased due to the working conditions and the stresses found within the rocks. In an effort to reduce this danger to miners, computer control systems have been installed on mining excavation vehicles, effectively turning them into robots.

- 3 What effect could this change in the way that mining is being done have on the mining workforce?
- 4 What new skills will be required of workers if more mines are to operate in this way?
- 5 One of the largest expenses in any mining operation is payroll. If a mine could reduce its payroll by decreasing the number of miners employed by introducing robotic control on sections of the operation, what would be the overall effect on:
 - a employment prospects of untrained mine workers?
 - b overall profitability of the mining operation?
 - c share payments to shareholders?
 - d the town and the people that service the mine?
- 6 What ethical factors need to be considered around this type of change to the workforce?
- 7 List three careers that could become more important in mines as a result of the mechanisation of processes. Where would these people work?



KEY CONCEPTS

- Mining provides export income as well as employment.
- Mining exports make up over 50% of Australia's total export earnings.
- Mining not only employs people directly but also provides employment for many more people downstream.

- 1 Copy Table 5.3 and re-order the commodities to place them in decreasing order of tonnages exported in 2016–2017. State the three commodities that made up the greatest tonnage of export.
- 2 In November 2016, the Australian mining industry employed 223 400 people. Calculate the percentage difference between then and February 2018.
- 3 List five jobs or industries that would have been created and or supported downstream due to mining.

CHECK YOUR UNDERSTANDING

5.3

5.4

Sampling and sensing techniques

Before mining can take place, the sites of economically viable ore deposits need to be located. Because large areas of Australia are remote and inaccessible, and ore is usually buried, locating valuable ore deposits can be costly and time consuming. Geologists go about this task using sampling and sensing techniques.

Remote sensing

Remote sensing is the gathering of information about a rock or soil from far away, usually by using equipment on a satellite or a plane.

Satellite images

Satellite imagery is typically one of the first data types acquired by anyone working in a new area. Early in any exploration project, exploration geologists aim to identify areas of land that have a high likelihood of containing mineral prospects. Satellite imagery and aerial photographs allow this aim to be achieved in a highly cost-effective way. Satellite imagery combined with field mapping and geophysics is a very efficient method of gaining understanding of what the geology of a certain region might contain.

Today, satellite imagery can be obtained from a variety of systems, such as Landsat, WorldView, SPOT, RapidEye and EROS (Figure 5.14). These satellites are usually government or commercially owned. The data collected can be sent directly to the geologists via the Internet, allowing them to employ the satellite's capabilities from the comfort of their own offices. This allows the geologists to narrow down the search areas quickly for a relatively small financial outlay.

FIGURE 5.14
A remote-sensing satellite



Science Photo Library/EUROPEAN SPACE AGENCY

The various satellite systems differ in how often they overfly the same location, the depth of detail they record and the number of different wavelengths of the electromagnetic spectrum that they pick up. The sensors onboard the spacecraft record radiation (originating from the Sun) that is reflected from Earth's surface. This can be used to identify particular features of rocks and/or soil in an area that can aid in the discovery of new mineral deposits.

Many satellites have no optical components and instead use specific detectors to record reflected electromagnetic wavelengths outside the visible spectrum. The raw data is then processed by specialist

software so it can be analysed. As a result, most geoscientists and researchers describe the material produced by the satellites as ‘images’ and not ‘photographs’. New satellites with improved sensors allow better resolution of Earth’s surface and this makes the identification of likely exploration targets easier, particularly in undeveloped regions.

Remote sensing from satellites is highly cost effective because the satellites regularly have a 20-year lifespan. Also, the data is recorded continuously and downloaded to ground station receivers automatically, eliminating the need for intervention by controllers once the satellite’s programming is installed.

Aerial photographs

Aerial photography is recorded on flight-line diagrams, which show aircraft flightpaths (also known as runs), in the centre of the photos in relation to ground features, and film reference numbers. Each photo has a photo title strip containing the following information.

- film number
- aircraft run number
- photo number
- time and date of photo
- altitude of aircraft / scale

Aerial photography was initially developed during World War I as a way of gathering military intelligence and was used extensively for this purpose until the development of good-quality satellite images in the 1980s. Aerial photography was conducted across all states in Australia between the end of World War II and the late 1980s. In the years before GPS, aerial photographs were used because they allowed locations to be identified accurately. Geological structures of interest, such as folded rock layers or resistant layers that protruded above the general landscape, could be identified in photographs of regions with little or no road access, thus saving time and resources in geological exploration.

Geophysical data

Geophysics is the study of the physical characteristics of surface and buried rocks, such as their magnetic properties, electrical conductivity, density and natural radioactivity. A range of geophysical surveys can be accessed through state government bodies such as the Geological Survey of New South Wales or by specialist companies.

Airborne geophysical surveys use magnetometer sensors to collect and record total magnetic intensity data and radiometric data. Different rocks contain different amounts of magnetite, a magnetic mineral, and the local strength of Earth’s magnetic field is directly influenced by the geological structures, the geological composition and the amount of magnetic minerals in particular areas. Airborne surveys are particularly useful in areas with limited rock exposure where the rock units of interest are covered by soil, alluvium or younger rocks, and are a quick and cost-effective way of gathering data over broad areas.

Gravity surveys measure the gravitational acceleration of a suspended weight and can be either ground based or airborne. They can help identify areas of possible mineral deposits because base metal deposits typically have a higher gravity signature (due to the presence of heavy metals such as lead, copper, zinc, silver and gold). Potential petroleum-producing areas have a lower gravity signature.

Seismic reflection surveys require the controlled generation of seismic waves by means of explosives, powerful airguns or by striking the land or sea floor using a hydraulic ram. The reflections of the seismic waves are analysed to obtain information about the stratigraphy and structure of sedimentary basins, useful in the exploration of petroleum and gas reserves.

Teleseismic surveys use recordings of distant earthquakes to determine structures deep below the surface geology. They assist in locating and defining trends of mineralised belts or major faulting, particularly where there is little exposed rock. This method is one of the few ‘passive’ exploration tools because all it requires is a seismometer and the vibrations from a distant earthquake.



Geological Survey of New South Wales

List the types of geophysical information that can be accessed from the Geological Survey of New South Wales.

INVESTIGATION 5.5

Using magnetism to find a magnetic ore body



Critical and creative thinking

INTRODUCTION

In this investigation you are going to model the use of a compass to locate a magnetic ore body. In a model, you use smaller and readily available materials to simulate real-life situations.

AIM

To use a simple compass to find a hidden magnetic source

MATERIALS

- 6 bar magnets
- Ziplock sandwich bag
- Simple compass
- 20 toothpicks
- 2 different-coloured whiteboard markers
- Sand tray

METHOD

For the teacher

- 1 Group the six bar magnets so that they are joined as a block, not end to end.
- 2 Place the magnets inside a ziplock sandwich bag and seal the bag.
- 3 Place the magnets on the bottom of a sand tray, ensuring students do not know where in the tray the magnets have been placed.

For the student

- 1 Using the two whiteboard markers, colour the wider end of the toothpicks so that there are 10 of each colour.
- 2 Smooth the surface of the sand in the tray and use a ruler to mark a regular grid pattern on the surface of the sand.
- 3 Starting at one end of the grid, slowly and methodically use the compass to follow the grid lines.
- 4 When the compass needle starts to move, place a coloured toothpick into the sand.
- 5 Repeat the motion of moving the compass along the grid lines, only this time do it at a much faster pace.
- 6 When the magnetic needle in the compass changes direction completely, place a toothpick of the other colour in the location where the direction change occurred.

RESULTS

Record your results in a carefully planned grid table showing the location of both sets of coloured toothpicks.

CONCLUSION

Summarise your findings about how the magnetic needle in the compass allowed you to locate the magnets.

DISCUSSION

This is a model investigation. Discuss how the model could be improved to make it more realistic. What are the problems in using a simple model? What are the advantages of using models such as this?

EXTENSION

Investigate which common minerals exhibit magnetic properties.

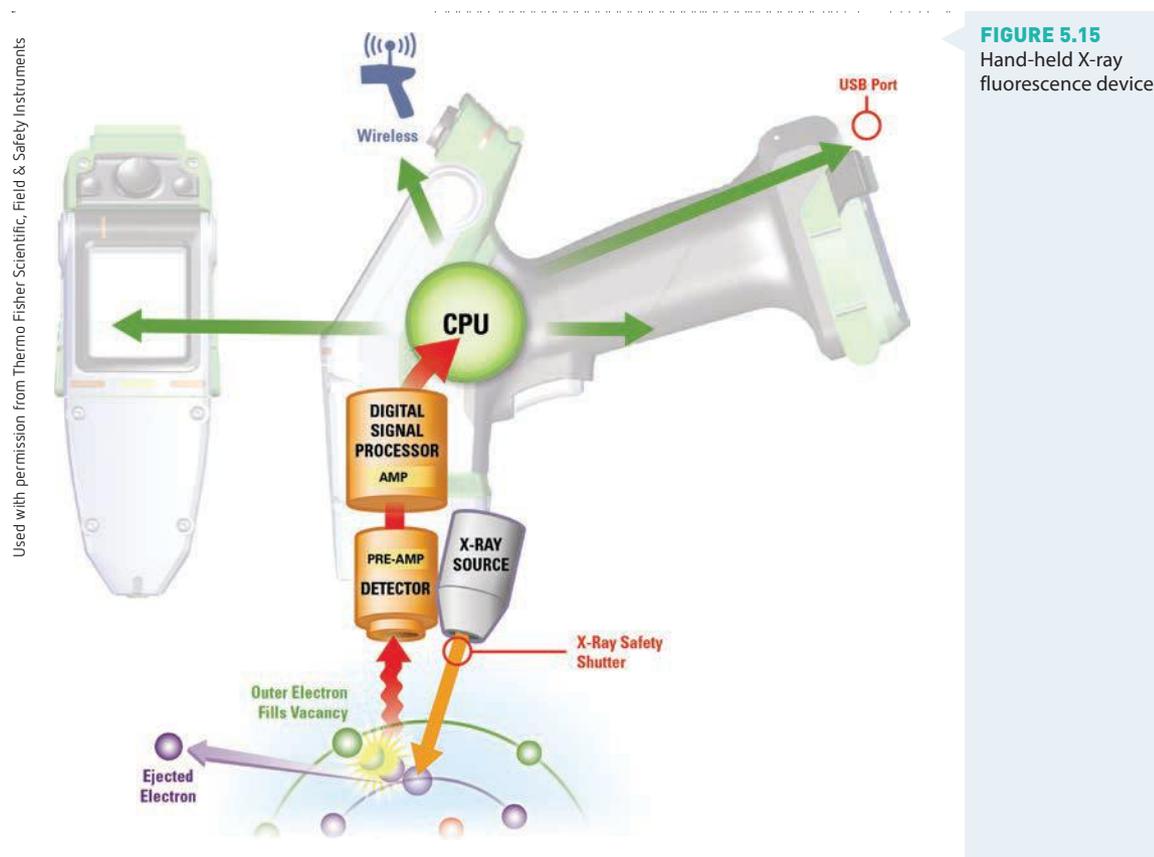
Direct sampling

Direct sampling refers to gathering a piece of rock or sample of soil in the field.

Geochemical data

Geochemical data is the determination of the chemical composition of materials sampled in the field. The most common method is **stream sediment sampling**, in which river sediment samples are collected, generally downstream of a creek or river junction. The samples are analysed for specific metals. Areas that have higher than average metal content become 'target areas' requiring more detailed sampling. Lake sediment and heavy beach-sand minerals are also useful sources of samples to help locate hidden ore deposits.

The primary objective of any **soil sampling** program is to collect samples that are representative of site conditions. Representative samples are collected by careful planning, selecting the appropriate sampling devices, taking measures to avoid contamination and using proper procedures. The technical planning process used to develop the sampling strategy is critical because of the difficulties in acquiring truly representative samples; measuring the concentration of the mineral of interest, which can be very low; and maintaining clean conditions to avoid trace-level cross-contamination. The sampling strategy should follow a rational, scientific approach, usually in a grid pattern that covers the area of interest. Sample locations (latitude, longitude and elevation) can be accurately recorded using GPS. Before the advent of GPS systems, geologists would use marker pegs hammered into the ground in a large grid pattern over the exploration area and take samples next to each peg for analysis. This would allow them to refine the exploration program to target even smaller areas. Hand-held sampling systems (Figure 5.15) have now been developed that provide data to a field geologist in real time. This avoids the expensive delay of waiting for a laboratory to perform a chemical analysis of the samples and for the data to be sent back to the geologist in the field. These devices can reduce costs dramatically because they can be used in the field on just about any geological sample and, if paired with a GPS system, are very accurate for data collection.



INVESTIGATION 5.6

Plotting and contouring geochemical data

Geochemical sampling is conducted in the field to enable geologists to narrow down the search area for a mineral deposit. The samples are typically taken from locations in a grid pattern. This process allows geologists to refine regions that may have an increased possibility of hosting mineralisation that could be exploited economically.

AIM

To contour a geochemical data set

MATERIALS

- Graph paper

METHOD

- On the sheet of graph paper, draw a 10 cm square. Mark each centimetre position with a small cross to indicate a sampling location. Repeat this process throughout the square until you have marked all of the sampling positions.
- Place a North arrow to the right of the crosses.
- Using the table below, write the lead value at each grid location.
- Using 50 ppm intervals, draw contour lines linking sites with the same lead values. You may need to estimate where to place the lines between the data points. Remember that contour lines do not cross.

EASTINGS	NORTHINGS	LEAD VALUE (PPM)
0	0	50
0	10	75
0	20	110
0	30	200
0	40	125
10	0	50
10	10	75
10	20	130
10	30	210
10	40	200
20	0	50
20	10	75
20	20	200
20	30	200
20	40	75
30	0	50
30	10	125
30	20	150
30	30	120
30	40	75
40	0	50
40	10	50
40	20	60
40	30	80
40	40	75



» RESULTS

Record your results in a carefully planned grid table that shows the contouring.

CONCLUSION

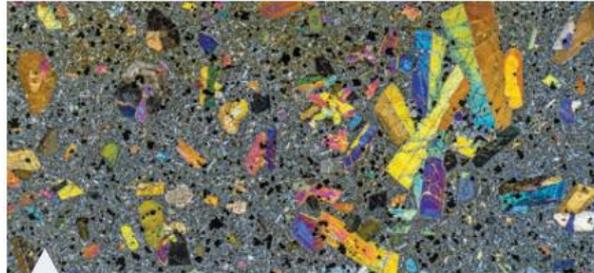
From the contouring, what is the location or locations with the highest lead values?

EXTENSION

Suggest what other sampling could be carried out over the location to further define the zone of lead mineralisation in the soil.

Rock-chip sampling

Rock chips or pieces of rock outcrop can be sampled in the field and brought back to the laboratory for more detailed analysis. If larger pieces of rock can be cut, a thin section can be made from this. Thin section analysis greatly enhances field work because it enables accurate rock descriptions to be obtained (Figure 5.16).



Shutterstock.com/Mirko Graul

FIGURE 5.16 Thin section of a porphyry with augite crystals under cross-polarised light

KEY CONCEPTS

- Satellites and aerial photographs are the two methods of remote sensing.
- Geophysical testing measures the physical characteristics of an ore body.
- Geochemical testing determines the chemical composition of a sample.

- 1 Distinguish between remote sensing and direct sampling.
- 2 Complete the following table about remote-sensing techniques. You may need to consult other sources to complete this table.

TECHNIQUE	WHY IT IS USED	ADVANTAGES	DISADVANTAGES
Satellite images			
Aerial photography			
Regional airborne geophysical survey			
Gravity survey			
Teleseismic survey			

- 3 Which geophysical testing method gives information about structures underground?
- 4 What is the purpose of direct sampling?
- 5 List the different types of direct sampling and state why each type is used.
- 6 You are a geologist who is investigating a large area of land for possible copper mining in remote South Australia. You have a budget and time limit imposed by the mine owner. Copper is usually found in association with igneous rock that has been altered by volcanic activity. Explain which techniques you would use to locate the best site to mine and why you would choose these techniques.

CHECK YOUR UNDERSTANDING

5.4

5.5 Methods of mining



Designing mining methods

The choice of mining method depends on how close the resource is to the ground surface and whether it is spread out horizontally or descends vertically.

Open-pit mining

An open-pit (open cut or open cast) mine is an excavation made in the ground's surface. The mine remains open to the surface for the period of its life. The main aim in any mining operation is the recovery of the mineral deposit at the lowest possible cost. Mining engineers design the shape of the pit and oversee the extraction schedule of both **waste rock** and the ore body. Planning an open-pit mine is a complex exercise that must take into account the unique geological and mining engineering aspects of the particular ore deposit.

In the open pit, a bench is a ledge that forms a single level of operation above which mineral or waste materials are mined back to a bench face. The ore and waste rock are removed in successive sections, each of which is a bench. Several benches may be in operation at the same time in different locations around the pit and at different elevations within the mine. Open-pit mining allows for work to occur on a massive scale using large trucks (Figure 5.17). This makes it much more profitable to mine lower-grade deposits that otherwise would not have been mined.

FIGURE 5.17

The Kalgoorlie Super Pit is the largest open-pit gold mine in Australia. Note the many benches.



Alamy Stock Photo/McPhoto/Lelther

Open-pit mines are used to extract coal that is close to the surface (such as the coal mines in the Hunter region in New South Wales and the Bowen Basin in Queensland). They are also used extensively in hard-rock mining for ores such as copper, gold, iron, aluminium and many other minerals where the mineralisation is close to the surface. In an open-pit coal mine, the pit bottom would be the base of the lowest mined coal seam because it is often possible to extract coal from a number of coal seams when surface-mining coal. In a hard-rock mine, the bottom or base of the pit is the lowest level that mining could be conducted on the ore body being mined.

INVESTIGATION 5.7

Muffin mining

In this investigation you are going to model mining a mine site. Your mine site is represented by a choc-chip muffin, with the cake mixture part of the muffin representing the waste rock and the choc chips representing the valuable ore to be mined.

Once mining is complete you are going to reclaim the site and restore it to as close as possible to the pre-mining condition.



WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Bench tops may be contaminated by chemicals from previous classes.	Do not eat the muffin. Wash your hands at the end of the investigation.



What other risks are associated with your investigation, and how can you manage them?

AIM

Write an aim for this investigation.

MATERIALS

- Large choc-chip muffin
- Paper towel
- Toothpicks
- Plastic knife
- Piece of graph paper
- Digital camera or smartphone
- Stopwatch

METHOD

Part A: Mining

- 1 Place your mine site (choc-chip muffin) into the middle of the piece of graph paper. Draw a circle around the bottom of your mine site and count the number of squares that your mine site occupies.
- 2 Take an aerial photograph of your mine site.
- 3 Use the aerial photograph to inspect your mine site for surface deposits. Using the surface deposit count, predict how many pieces of ore you expect to extract from underground deposits. Record your prediction.
- 4 Set your stopwatch to 10 minutes.
- 5 Use the tools provided (toothpicks) to remove all the surface deposits. Do not clean up the waste rock, let it lie where it falls. Place the ore into a pile onto the paper towel.
- 6 Use the plastic knife to cut a bench into your muffin so you can extract the next layer of ore.
- 7 Keep mining your site in this way until the 10 minutes is up, then finish mining.
- 8 Count your pieces of ore. How does this compare to your prediction?
- 9 Draw a line around the squares of graph paper that contain waste rock. Count the number of squares contained within the line.

Part B: Reclamation

- 1 Use only the tools provided (toothpicks and plastic knife) and the waste rock available to restore the mine site to as close to the original condition as you can.
- 2 Take an aerial photograph of the restored site and compare to the original pre-mined aerial photograph.





RESULTS

Prediction of pieces of ore: _____

Actual pieces of ore mined: _____

Number of squares of mine site: _____

Number of squares of graph paper that contained waste rock: _____

ANALYSIS OF RESULTS

- 1 How did your prediction compare to the actual number of pieces of ore mined? Compare this to other groups.
- 2 Of the total area that your mining site occupied (mine site + waste rock), calculate the percentage that was occupied by:
 - a the mine site
 - b the waste rock.
- 3 Were you able to complete the mining process in the time available?
- 4 What problems did you experience during the mining process?
- 5 Were you able to reclaim the mine site to pre-mining conditions? Give reasons.
- 6 What problems did you encounter when you tried to reclaim your land?
- 7 Did your total mine site extend beyond the initial mine site? By how much? What problems does this pose for real-life mining sites?

CONCLUSION

Write a summary sentence for each part of your investigation.

Underground mining methods

A number of methods are used for underground mining. The method selected is determined by the size, shape, orientation and type of orebody to be mined. An orebody could be a narrow vein type, such as the gold mines in the Witwatersrand, South Africa. The orebody can also be massive (a broad zone of mineralisation), such as the Olympic Dam mine in South Australia or the Cadia-Ridgeway mine in New South Wales.

The width or size of the orebody is determined by the contained metal (grade), as well as the way the ore is distributed throughout the enclosing rocks. The orientation or 'dip' of the orebody can also have a major influence on the mining method. A horizontal orebody can be mined by a room-and-pillar or longwall method. A vertical orebody will be mined by an open-stopping or cut-and-fill method.

Room-and-pillar method

The **room-and-pillar method** is used in mining for coal, iron and copper ores and can occur many hundreds of metres below the ground surface. In this method, illustrated in Figure 5.18, a series of 'rooms' are mined by miners continually, leaving large 'pillars' behind to support the roof. The mined ore is placed on conveyor belts to be taken away.

The size and placement of pillars must be carefully calculated to ensure that the maximum amount of ore can be mined without the roof collapsing. To add strength, metal rods are inserted into the roof rock bolts.

Room-and-pillar mining is one of the more ecologically friendly methods because it preserves the surface above.

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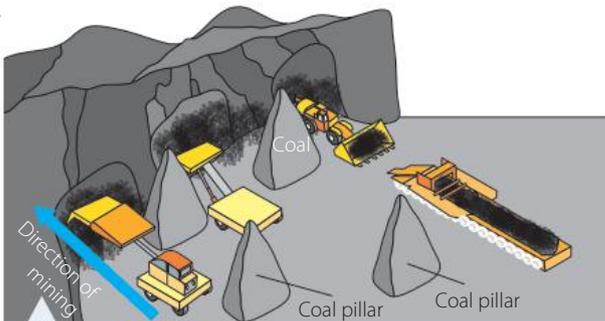


FIGURE 5.18 Room-and-pillar mining method

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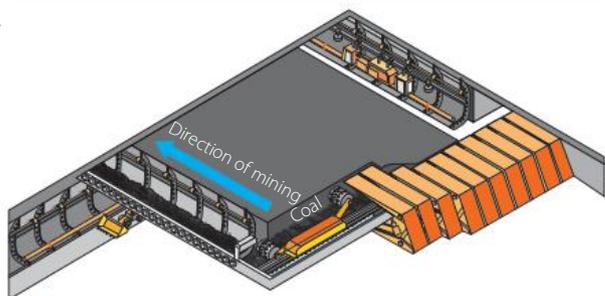


FIGURE 5.19 Longwall-mining method

Longwall method

The **longwall method** is used in coal mining where a large panel of coal up to 350 metres long and 3–4 metres thick is sheared away from the wall by longwall shearing machines (Figure 5.19). The machine travels back and forth along the longwall, cutting the coal from the coalface as it goes. The cut coal is placed on a conveyor belt to be removed from the mine. Once the coal is removed the roof supports are moved forward and the roof is collapsed behind.

Open-stoping method

The **open-stoping method** is used in hard-rock mining where the ore is removed by drilling and blasting and an open stope, or hole. The rock that remains is considered strong enough to support the roof of the mine.

Cut-and-fill method

The **cut-and-fill method** is used when an orebody is located in steeply dipping rock that has a low strength. The ore and waste rock is removed from the mine in a series of slices and the hole left behind is backfilled with the waste rock. The backfilled area forms the floor for the next level of development.

Drilling

Advances in drilling techniques have expanded the amount of oil and gas that can be extracted from the earth. The two types of drilling techniques are onshore and offshore drilling.

Onshore drilling

In **onshore drilling**, deep holes are drilled into the land surface (Figure 5.20). At East Mereenie in the Northern Territory, onshore drilling is used to extract gas from gas reserves below ground. A drill is used to create a hole in the sandstone rock, into which a large steel tube is inserted. As pressure is reduced at the surface, the pressure in the underground gas reserve drives the gas into the tube where it can be directed to the processing plant.

Offshore drilling

In **offshore drilling**, deep holes are drilled into the sea bed. Offshore drilling is typically carried out to extract petroleum (oil) or natural gas that lies in rock formations beneath the sea bed. Most commonly, the term is used to describe drilling activities on the **continental shelf**, though the term can also be applied to drilling in lakes, inshore waters and inland seas.

Offshore drilling presents environmental challenges, from the hydrocarbons produced and the materials used during the drilling operation. It represents the most capital-intensive form of mineral exploration and is usually conducted from a ship-based drilling platform. The largest offshore oil field in Australia is the Kingfisher in Bass Strait, discovered in 1967. There are now 23 offshore platforms in Bass Strait (Figure 5.21).



FIGURE 5.20 A land-based drilling rig in a vertical drilling position



FIGURE 5.21 Historical photograph of the Kingfisher platform, Bass Strait

INVESTIGATION 5.8

Locating mining sites



Information and communication technology capability



Map of Australia

Use the Internet and other resources to complete the following table listing Australian mining sites that use the different types of mining methods discussed. The first row has been done for you but you can add to it.

Use the Map of Australia worksheet to show where these mining sites are located.

TYPE OF MINING	ORE BODY BEING MINED	SITES IN AUSTRALIA
Open pit	Gold Gold and copper Uranium Coal	Super Pit, Kalgoorlie, WA Cadia mine, NSW Ranger mine, NT Peak Downs mine, Qld
Room-and-pillar		
Longwall		
Open-stoping		
Cut-and-fill		
Onshore drilling		
Offshore drilling		

KEY CONCEPTS

- An open-pit (open cut or open cast) mine is an excavation made on the ground's surface to extract ore.
- The method of underground mining to be used is determined by the size, shape, orientation and type of orebody to be mined.
- The room-and-pillar method and the longwall method are used to mine horizontal ore bodies.
- The open-stoping method and the cut-and-fill method are used to mine vertical ore bodies.
- In onshore drilling, deep holes are drilled into the land surface.
- In offshore drilling, deep holes are drilled into the sea bed.

CHECK YOUR UNDERSTANDING

5.5

- 1 List three advantages of open-pit mining.
- 2 List two disadvantages of open-pit mining.
- 3 Under what circumstances would you use the following types of mining: open pit, longwall, offshore drilling?
- 4 Distinguish between the four types of underground mining methods.
- 5 You are planning on mining a deep ore body running vertically in low-strength rock. Choose the best mining method and give reasons for your choice.
- 6 Distinguish between onshore and offshore drilling.
- 7 Drilling is used in Australia for oil and gas extraction. Provide reasons as to why this is the best method to be used.

5 CHAPTER SUMMARY

- ▶ Aboriginal peoples quarried stone to fashion into stone tools.
- ▶ Aboriginal quarry sites show evidence of above- and below-ground stone removal.
- ▶ Ochre is used for ceremonial body paint, art and trade.
- ▶ There is evidence of Aboriginal use of wooden scaffolding and platforms when mining for ochre.
- ▶ Stone and wooden tools were used to remove ochre from the earth.
- ▶ Non-renewable resources are those materials that cannot be renewed by natural processes in the short to medium term.
- ▶ A mineral:
 - occurs as a solid on Earth's surface
 - is non-organic
 - is a naturally occurring material
 - has a distinctive chemical composition
 - has an ordered crystalline structure.
- ▶ Fossil fuels are formed from biological and geological processes occurring over long periods of time.
- ▶ Examples of fossil fuels are coal, petroleum and natural gas.
- ▶ Economically significant metallic ores include iron ore, gold, sulfide and aluminium.
- ▶ Economically significant non-metallic ores include limestone, sandstone and diamonds.
- ▶ There is a strong relationship between the geological setting and the type of material extracted.
- ▶ Mining provides export income as well as employment.
- ▶ Mining exports make up over 50% of Australia's total export earnings.
- ▶ Mining not only employs people directly but also provides employment for many more people downstream.
- ▶ Satellite sensors and aerial photographs are the two methods of remote sensing.
- ▶ Geophysical testing measures the physical characteristics of an orebody.
- ▶ Geochemical testing determines the chemical composition of a sample.
- ▶ An open-pit (open cut or open cast) mine is an excavation made on the ground's surface to extract ore.
- ▶ The method of underground mining to be used is determined by the size, shape, orientation and type of orebody to be mined.
- ▶ The room-and-pillar method and the longwall method are used to mine horizontal ore bodies.
- ▶ The open-stoping method and the cut-and-fill method are used to mine vertical ore bodies.
- ▶ In onshore drilling, deep holes are drilled into the land surface.
- ▶ In offshore drilling, deep holes are drilled into the seabed.

5 CHAPTER REVIEW QUESTIONS



Review quiz

- 1 List five non-renewable resources mined by Aboriginal peoples and state what they were used for.
- 2 Provide evidence to support the claim that Aboriginal peoples were using sophisticated mining techniques to extract material from the earth.
- 3 Using one example, explain the relationship between the material mined and the geological setting of the deposit.
- 4 Referring to Figure 5.6 (page 114), list the minerals that occur in significant amounts in Australia.
- 5 Coal deposits are usually found in terrestrial sedimentary basins in Australia. Explain why.
- 6 Distinguish between black coal and brown coal.
- 7 What is the main use of coal in Australia? List five by-products of coal.
- 8 Explain why petroleum is considered a fossil fuel.
- 9 The mining industry generated export earnings of \$139 billion in 2010, \$195 billion in 2016 and \$248 billion in 2018. Plot this information as a line graph showing a line of best fit. Predict what the likely export earnings would be in each of the next five years if growth in mining exports is maintained.
- 10 A mining company has located a medium-sized gold deposit in outback Western Australia. There are no road or rail links nearby, and the international gold price has just tumbled to an all-time low. What advice would you give to the mine manager? Provide reasons for your advice.
- 11 Draw a flow chart to show the steps in conducting a mineral-exploration program from the use of remote sensing to mining.
- 12 Iron ore is mined using the open-pit method. What are the economic constraints that make this the most efficient method of mining iron ore?
- 13 Aluminium recycling is a very efficient way to reduce the amount of wasted materials going to landfill. Almost 85% of all aluminium is recycled. List other mined materials that could be recycled and suggest methods to encourage the public to recycle.
- 14 Evaluate the benefits of satellite remote sensing against other types of exploration methods.

- 15 Table 5.4 shows the sales by commodity of some of the leading minerals for the calendar years 2016 and 2017.

TABLE 5.4

COMMODITY	UNIT	CALENDAR YEAR 2016		CALENDAR YEAR 2017	
		QUANTITY	VALUE (\$B)	QUANTITY	VALUE (\$B)
Iron ore	000 t	769 278	55.16	794 937	62.91
Gold	000 kg	197	10.64	210	11.10
Alumina and Bauxite	000 t	13 922	4.59	14 600	5.88
Nickel	000 t	165	2.12	165	2.23

Table from 'Mineral sector highlights' from 'Latest Statistics Release', Government of Western Australia, Department of Mines, Industry Regulation and Safety, <http://www.dmp.wa.gov.au/About-Us-Careers/Latest-Statistics-Release-4081.aspx>

- a Calculate the percentage increase or decrease in quantity for each commodity from the 2016 calendar year to the 2017 calendar year.
 - b Calculate the percentage increase or decrease in value for each commodity from the 2016 calendar year to the 2017 calendar year.
 - c Which commodity had the largest percentage increase in quantity over the 2016 calendar year to the 2017 calendar year?
 - d Which commodity had the largest percentage increase in value over the 2016 calendar year to the 2017 calendar year?
- 16 Companies mining iron ore often negotiate contracts with customers for supplying the iron ore up to two years ahead of time. Describe the benefits of this type of contract to both the supplier and the buyer.
 - 17 An open-cut mine was developed to extract copper, lead and zinc from an orebody located in steeply dipping rocks. The mine closed due to poor export prices, but a new extension of the orebody was discovered below the open cut at a time of improving export prices. Design a strategy to convince the mine owners that the mineral resource is large enough to warrant mining and suggest the best method for mining it.
 - 18 a Use Google Maps to locate Cadia Hill Gold Mine and take a screenshot of the gold mine and surrounding area. See weblink.
b Use the screenshot of the Cadia Hill mine to identify the type of mining that you can see being carried out there. What features can you identify that make this an ideal mining site? (Refer to the factors on page 119 to assist with your answer.)



Cadia Hill Gold Mine

Cadia Hill mine is located about 20 km south-west of Orange, NSW.

Figure 12. 'WA mineral exploration spend by commodity p10, from Mineral and Petroleum Statistics Digest, 2016-2017, Government of Western Australia, Department of Mines Industry Regulation and Safety, http://www.dmp.wa.gov.au/Documents/About-Us-Careers/AboutUs-StatisticsDigest_2016-17.pdf

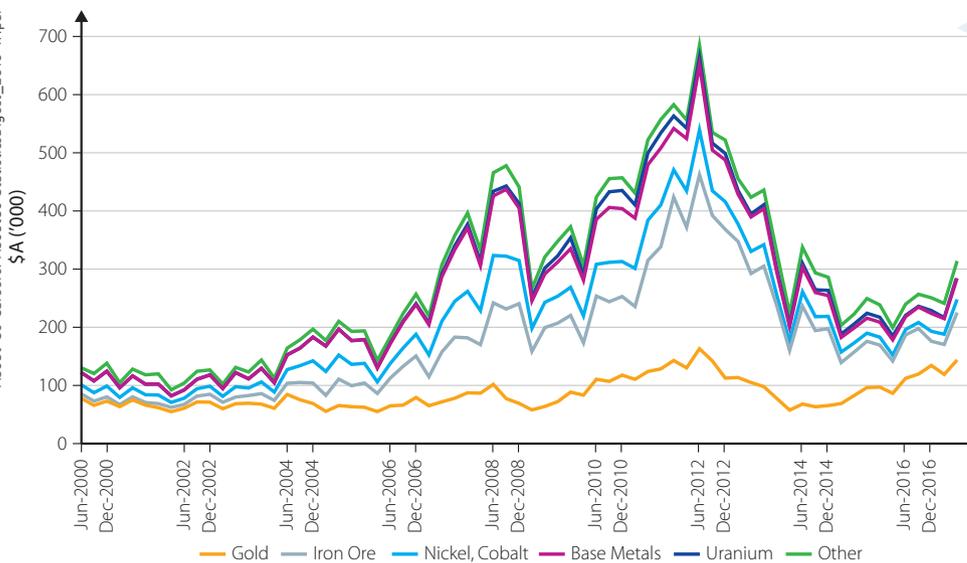


FIGURE 5.22
Western Australia
mineral exploration
spend by commodity

- 19** Figure 5.22 shows the expenditure on mineral exploration in Western Australia. Use the information provided in Figure 5.22 to answer the following.
- How much expenditure was there on iron ore exploration in December 2007?
 - When did gold exploration expenditure peak?
 - Which two commodities received the highest spend on exploration from June 2000 to June 2017?
- 20** Petroleum exploration licences have been granted to petroleum exploration companies for much of the coastline between Newcastle and Wollongong. Provide arguments both for and against the development of any petroleum reserves discovered along the central New South Wales coastline.
- 21** 'Fine finishing sand' is the name given to a type of quartz sand that is needed for concreting to produce a smooth surface. The major sources of fine finishing sand are quickly running out in New South Wales and Victoria. If an alternative source was located in a national park between Sydney and Melbourne, what ethical and economic considerations would need to be taken into account to either approve or reject a mining application in the park?
- 22** Between 1980 and 2000, mines in remote regions often had towns built alongside them to accommodate mine workers and their families. Since the early 2000s, mine workers are more likely to be 'fly-in, fly-out' (FIFO) than residents of a nearby town. Assess the effects on mine workers and their families involved in FIFO operations at a mine in central Australia.

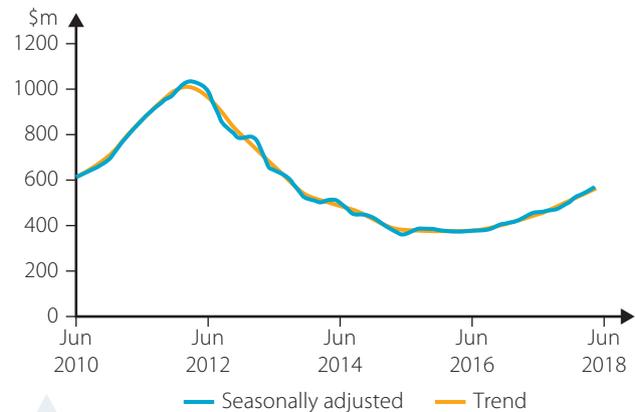
Answer the following questions.

- 1 The table shows the mineral composition of two igneous rock types.

ROCK NAME	Basalt	Dacite
MINERALS PRESENT	plagioclase feldspar	plagioclase feldspar
	pyroxene	pyroxene
	olivine	hornblende
	magnetite	biotite mica quartz
ROCK COLOUR	black	grey

- a What additional information is needed to identify the rocks as being extrusive or intrusive?
- b Explain how the presence of felsic minerals in dacite influences the colour of the rock.
- c Describe possible changes that might occur to these rocks if they were to be buried deep in Earth.
- 2 Soils change over time as the atmosphere, biosphere and hydrosphere act on mineral material.
- a Outline the nature of organic material found in a soil.
- b Describe a procedure you would use to measure a property of a soil horizon.
- c Assess the roles of water and time in the creation of a soil profile.
- 3 Corundum is an extremely hard mineral composed of aluminium and oxygen. It is used to make sandpaper for polishing and smoothing softer materials. It is also valued as a gemstone in the form of ruby and sapphire.
- a Describe two properties, other than hardness, that could be used to describe corundum.
- b Contrast how modern scientists and Aboriginal people might classify a mineral such as corundum.
- 4 Construct a table to compare Aboriginal mining methods with those currently used by mining companies in terms of the longevity of the resources and the disturbance of the environment.
- 5 Design an experiment that would allow you to distinguish between the following five rock types: pumice, grey granite, limestone, andesite and grey siltstone. Present your method as a flow chart.
- 6 Evaluate the economic benefits from continued mining and export of Australian fossil fuels. As part of your answer, consider coal from New South Wales and Queensland along with natural gas from Western Australia.

- 7 Refer to Figure EOM1.1.



8412.0 - Mineral and Petroleum Exploration, Australia, Sep 2018. Source: Australian Bureau of Statistics

FIGURE EOM1.1 Mineral exploration expenditure seasonally adjusted and trend

- a Calculate the percentage change in expenditure between June 2012 and June 2016.
- b Describe the trend in exploration expenditure from June 2016 to June 2018.
- c Evaluate the impact of the change in expenditure for future employment in the mineral exploration sector.
- 8 The use of ground-based geophysics, airborne geophysics and satellite-based geophysics has continued to expand over time. The set-up cost of each type of platform has also increased over time.
- Justify the continued investment in satellite-based geophysical systems in terms of area covered and benefit to exploration companies.
- 9 Identify a single type of mineral used to date materials that is commonly found in Earth's rocks, lunar rocks and some meteorites.
- a Which types of meteorites usually contain this mineral?
- b Describe the processes and methods that are used to separate the mineral from its host material and then determine its age.
- c List the range of ages commonly determined for Earth's rocks, lunar rocks and meteorites. Explain why these age ranges are different.
- 10 Fossils are usually found in sedimentary rocks but are also occasionally identified in sedimentary rocks that have been slightly metamorphosed at relatively low temperatures and pressures. Explain why fossils are found in these sedimentary materials but are not found in igneous rocks and high-temperature metamorphic rocks.

- 11** Physical and numerical models are often used to understand how geological processes and natural systems function.
- a** Describe a physical or numerical model that you used to investigate the evolution of a natural Earth system or geological process.
 - b** What was the purpose of the model and what did it help you understand?
 - c** What were the limitations of the model?

- 12** 'Absolute dating methods are more useful than relative dating methods.' Assess this statement and comment on its accuracy and usefulness.

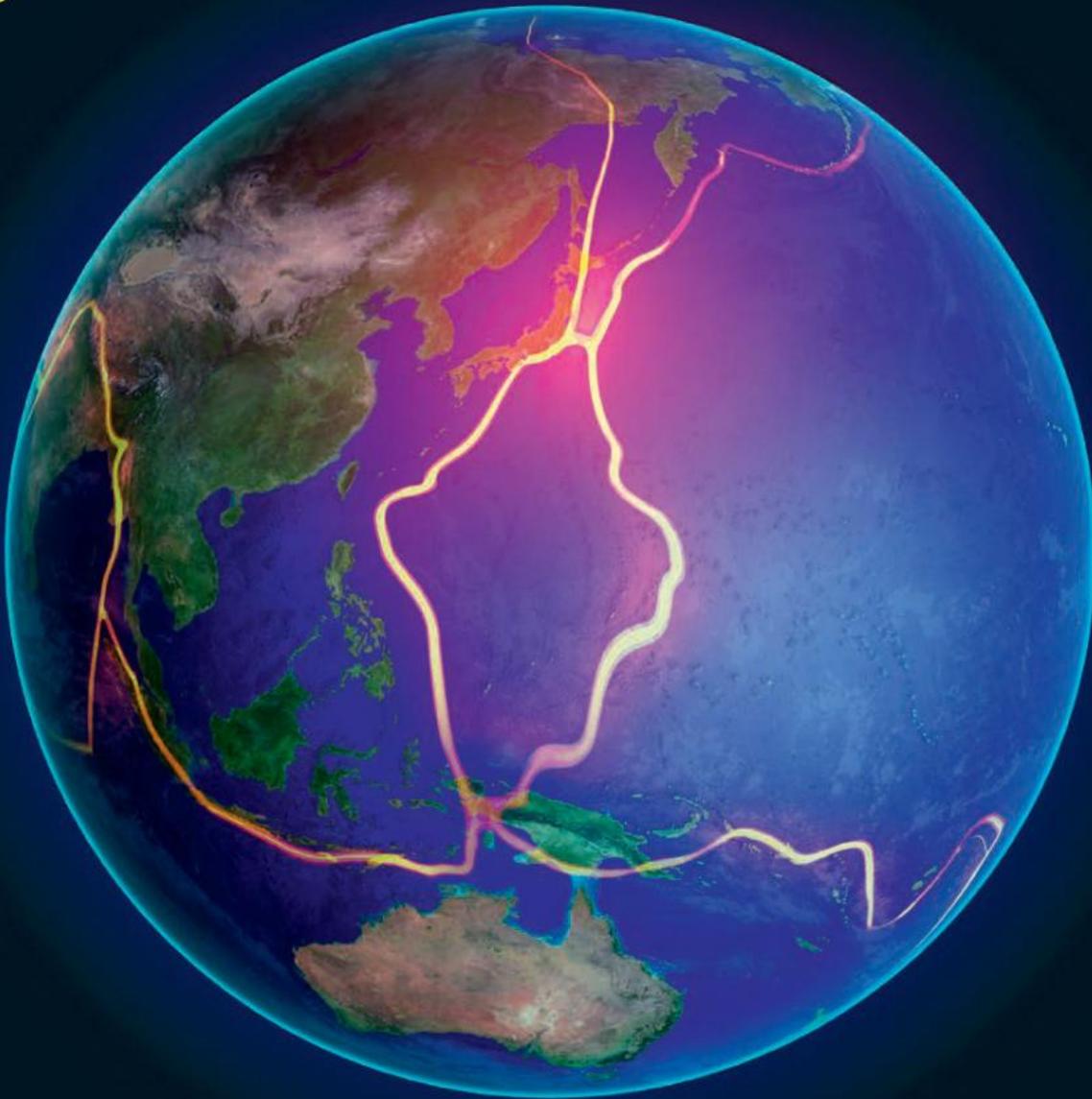
DEPTH STUDY SUGGESTIONS

- Build a simple static seismometer and monitor Earth's seismic events for two weeks.
- Investigate the age, composition and mineralogy of stony, iron and stony-iron meteorites and how this information is used to develop models of the formation of the solar system, including Earth.
- How is the distribution of soil types related to the geology or plant communities where you live?
- How are minerals used as indicators of temperature and pressure in metamorphic rocks?
- Explore the processes that cause rocks found in your area to weather.
- Trade in stone, ochre and tools was vital to the success of Aboriginal peoples in Australia. Investigate how the nature of stone tools provides information about Aboriginal culture and the history of Aboriginal peoples in Australia.
- Investigate the geochemical and geophysical techniques used to discover the Woodlawn base metal deposit.
- Investigate the geophysical and drilling methods used to discover the Roxby Downs copper/gold/uranium deposit.
- Coal is the major material mined in the Sydney region. Investigate the reasons why some of the coal mines are open cut and others are underground mines. Include the mining techniques used to extract the coal.
- Investigate the use of a particular group of fossils to subdivide a particular span of geological time; for example, subdivision of the Cenozoic eon using foraminifera or subdivision of the Cretaceous using ammonites.
- Investigate the dating of igneous rocks using whole-rock methods such as the potassium-argon method.

» MODULE TWO

PLATE TECTONICS

- 6 Theory of plate tectonics
- 7 Plate boundaries



6 Theory of plate tectonics

OUTCOMES

In this chapter you will learn about:

- the theory of plate tectonics
- how to analyse the different types of evidence that support the theory of plate tectonics, such as: [CCT ICT L](#)
 - the jigsaw shape of the continents
 - fossil locations
 - the shape of the ocean floor
 - magnetic reversals
 - sea-floor rocks
- the contributions of scientists to our understanding of the theory of plate tectonics, including: [CCT L](#)
 - Wegener
 - Holmes
 - Hess
 - Vine, Matthews, Wilson and McKenzie
 - Deep Sea Drilling Project Leg 3 – The *Glomar Challenger* scientists





At the beginning of the 20th century it was widely accepted that Earth had solidified from a molten mass and was gradually cooling down. Geologists based their explanations of large-scale geological events and processes on this fundamental concept. From it, they developed two models, **contractionism** and **permanentism**, to explain mountain building and other geological processes. Both models were based on the idea that Earth shrank and became smaller as it cooled down. As a consequence, rocks were folded, faulted and metamorphosed to form mountains.

Contractionists believed that the process of cooling and shrinking was constant throughout time. Mountain ridges and valleys formed like the wrinkles that appear on the skin of an apple as it gradually dries out (Figure 6.1). Permanentists believed that there had been rapid cooling early in Earth's history. High-standing continents had formed first, closely followed by subsidence of the areas between the continents to form the ocean basins. Then Earth shrank intermittently as the rate of cooling slowed. These occasional bursts of activity developed the compressional forces necessary to build mountains.

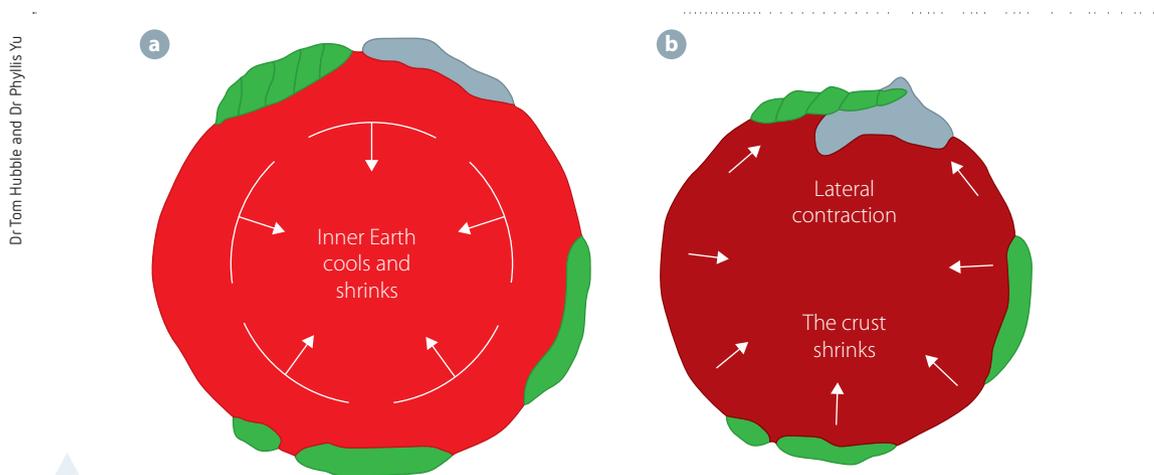


FIGURE 6.1 Stages of contractionism **a** Internal contraction **b** Crustal collapse and mountain building

Contractionism and permanentism fell out of favour when it was discovered that radioactive decay was heating Earth and maintaining its internal temperature. A new explanation, called **geosynclinal** theory, was developed, based on permanentism. During the first half of the 20th century this theory was used by geologists to explain mountain building and to interpret the geological features they examined and mapped in the field.

According to this model, geosynclinal sedimentary basins and mountain belts formed in three main stages. To begin, a large depression, the geosyncline, developed at the edges of the continents as a result of the cooling and subsidence of the adjacent ocean crust. Then the geosyncline filled with sediment eroded from the continent. Finally, the geosyncline became unstable and an episode of contraction and deformation occurred. This built a **fold belt** mountain range composed of folded and metamorphosed sedimentary rocks, as well as some of the oceanic crust that had subsided to form the geosyncline. Some of the sedimentary rocks at the base of the geosynclinal sequence melted to produce granites that intruded the rocks higher up in the fold belt.

Like contractionism and permanentism, geosynclinal theory accepted as fact that the geography of the continents and the oceans was fixed and unchanging through time. Until the 1970s, most geologists accepted without question that continents were stationary and stable on Earth's surface. The theory of plate tectonics changed this view completely.

6.1 Theory of plate tectonics

The theory of plate tectonics states that Earth's crust and brittle upper mantle are combined into a single rigid layer of material called the lithosphere. The lithosphere is divided into distinct segments called **plates** that move relative to each other.

There are two types of lithosphere: **oceanic lithosphere**, which is composed of oceanic crust and mantle, and **continental lithosphere**, which is composed of continental crust and upper mantle. There are seven large lithospheric plates and ten minor plates that are large enough to appear on maps of the globe as shown in Figure 6.2, and another fifteen or so much smaller plates. The largest of the major plates is the Pacific Plate, which is nearly entirely composed of oceanic lithosphere. The other large plates contain both oceanic and continental lithosphere and are named for the continents they transport as they move.

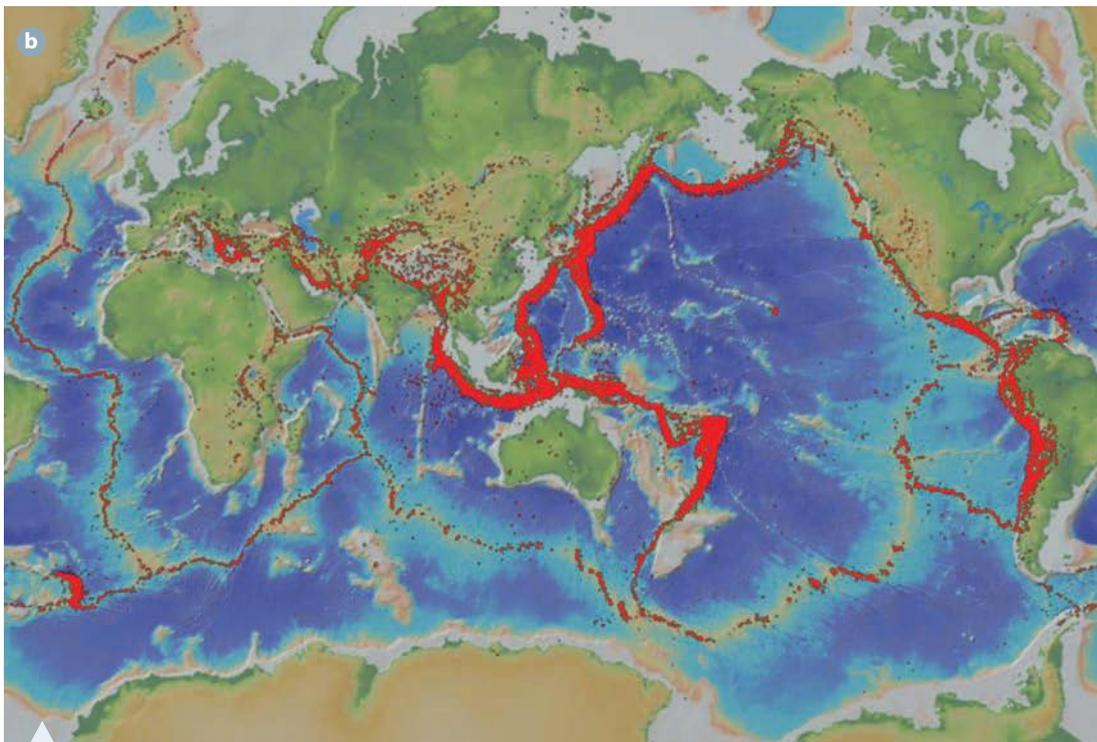
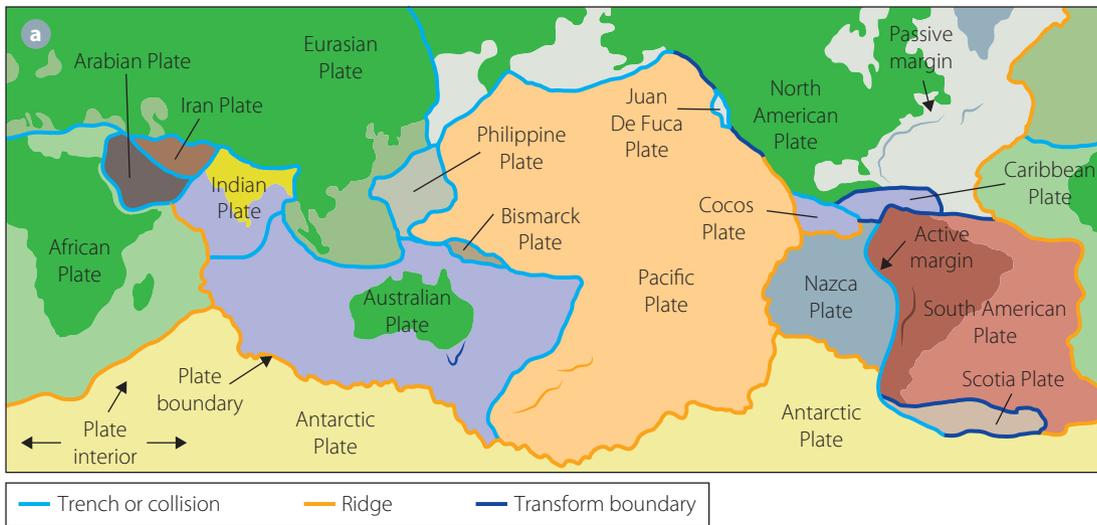


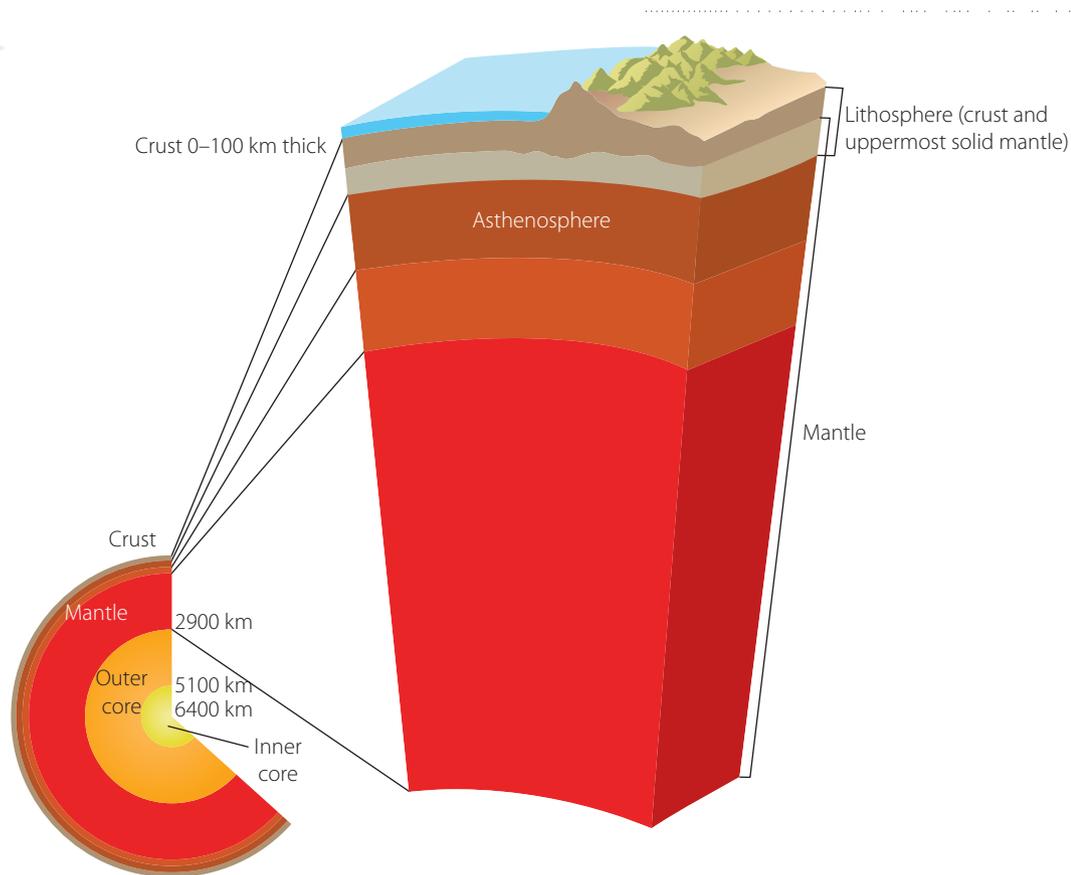
FIGURE 6.2 **a** The locations of the major and minor lithospheric plates **b** determined from distribution of earthquakes of magnitude 5 or greater from 1960 to 2018.

Maps generated using the Global Multi-Resolution Topography (GMRT) Synthesis. Ryan, W.B.F., S.M. Carbotte, J.O. Coplan, S. O'Hara, A. Melkonian, R. Arko, R.A. Weisse, V. Ferrini, A. Goodwillie, F. Nitsche, J. Bonczkowski, and R. Zensky (2009), Global Multi-Resolution Topography Synthesis, *Geochem. Geophys. Geosyst.*, 10, Q03014, doi:10.1029/2008GC002332. Reproduced with permission of GeoMapApp <http://www.geomapapp.org>.

Laser ranging experiments conducted in the 1970s and GPS measurements have shown that continents and the rigid lithospheric plates move very slowly around the surface of Earth, at 1–15 cm/year, floating on the **mantle** material beneath them. The layer of mantle beneath the plates is called the **asthenosphere** and it is denser and hotter than the lithospheric mantle. Figure 6.3 shows the dimensions of these layers.

In contrast to the rigid lithospheric plates, which are giant moving curved slabs, asthenospheric mantle flows. It behaves like a solid material instantaneously (seconds, hours and days) but it is soft and ductile. Although its velocity cannot be measured directly, modelling studies suggest that the speed of flow in the asthenosphere is 10–15 cm/year, about the same as the maximum speed a rigid plate can move. In some places the direction and speed of asthenospheric flow and the direction and speed of plate motion are thought to be similar. In other places it is thought that they are different. The relationship between plate motion, which can be measured, and asthenospheric flow, which can only be modelled, is one of the major unanswered questions of plate tectonics.

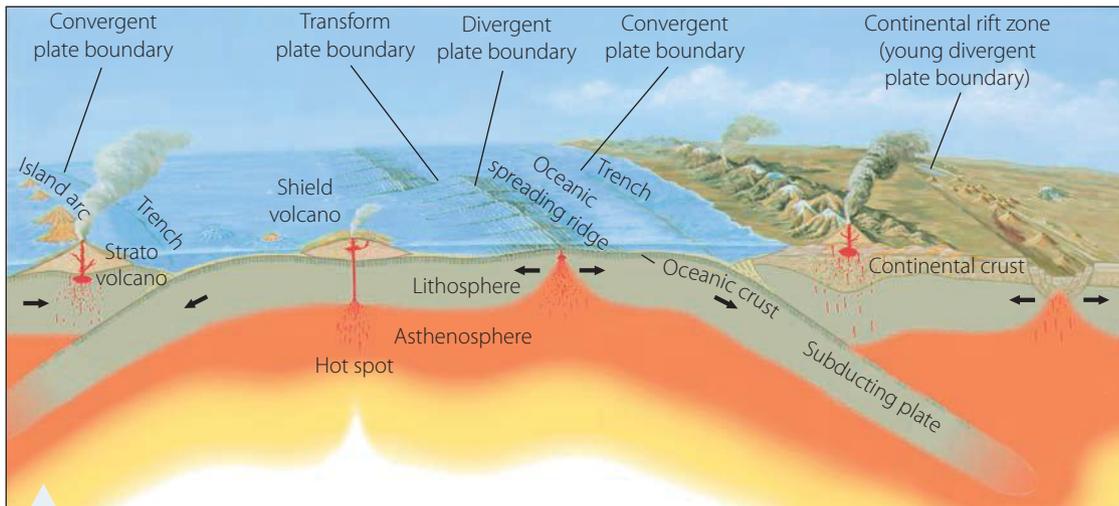
FIGURE 6.3
Dimensions of the upper layers of Earth



Relative motion between the lithospheric plates is concentrated at the plate boundaries. This motion generates earthquakes, the locations of which are used to identify the plate boundaries. The three types of boundaries between plates are described as divergent (where the plates are moving apart), convergent (where they are colliding) and transform or conservative (where the plates are moving past each other).

You will learn more about lithospheric plate motions and plate boundaries in Chapter 7.

New oceanic lithosphere is formed at **divergent** boundaries and is **subducted** at convergent boundaries, where it sinks beneath an overriding continental or oceanic plate (Figure 6.4). Over time, the amount of new oceanic lithosphere created at divergent boundaries is equal to the amount of lithosphere subducted at convergent boundaries. This keeps the system of lithospheric plates in balance as expected because the surface area and the mass of Earth must remain constant.



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

FIGURE 6.4 An overview of the plate tectonic system showing the creation of oceanic lithosphere at a divergent boundary and its subduction at a convergent boundary

KEY CONCEPTS

- The theory of plate tectonics states that Earth's crust and brittle upper mantle are combined into a single rigid layer of material called the lithosphere.
- The lithosphere is divided into plates.
- Oceanic lithosphere is composed of oceanic crust and mantle. Continental lithosphere is composed of continental crust and upper mantle.
- Oceanic and continental lithospheres are named for the continents they transport as they move.

- 1 What were the three early theories on how Earth was formed? What new theory completely replaced these older theories?
- 2 State the theory of plate tectonics.
- 3 What is a lithospheric plate?
- 4 How fast do lithospheric plates move?
- 5 How are the boundaries of the lithospheric plates identified?
- 6 Name the geological feature where oceanic lithosphere is formed.
- 7 Where are most transform faults found?
- 8 What is the name of the largest lithospheric plate and where is it located?
- 9 Most of the large plates are composed of two types of lithosphere. Name these two types of lithosphere and describe how they differ.

CHECK YOUR UNDERSTANDING

6.1

6.2 Evidence supporting plate tectonics

The theory of plate tectonics was developed as a collective effort during the 1960s. The starting point was the continental drift hypothesis, which had been proposed by Alfred Wegener in 1912. The supporting evidence was eventually gathered together, interpreted and presented by a large group of geologists and geophysicists over the next 50 years.

Library of Congress, Geography and Map Division.

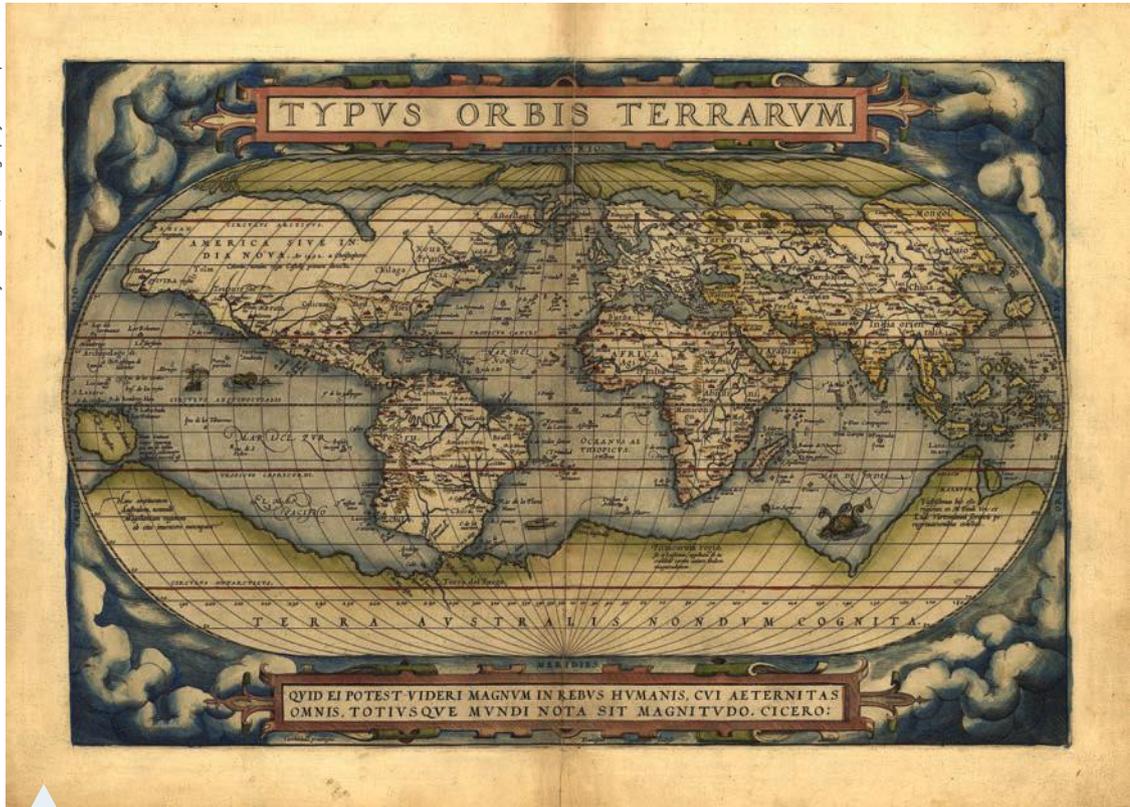


FIGURE 6.5 A map of the world published in 1570 by Abraham Ortelius

Jigsaw-like fit of continents

The possibility that continents might have been joined together at some point in the past has probably occurred to many people. It is not clear who first made this suggestion, but it was probably someone who looked at one of the first good maps of the Atlantic Ocean. These were published in the second half of the 16th century. Figure 6.5 shows one such example.

When you look at one of these old maps your eye is drawn to the coastlines of South America and Africa. This happens for two reasons. First, the maps are often drawn with these two continents at the centre. Second, the shapes of the two opposing coastlines seem to match each other. Examination of maps of the world is where the idea of the jigsaw-fit of the continents emerged.

Many people have investigated the apparent jigsaw-fit of the continental coastlines. It is quite easy to do. Cutting up a map and matching the shapes works well. Special globes that have movable magnetised continents work better. These are like a three-dimensional jigsaw puzzle.

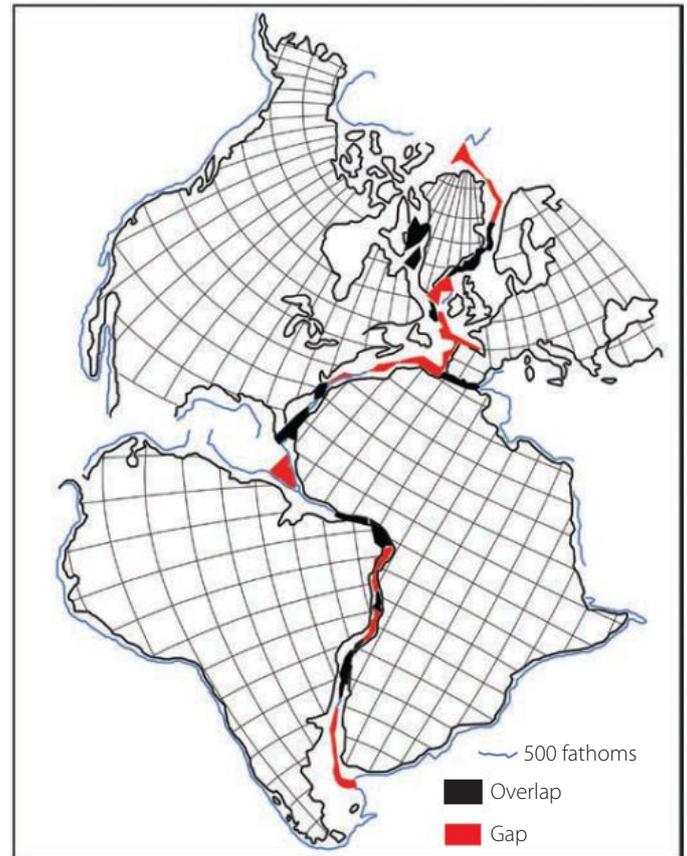
Figure 6.6 shows the jigsaw-fit reconstruction of the circum-Atlantic continents (North America, South America and Africa) that scientists used as evidence to support the theory of plate tectonics. It was published in 1965 by geophysicists working at Cambridge University.

The Cambridge jigsaw-fit reconstruction produces a very neat fit, but for this reconstruction to work convincingly you need to do two things. First, Iceland has to be removed because it just does not fit. Second, you have to decide where the edges of the continents are really located.

The Cambridge team decided that Iceland was a piece of a different jigsaw puzzle that had got mixed in with the puzzle they were trying to solve. It was assumed that Iceland was a high-standing part of the Atlantic Ocean sea floor because it is composed of young basalts that are only one million years old, whereas the rocks located at the edges of continents were known to be hundreds of millions of years old. This meant it was reasonable to take Iceland out of the reconstruction and it removed the need to fit Iceland into the puzzle.

Continents are surrounded by extensive regions of submerged continental crust. We call these shallow areas of ocean **continental shelves**. The 1000m ocean depth contour locates the seaward limit of the continental shelves and the Cambridge team used this to represent each continent's edge.

Using the present-day coastlines instead of the 1000m ocean depth contour gives a less convincing fit because the gaps and the areas of overlap between the continents are much greater. Fitting the continents together like jigsaw pieces is a tool that geologists and geophysicists use routinely to model changes in Earth's surface over geological time.



Jacques Kornprobst (redesigned after Bullard, E., Everett, J.E. and Smith, A.G., 1965, The fit of the continents around the Atlantic. *Phil. Trans. Royal Soc.*, A 258, 1088, 41–51). Creative Commons Attribution-Share Alike 4.0 International license, https://commons.wikimedia.org/wiki/File:Bullard%27s_fit.jpg.

FIGURE 6.6 The 1965 Cambridge jigsaw-fit reconstruction of the circum-Atlantic continents

Fossil evidence

If continents really had been joined together as neatly as the jigsaw-fit reconstructions indicated, this meant that at some time in the past the oceans that separate them had not existed. The Atlantic Ocean was not there when South America and Africa were joined together (Figure 6.7). The distance between Rio de Janeiro in Brazil in South America and Luanda in Africa would have been a short 200 km day-trip by car rather than the 6200 km two-week sea journey it is today. Large land animals could have walked from Rio to Luanda in a week.

One way to support the idea that South America and Africa had been joined in the past was to identify fossils of animals and plants that had lived in the places where the continents had once been joined together. When the continents drifted apart the animals and plants were isolated onto separate continents as shown in Figure 6.8.

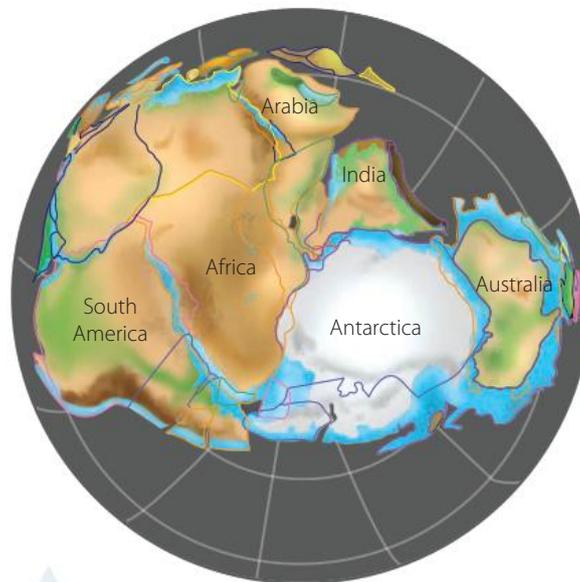


FIGURE 6.7 Plates jigsaw-fit reconstruction for Gondwana, 420 million years ago



Global plate reconstruction

Play the animation of moving plates from Late Proterozoic to present.

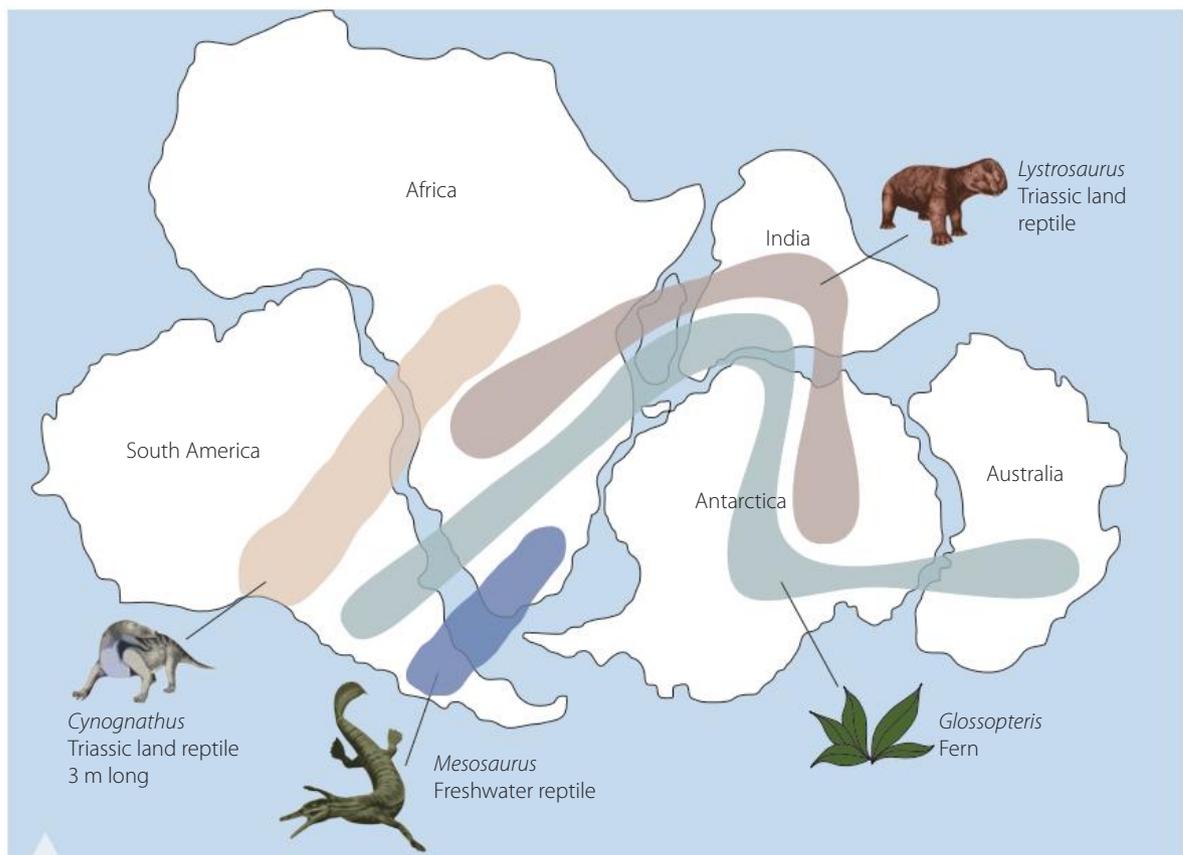


FIGURE 6.8 The ranges of *Cynognathus*, *Mesosaurus*, *Lystrosaurus* and *Glossopteris* in the Permian and/or the Triassic

Mesosaurus was a freshwater reptile that lived in the Permian Period. Fossils of *Mesosaurus* have been found in both South America and Africa. *Glossopteris* was a fern that was found extensively throughout the southern supercontinent of Gondwana during the Permian and the Triassic. *Cynognathus* was a terrestrial reptile that also lived in the Triassic Period and its fossils have a **range** that extends from South America and Africa into Antarctica. *Lystrosaurus* was another terrestrial reptile that lived in the Triassic Period and its fossils have been found in Africa, India and Antarctica.

The presence of fossils of the same species on both sides of the jigsaw join between two continents can be used as supporting evidence for the theory of plate tectonics. The evidence is particularly useful if the species ranged over a relatively restricted geographic area.

If the locations where fossils of the animals *Cynognathus*, *Mesosaurus* and *Lystrosaurus* and the plant *Glossopteris* are found are drawn onto a map of joined continents, the boundaries of the areas where these animals and plants lived during the Permian and Triassic Periods cross the matching continental coastlines in exactly the right places.

The occurrence of the two terrestrial reptiles *Lystrosaurus* and *Cynognathus* in Antarctica is considered by many people to be the best fossil evidence supporting the jigsaw-fit of the continents and the theory of plate tectonics. This is because Antarctica is now completely isolated from the other continents by the vast Southern Ocean. It is difficult to argue that these large animals swam across the Southern Ocean. It is also difficult to accept the idea that pairs of young male and female animals travelled to, or from, Antarctica as passengers on floating logs. Terrestrial animals walk. If the continents were joined in the way that the jigsaw-fit reconstructions suggest, then it would have been easy for *Cynognathus* and *Lystrosaurus* to have walked to Antarctica from Africa, South America or India (Figure 6.9). This makes much more sense.

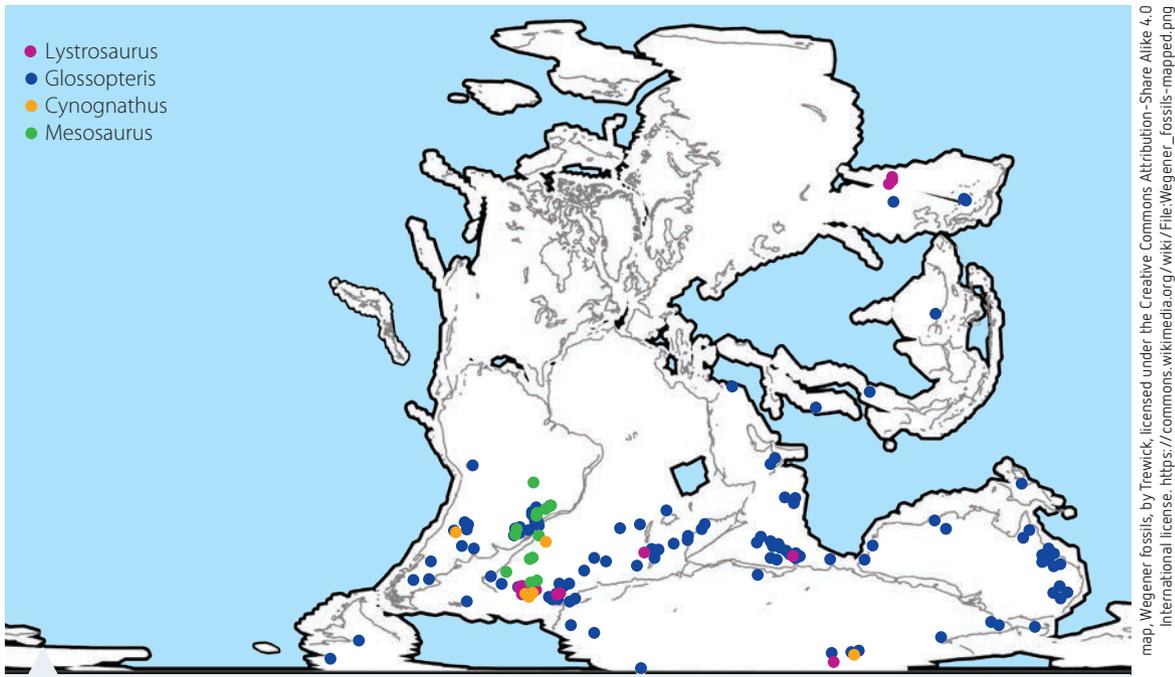


FIGURE 6.9 Permian and Triassic age fossil localities on a jigsaw-fit reconstruction of the continents

Apart from fossil evidence, other geological features should appear when the continental jigsaw is put together. Boundaries between different major rock sequences should cross one coast and line up with a similar boundary on the matching coast. The rock types should match up as well. Geological structures such as mountain belts should cross the coasts and appear aligned on both continents. Figure 6.10 shows that geological boundaries match across continental borders.

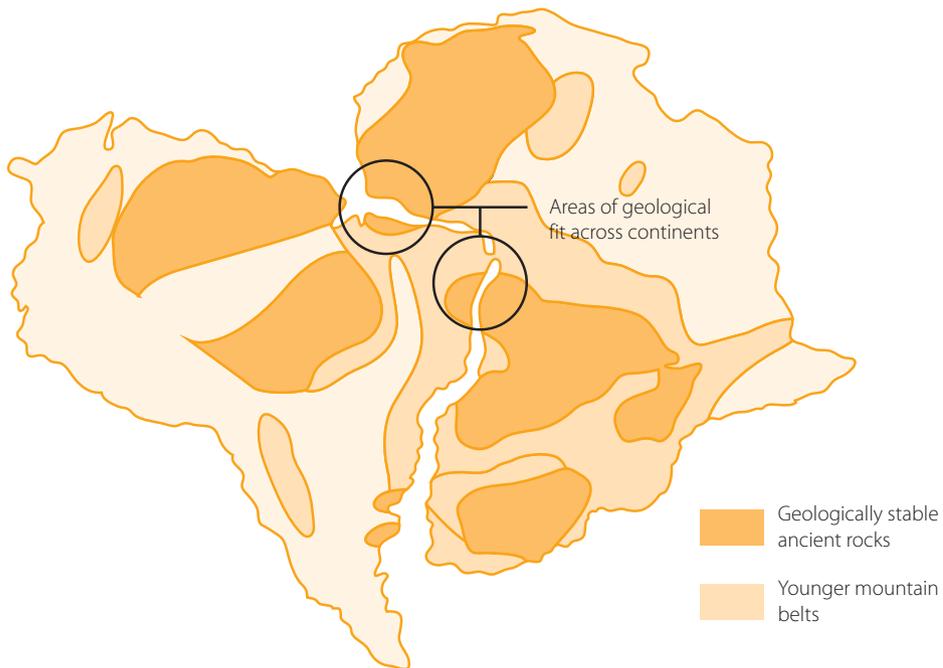


FIGURE 6.10 Aligned geological boundaries of matching coastlines of South America and Africa

INVESTIGATION 6.1

Analysing the evidence: jigsaw-fit

Critical and creative thinking

Information and communication technology capability

Literacy



MATERIALS

- Blank sheet of A4 paper
- Scissors
- Glue
- 6 different coloured highlighters or pencils
- Printout of Worksheet Investigation 6.1 material

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?

Scissors are sharp and will cause injury or damage if used inappropriately.

HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

Always cut with the scissors pointing away from yourself and other people.

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

METHOD

- 1 Carefully and accurately cut around each of the continents on the Worksheet Investigation 6.1 material and place them separately on your table.
- 2 Use printed and online sources to find the range of each of the fossil plants or animals shown.
- 3 Carefully cut out the drawings of the fossils. Show where each animal or plant lived by gluing a picture into the correct place on the correct continent. Print out another copy of the worksheet if you require more pictures of fossils.
- 4 Move the continents into position to show how geologists thought they were arranged before they split apart.

RESULTS

Glue your arrangement onto the sheet of blank A4 paper. Use different coloured highlighters or pencils to show the range of each animal or plant.

ANALYSIS OF RESULTS

- 1 Did the continents fit together easily to form one large land mass?
- 2 When you put the continents together, did the ranges of any animals or plants overlap continents? Which plants or animals and which continents?
- 3 Use your answers from questions 1 and 2 as evidence to formulate an answer to the question: were the continents once joined into one large landmass?
- 4 Can you think of an alternative explanation for what you have discovered in this investigation? What is that explanation?

CONCLUSION

Summarise the evidence that supports the theory that the continents were once joined.



Investigation 6.1 material

KEY CONCEPTS

- The theory of plate tectonics is supported by many different sets of evidence, including:
 - the jigsaw-fit of the continents
 - the location of large, extinct, terrestrial animals on several continents that are now separated by oceans
 - geological boundaries that match across continental borders.

- 1 Imagine you looked at a map of the world in the late 1500s. What evidence would you see to suggest that the continents were once joined?
- 2 What evidence is there to suggest that science is a collaborative task rather than one undertaken by a single researcher?
- 3 What assumptions need to be made in order for the Cambridge jigsaw-fit reconstruction to work? Are these assumptions reasonable?
- 4 Provide the most plausible explanation of why fossils of *Mesosaurus* are found in both present-day Africa and South America.
- 5 Explain how matching rock types between the coasts of Africa and South America provide evidence for the theory of plate tectonics.

The shape of the sea floor

Sailors, cartographers and naturalists have been investigating the geography of the oceans and the shape of the sea floor for thousands of years. The ancient Greeks and Romans used sounding poles and lead-weighted ropes to determine water depths in their harbours. These techniques were used for millennia until they were eventually superseded by the single-beam **echo sounder** in the 1920s.

Today, ocean depths are measured and mapped with sophisticated multibeam echo sounders, lidar and satellite measurements of Earth's gravitational field. As the available techniques have improved, cartographers have produced progressively better and more detailed maps of the sea floor.

The study of the shape of the sea floor is called **bathymetry** and maps of the sea floor are called **bathymetric maps**. These maps show that areas of the sea floor have distinctly different shapes. Most of the sea floor is flat and smooth but there are other types, each a product of plate tectonic processes.

The major types of sea floor that geologists have identified as providing evidence for plate tectonics can be seen on global maps of the sea floor such as Figure 6.11 – mid-ocean ridges, abyssal plains, deep-ocean trenches and chains of hotspot volcanoes.

The studies of the shape of the sea floor indicated to marine geologists that Earth's oceans were probably geologically active and much younger than previously thought. This contradicted both the contractionist and geosynclinal geological theories, which stated that the oceans were ancient, permanent, unchanging and geologically inactive.

Mid-ocean ridges

Maps of the Atlantic Ocean's sea floor show that it is dominated by its high-standing, symmetrical **mid-ocean ridge**, which is surrounded by flat areas of sea floor called **abyssal plains**. The **Mid-Atlantic Ridge** is located halfway between North America and Europe in the North Atlantic and halfway between South America and Africa in the South Atlantic. These facts puzzled the marine geologists who first mapped it. Iceland is a part of the Mid-Atlantic Ridge that is elevated above sea level. Geological studies of Iceland's basalts determined that they were very young rocks, less than six million years old.

Mid-ocean ridges are broad, wide features with relatively gentle slopes. They usually occupy ocean depths above 4000 m. In Figure 6.12, the Mid-Atlantic Ridge occupies the light blue area on the map. The crest of the ridge is shown by the thin brown line in the middle of the blue area and it mostly occurs at depths between 1500 m and 2000 m.

Oceanic lithosphere is formed at mid-ocean ridges as two plates move apart. Abyssal plain sea floor is usually smoother and deeper the further it is located away from the mid-ocean ridges.

Mid-ocean ridges are also present in the other oceans. On maps such as Figure 6.11 they also occupy the light blue areas and have light brown coloured crests. The light-brown trace of the Mid-Atlantic Ridge takes a sharp bend to the east at its southern end, and then winds its way through the Indian Ocean to the Southern Ocean, where it is located halfway between Australia and Antarctica. Just to the south of New Zealand, the mid-ocean ridge takes a bend to the north and heads towards Central America.

Maps generated using the Global Multi-Resolution Topography (GMRT) Synthesis. Ryan, W.B.F., S.M. Carbotte, J.O. Coplan, S. O'Hara, A. Melkonian, R. Arko, R.A. Weisse, V. Ferrini, A. Goodville, F. Nitsche, J. Bonczkowski, and R. Ziemsky (2009), Global Multi-Resolution Topography Synthesis, *Geochern. Geophys. Geosyst.*, 10, Q03014, doi:10.1029/2008GC002332. Reproduced with permission of GeoMapApp <http://www.geomapapp.org>.

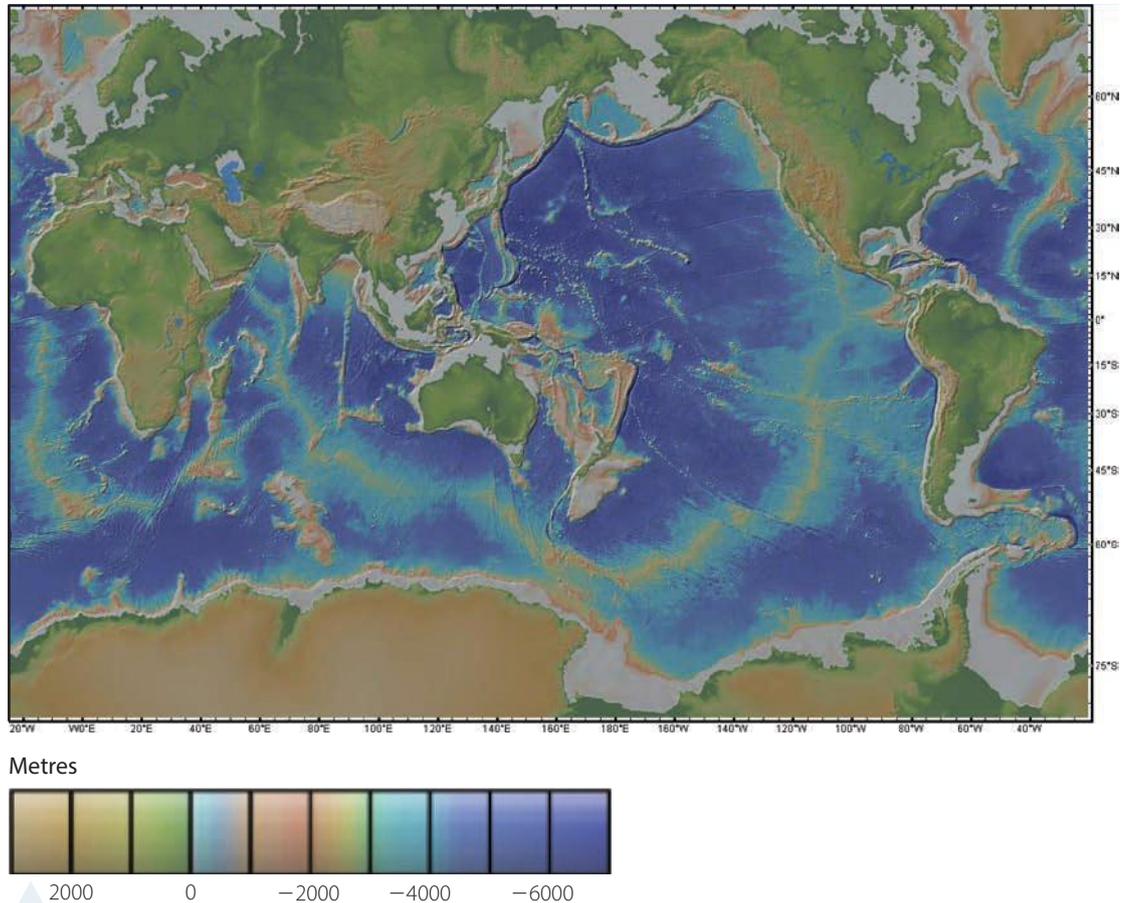


FIGURE 6.11 Colour-coded map showing the topography of the continents and depth of the oceans

You will learn more about transform faults in Chapter 7.

Other sea-floor features related to mid-ocean ridges are transform fault fracture zones, which divide the mid-ocean ridges into segments. A **transform fault** enables two plates to slide past each other. Large displacement transform faults are obvious in the detailed bathymetric map shown in Figure 6.12a. Other large transform faults that divide the mid-ocean ridge in the south-east Pacific are clearly visible in Figure 6.11. This ridge is called the East Pacific Rise.

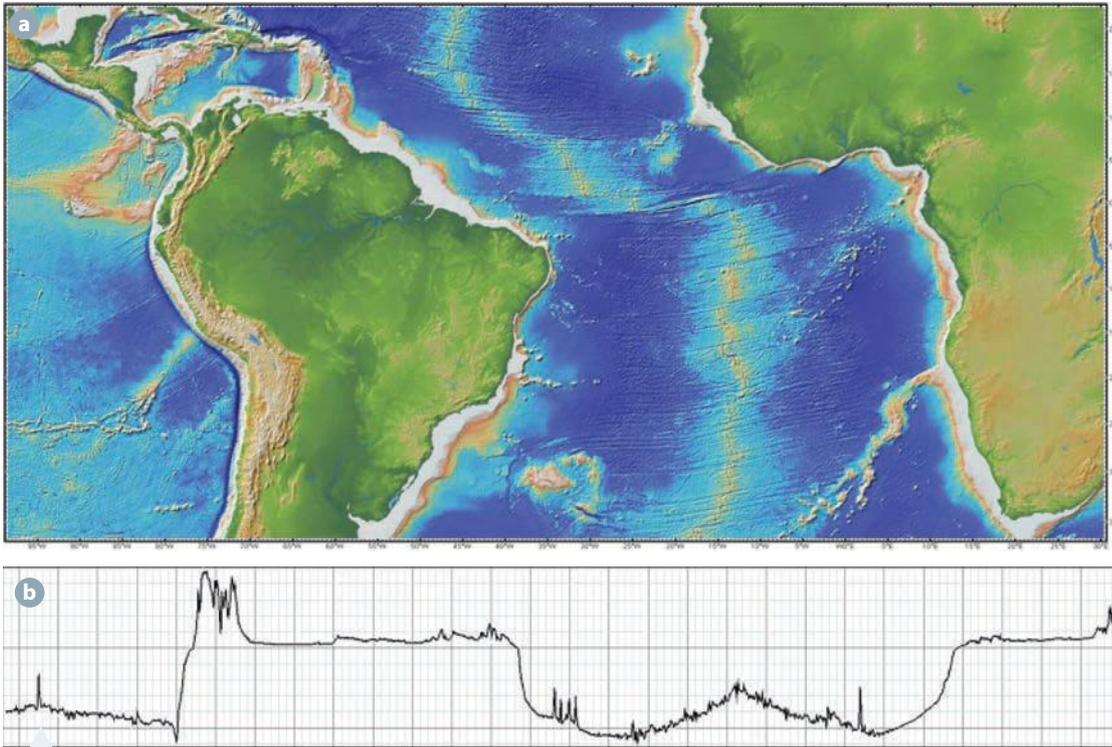
Abyssal plains

The large dark blue areas on the maps presented in Figures 6.11 and 6.12 are abyssal plains. These are flat areas of sea floor 4000–6000m deep and are smooth because thick deposits of sediment have been deposited above the basalts of the ocean lithospheric plate. The presence of these sediment layers indicates that the abyssal plain sea floor is older than the young basalts erupted at mid-ocean ridges. Abyssal plains occupy about 50% of Earth's total surface area.

Deep-ocean trenches

The Pacific Ocean has a mid-ocean ridge system with a pair of related abyssal plains, but its ridge is located on the eastern side of the Pacific Ocean, not in the middle of the ocean. It is called the East Pacific Rise. Its abyssal plain sea floor stretches out and away from the ridge and eventually merges with **deep-ocean trenches**.

The Pacific's deep-ocean trenches are located around the western, northern and eastern rim of the Pacific Ocean, just seaward of main land masses and groups of islands. The main trenches are the Tonga Trench, the Mariana Trench, the Bonin Trench, the Philippines Trench, the Japan Trench, the Aleutian Trench and the Andes Trench. There is another major trench located just to the south of the Indonesian Islands. The locations of the major trenches are shown in Figure 6.13.

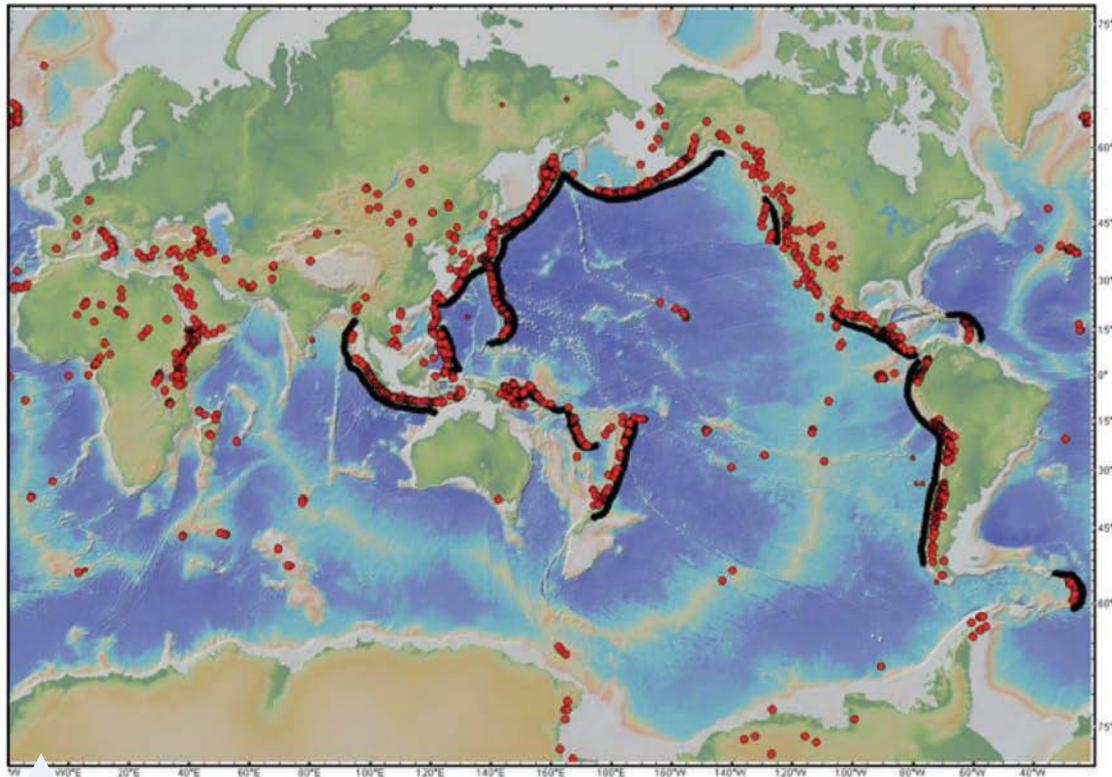


Maps generated using the Global Multi-Resolution Topography (GMRT) Synthesis. Ryan, W.B.F., S.M. Carbotte, J.O. Coplan, S. O'Hara, A. Melkonian, R. Akko, R.A. Weisseil, V. Ferrini, A. Goodwillie, F. Nitsche, J. Bonczkowski, and R. Zernsky (2009), Global Multi-Resolution Topography synthesis, *Geochem. Geophys. Geosyst.*, 10, Q03014, doi:10.1029/2008GC002332. Reproduced with permission of GeoMapApp <http://www.geomapp.org>.

FIGURE 6.12 **a** Bathymetric map and **b** profile of the South Atlantic and Western Pacific oceans

Trenches are unusually deep areas of the sea floor, between 6000–11000m deep. While they are usually several thousand kilometres long, they are quite narrow and are generally only 100–200km wide. They occur where oceanic lithosphere descends back down into the mantle and is subducted. The subduction zones are linked to the formation of explosive subduction zone volcanoes.

You will learn more about subduction zone volcanoes in Chapter 7.



Maps generated using the Global Multi-Resolution Topography (GMRT) Synthesis. Ryan, W.B.F., S.M. Carbotte, J.O. Coplan, S. O'Hara, A. Melkonian, R. Akko, R.A. Weisseil, V. Ferrini, A. Goodwillie, F. Nitsche, J. Bonczkowski, and R. Zernsky (2009), Global Multi-Resolution Topography synthesis, *Geochem. Geophys. Geosyst.*, 10, Q03014, doi:10.1029/2008GC002332. Reproduced with permission of GeoMapApp <http://www.geomapp.org>.

FIGURE 6.13 Locations of the deep-ocean trenches (black lines) and active volcanoes (red circles)

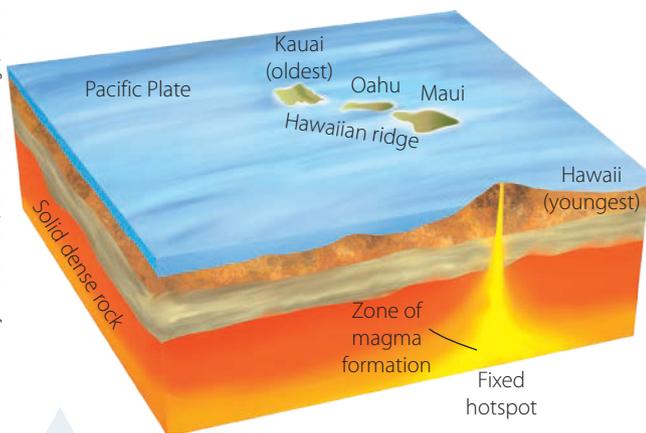


FIGURE 6.14 The formation of the Hawaiian chain of hotspot volcanoes. The current speed and direction of motion of the Pacific Plate can be calculated using the age differences and distances between the volcanoes.

Hotspot volcanoes

Chains of oceanic volcanoes such as the Hawaiian Islands are studied by geologists for information about the motions of the lithospheric plates. These volcanoes usually erupt basalts and form above stationary areas of unusually hot mantle called **hotspots**. As the plate moves over the stationary hotspot, new volcanoes form, as illustrated in Figure 6.14. This creates a line of progressively younger volcanoes known as **hotspot volcanoes**.

The speed of the lithospheric plate can be determined from the distance between the volcanoes and the ages of the volcanoes. Chains of hotspot volcanoes are found in all the oceans. They confirm that the lithospheric plates are moving as rigid segments of crust and mantle as predicted by the theory of plate tectonics.

Magnetic striping of sea-floor basalts

Marine geologists and geophysicists were making special magnetic maps of the sea floor during the 1950s and 1960s, using magnetometers that had been designed for detecting submarines. The maps were intended to help naval submarine hunters locate enemy submarines.

The geologists' investigations showed that the oceanic lithosphere presents a distinctive pattern of magnetic stripes that are oriented parallel to the mid-ocean ridges. A startling characteristic of these magnetic stripes is that the pattern they make on a map is symmetrical about the mid-ocean ridges.

At the time the magnetic maps of the sea floor were being made, it was already known that igneous rocks record the polarity and strength of Earth's magnetic field at the time they are formed. This is because they contain crystals of the iron oxide mineral magnetite. Basalts often contain 1–2% by weight of magnetite so their remnant magnetic fields can be measured easily. Granites contain about 0.2% magnetite. In both these types of rock, small domains within these magnetite crystals align with Earth's magnetic field as the rock cools.

Basalts are erupted onto the ocean floor at the mid-ocean ridges as part of the process that forms oceanic lithosphere, forming the upper layer of the new material. Magnetite in the basalts records how the strength and orientation of Earth's magnetic field has changed as oceanic lithosphere forms and moves away from the mid-ocean ridges (Figure 6.17). This means that the age of the sea floor can be determined from magnetic profiles. Geologists on land were able to confirm the timing of reversals of the magnetic field by dating basalt samples taken from volcanic chains such as the Hawaiian Islands.

Geophysicists have produced a magnetic timescale going back several hundred millions of years from their studies. The method they use to depict the magnetic field reversals looks similar to barcodes; periods of positive polarisation are often colour-coded according to their age, while the periods of reversed polarisation remain white (Figure 6.15).

The polarity of Earth's magnetic field swaps between two states, called normal polarity and reversed polarity. Normal polarity is the present-day orientation of the magnetic field. In reverse polarity, Earth's magnetic field reconfigures and inverts. If Earth's magnetic field is represented by a giant bar magnet located in the core, the process of inversion can be thought of as the bar magnet turning upside down (Figure 6.16). This means that in a period of reversed polarity, the north end of a compass needle would point towards the south pole. Magnetic field polarity reversals occur irregularly over time. Sometimes Earth's magnetic field is stable for tens of millions of years, and sometimes it flip-flops and inverts every half-million years or so.

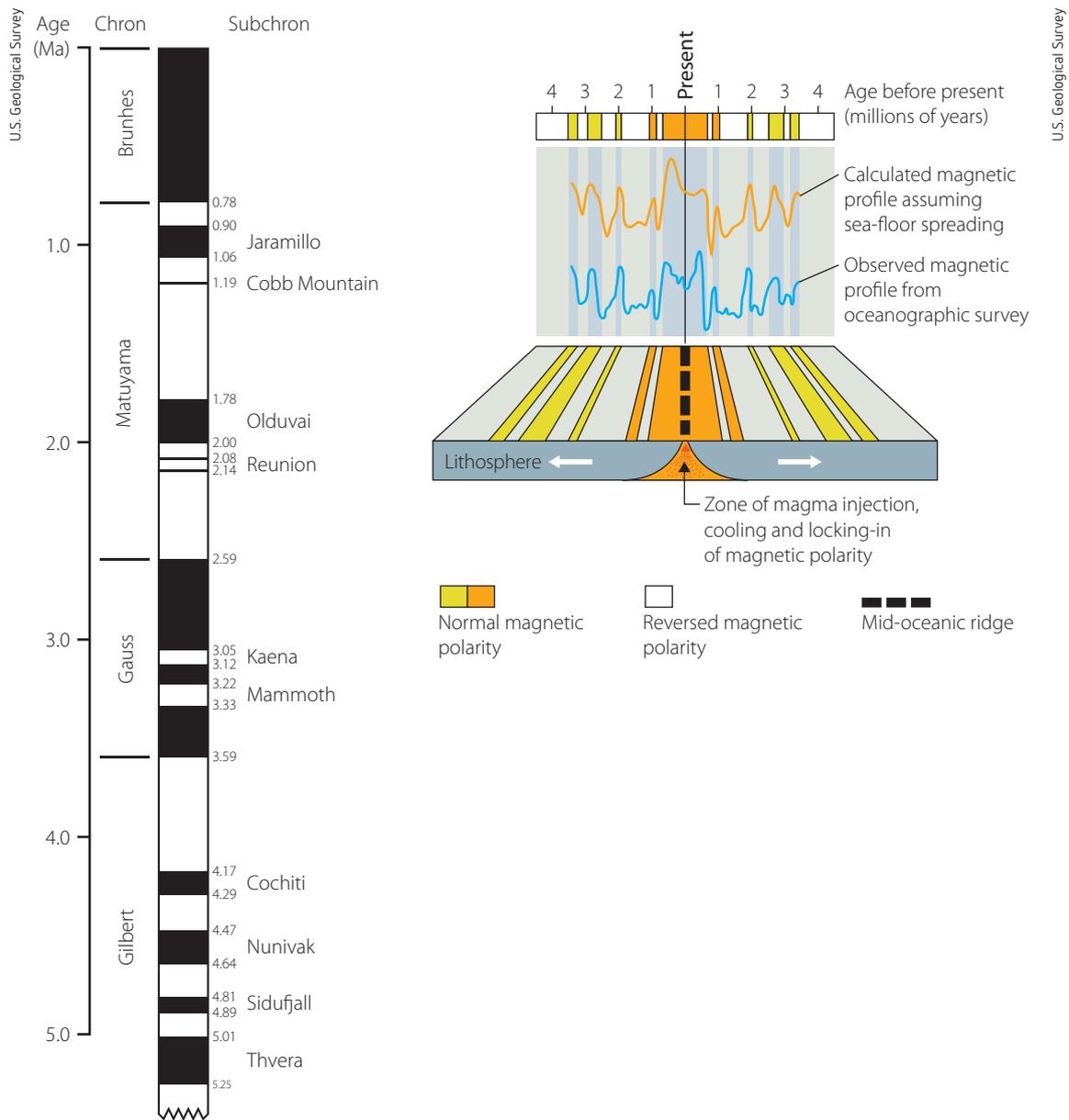


FIGURE 6.15 Examples of magnetic timescales

Detailed magnetic profile and polarisation maps such as Figure 6.18 show that the age of the sea floor increases away from the crest of the mid-ocean ridges. This is one of the most convincing pieces of evidence for the theory of plate tectonics.

The map also shows that the age of the sea floor in any particular location corresponds closely with the bathymetry of the sea floor. This means that the shape of the sea floor also corresponds with its age. The youngest sea floor corresponds with the location of the mid-ocean ridge crests and the deep abyssal plains are composed of the oldest sea floor. This is because the lithospheric plates sink slightly as they age, cool and become denser.

The sea-floor age maps also show a large number of slightly curved boundaries that divide the sea floor into strips. These strips are oriented roughly perpendicular to the ridge axes; the curves correspond exactly with the locations of the transform faults evident in the bathymetric maps that divide the ridge crests up into segments.

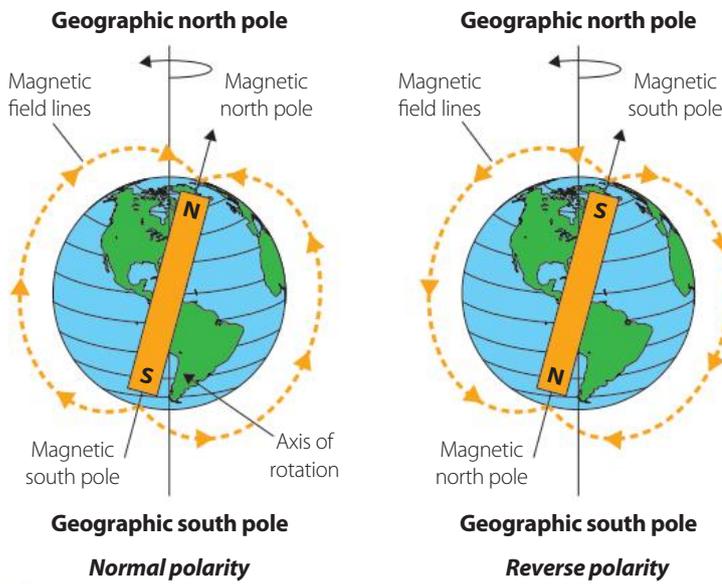


FIGURE 6.16 Polarity reversals of Earth's magnetic field represented by inversions of a bar magnet

From BROWN / DUNNING, BROWN IN-TERRA-ACTIVE WEST'S PHYSICAL GEOLOGY INTERACTIVE CD, 1E. © 1990 Cengage.

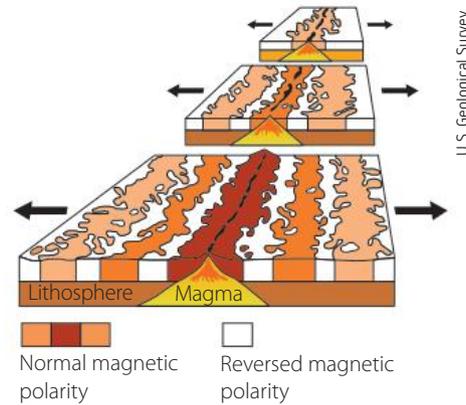


FIGURE 6.17 Magnetic striping of the sea floor reflects the polarity of Earth's magnetic field at the time when the rocks were formed.

Maps generated using the Global Multi-Resolution Topography (GMRT) Synthesis. Ryan, W.B.F., S.M. Carbotte, J.D. Coplan, S. O'Hara, A. Meikoniian, R. Arko, R.A. Weiszel, V. Ferrini, A. Goodwillie, F. Nitsche, J. Bonczkowski, and R. Zemsky (2009), Global Multi-Resolution Topography synthesis, *Geochern. Geosyst.*, 10, Q03014, doi:10.1029/2008GC002332. Reproduced with permission of GeoMapApp <http://www.geomapp.org>.

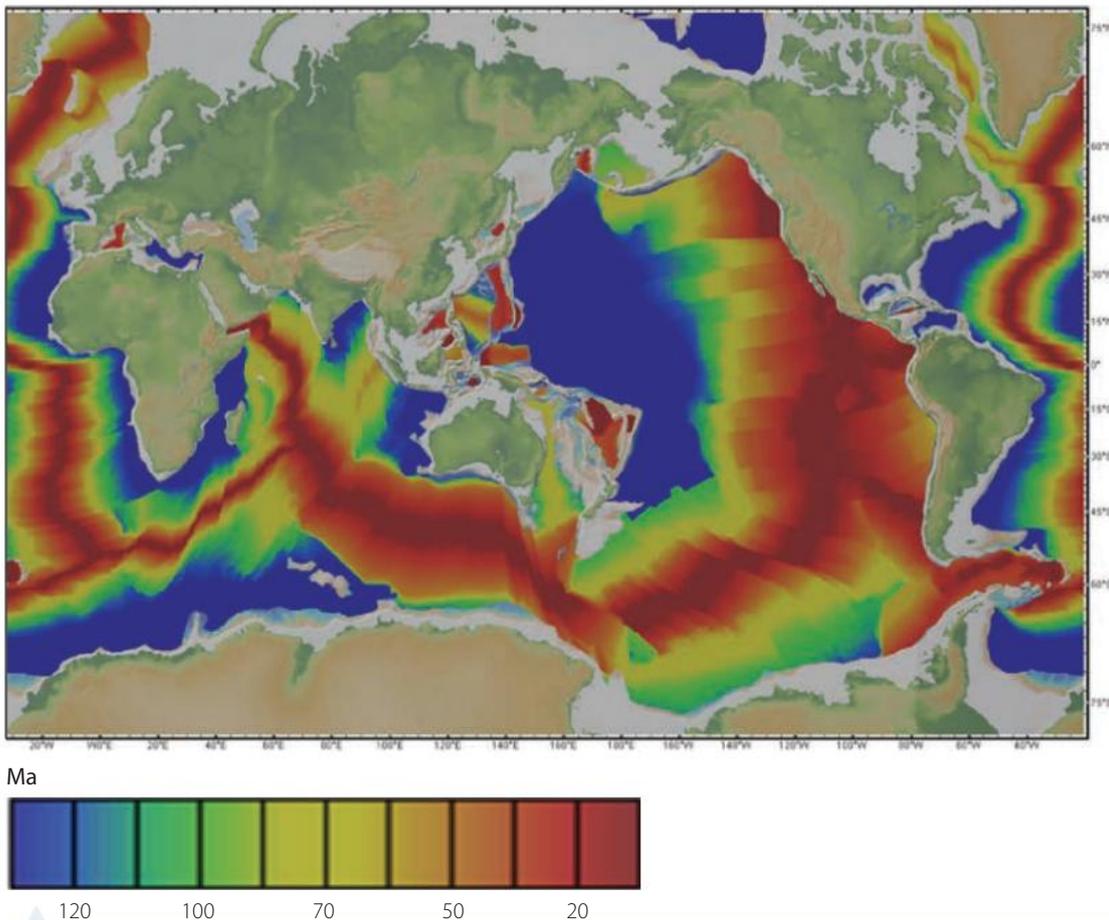


FIGURE 6.18 Sea floor age distribution as determined from remnant magnetism

INVESTIGATION 6.2

Modelling sea-floor spreading and magnetic reversal

INTRODUCTION

New sea floor is created at mid-ocean ridges and destroyed at subduction zones. This keeps the amount of crust almost constant and shows that Earth is experiencing constant change.

AIM

To model sea-floor spreading and magnetic reversals

MATERIALS

- 2 sheets of A4 paper
- Ruler
- 2 coloured pencils
- Scissors
- Transparent tape
- Masking tape
- Digital camera

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Scissors are sharp and will cause injury or damage if used inappropriately.	Always cut with the scissors pointing away from yourself and other people.



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

METHOD

- Using one piece of A4 paper, create the template shown in Figure 6.19. Use the scissors to cut along the three heavy lines.
- Reinforce the cut slits by placing masking tape along each side.
- Using the second piece of paper, draw 11 bands parallel to the short side, each 2.5 cm wide.
- Choose two coloured pencils. One colour represents normal polarity and the other represents reversed polarity. Using the two coloured pencils, alternately colour the bands starting with reversed polarity on the far left.
- Use the scissors to cut this sheet of paper in half, parallel to the long sides.
- Mark the bands on each strip of paper with arrows to indicate their polarity, with an up arrow indicating normal and a down arrow indicating reversed. See Figure 6.20.
- Insert one end of each strip through the central slit of your template, and then thread each through its nearest side slit. Use clear tape to tape the ends of each strip to make a loop as shown in Figure 6.21.
- Starting with normal polarity, move each loop of paper to model the movement of the ocean floor.

RESULTS

Make a short movie of your model. You could narrate it to explain what is happening.

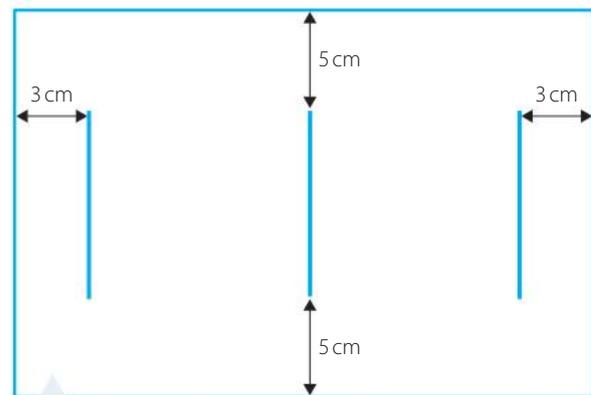


FIGURE 6.19 Cut along the heavy lines on this template.

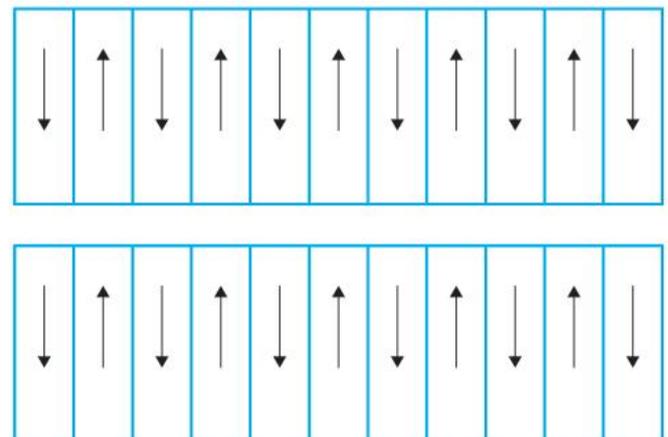


FIGURE 6.20 Mark the bands with arrows to indicate polarity.





DISCUSSION

- 1 What is represented by:
 - a the central slit?
 - b the side slits?
 - c the loops of paper?
 - d the bands and arrows?
- 2 If you were to measure the temperature of the sea floor starting from the central slit and moving to the outside slits, what would you find?
- 3 If you were to measure the age of the sea floor starting from the central slit and moving to the outside slits, what would you find?
- 4 How could you improve this model to better demonstrate sea-floor spreading?

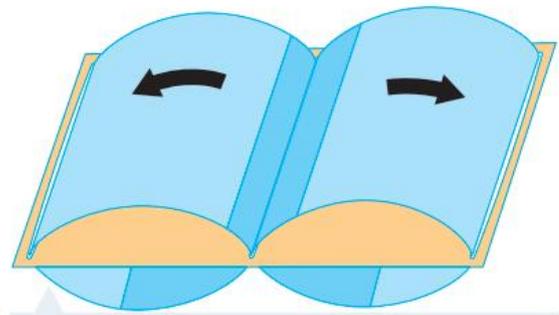
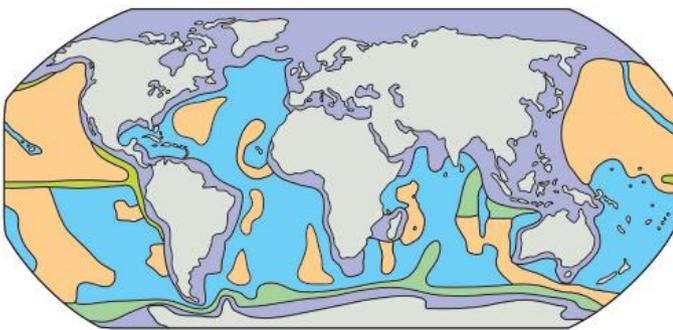


FIGURE 6.21 Thread each strip through the central slit and tape the ends to make a loop.

CONCLUSION

Write a conclusion about what you have learnt about sea-floor spreading and magnetic reversals.

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FIGURE 6.22 Global distribution of the four main types of ocean sediment

Dating sea-floor rocks and sediments

Sediment and basalt lavas are the most common materials on the sea floor. The basalts formed at the mid-ocean ridges form a basement layer on which the sea-floor sediments are deposited. Oceanic sediments are usually fine-grained muds. Muds composed of silt derived from the breakup of continental edges form **terrigenous** sediments; other sediments of continental origin may consist of clay. Shells of tiny planktonic animals that live in the surface waters sink through the water column and collect on the sea floor. These shells are usually composed of the mineral calcite or of opaline silica, which is a form of the mineral quartz. Sea-floor mud,

mostly composed of silica shells, is called **siliceous ooze**; the calcite shells form carbonate deposits. The distribution of sediment types present in the ocean is shown in Figure 6.22.

For direct determination of the age of the sea floor at a particular location, it is necessary to have samples from that location of the basalts that formed the sea-floor surface, or the sediments deposited on the sea floor just after the basalt was formed at a mid-ocean ridge. The sea-floor sediments and basalts can be dated using fossil-based methods or isotopic clocks.

Surface samples of the sea-floor rock and sediment are collected with grabs, dredges and short coring devices. Surface samples are usually geologically young because they are recently deposited clays, oozes and terrigenous sediments. Recently erupted basalts are usually recovered in dredge samples taken from the active mid-ocean ridges.

Away from the ocean ridges the basalts are gradually buried by sediment. The thickness of sediment deposited above the oceanic lithosphere increases with increasing distance from a mid-ocean ridge. This is because the age of the oceanic lithosphere increases with distance from the ridge.

Over time the sediment layers accumulate in layered deposits that can be many hundreds of metres thick. The layers of sediment deposited at the margins of the circum-Atlantic continents can be thousands of metres thick. This is because large amounts of sediment derived from the continents have been deposited on old oceanic lithosphere formed when the continents were first split apart.

Dating methods were discussed in Chapter 4.

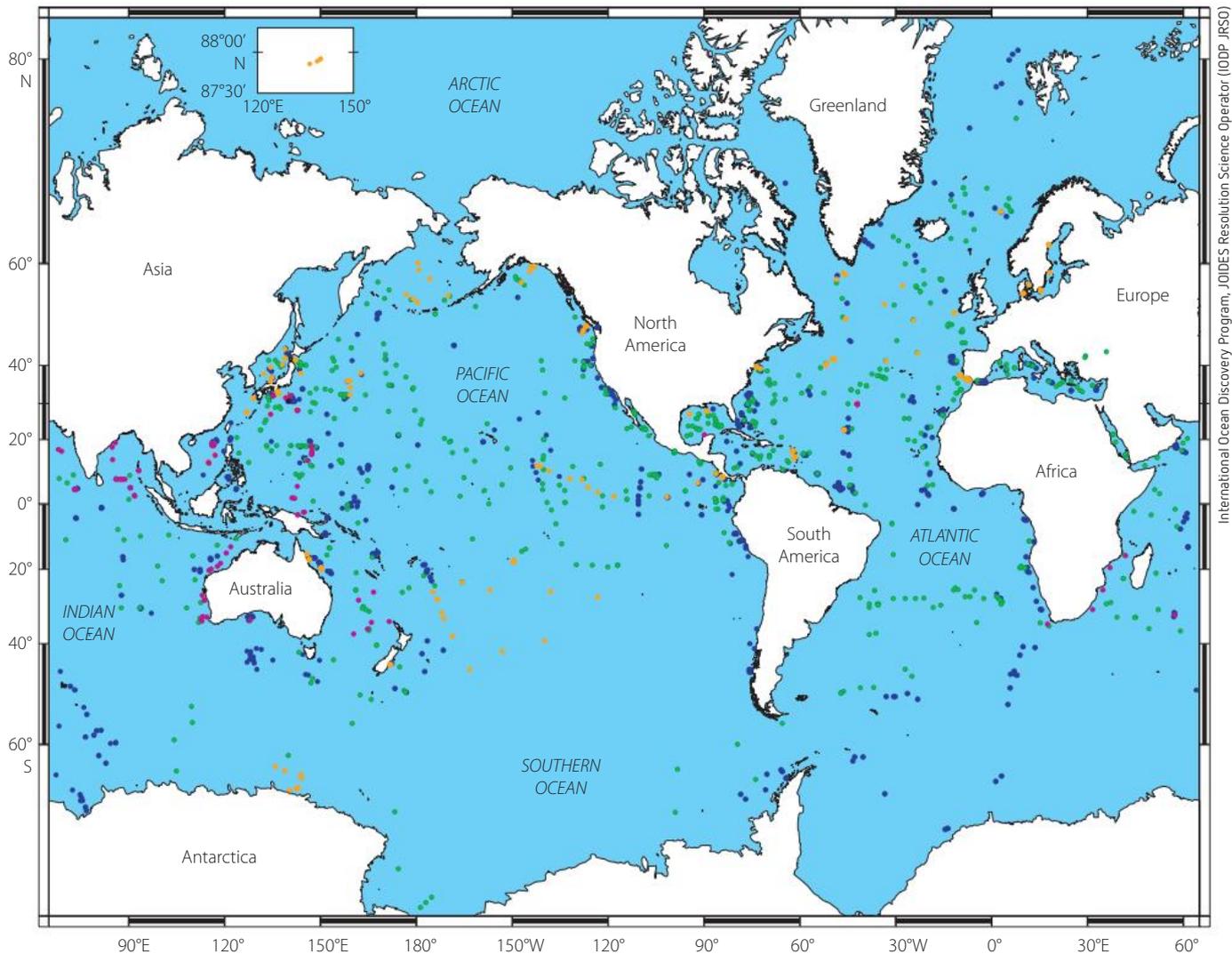
Deep-sea drilling projects

Specialist drilling ships such as the *Glomar Challenger* (Figure 6.23) are required to sample thick sequences of ocean floor sediment layers and the basalts located deep beneath them. Each sample is removed as a solid cylinder or drill core to preserve the layers intact. An international program of scientific drilling has been coring the ocean sediments and basalts since 1968. There have been four international programs so far: the Deep Sea Drilling Project (DSDP, 1968–1984), the Ocean Drilling Program (1985–2003), the Integrated Drilling Program (2004–2013) and the International Ocean Discovery Program, which started in 2014 and is still going strong.

By the beginning of 2018, the marine geologists and geophysicists taking part in these programs had drilled core holes at 1530 different sites located all over the world (Figure 6.24).



FIGURE 6.23 The deep-ocean drill ship *Glomar Challenger*



DSDP Legs 1–96 (●), ODP Legs 100–210 (●), IODP Expeditions 301–348 (●), IODP Expeditions 349–371 (●)

FIGURE 6.24 Locations of deep-ocean drill sites, 1968–2018

Nearly 90000m of sediment and rock core has been recovered. A specific objective of this program was to determine the age of the contact between the lowest layer of sediment and the uppermost basalts of the oceanic lithosphere. This is the age of the sea floor at that site.

The ages determined for sea-floor basalts increase with distance from the mid-ocean ridges. These ages are the same as the ages of the sea floor that are determined from magnetic profiling. The age of the first sediments deposited just above those basalts is usually a little younger than the basalt. These sediment ages also confirm the age of the sea floor that has been determined from the magnetic striping of the sea floor. This evidence is the strongest confirmation that exists for the theory of plate tectonics.

KEY CONCEPTS

- The theory of plate tectonics is supported by many different sets of evidence, including:
 - the shape and age of the sea floor
 - age (absolute) dating of hotspot volcanoes
 - age dating of sea-floor basalt and sediment drill core samples.

CHECK YOUR UNDERSTANDING

6.2B

- 1 Define bathymetry, terrigenous sediments and siliceous ooze.
- 2 Explain how the shape of the sea floor has contradicted both the contractionist and geosynclinal geological theories.
- 3 Describe how oceanic lithosphere is formed at a mid-ocean ridge.
- 4 Which is older, mid-ocean ridges or abyssal plains? Explain why.
- 5 Explain how the following provide evidence for the theory of plate tectonics:
 - a deep-ocean trenches
 - b magnetic striping on the sea floor
 - c hotspot volcanoes.
- 6 Copy and complete the following sentence: Older sea floor is found _____ the mid-ocean ridges.
- 7 Draw and label a diagram of a core sample taken from the sea floor. Show the relative ages of each layer.

6.3

Contributors to the theory of plate tectonics

The theory of plate tectonics was developed by teams of people working at four or five universities and research institutes. Each of the key pieces of evidence was itself an amalgamation of a large dataset and no person working alone could have done the work required.

Although the theory of plate tectonics is not owned by a particular person, key concepts of the theory are associated with particular people. Between 1955 and 1965, these key discoveries were gradually combined to develop the theory as we know it today. The theory illustrates how Earth functions as a global system and it requires a global overview.

Wegener's continental drift hypothesis

Alfred Wegener first proposed his theory of continental drift in a pamphlet in 1912. Four editions of a book that made the case for his theory were published between 1915 and 1928. At the time it was published, Wegener's theory was regarded to be highly controversial. Most geologists rejected his proposal and they ignored much of the evidence he presented to support it.

Wegener had been trying to solve a seemingly unrelated problem when he proposed continental drift. He was interested in the distribution of Earth's climate zones 300 million years ago during the Late Palaeozoic. He wanted to know why tropical conditions had existed in Europe and North America during the Carboniferous Period while most of the southern parts of Africa, Australia and South America had experienced very cold climates and widespread glaciation (Figure 6.25).

Figure 4.19 in Chapter 4 gives a timeline of these geological time divisions.

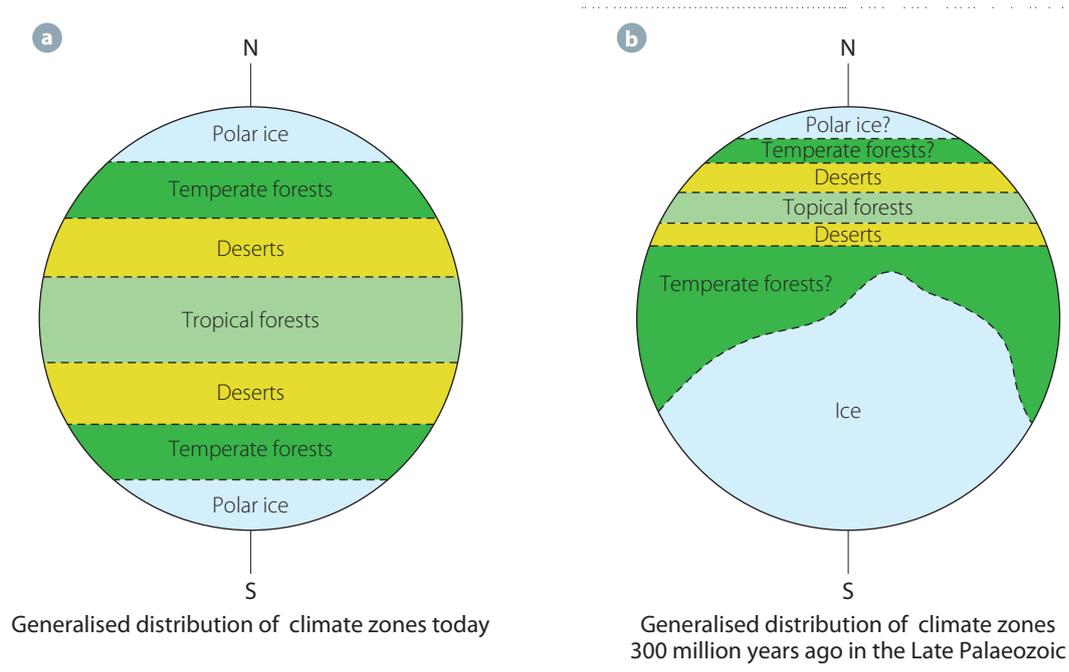


FIGURE 6.25 Alfred Wegener's climate conundrum. **a** Generalised distribution of climate zones today **b** Generalised distribution of climate zones in the Late Palaeozoic

Rocks from the northern continents located about 40° north of the equator contained abundant plant and animal fossils that indicated tropical forest environments. Thick coal deposits had collected on low-lying floodplains. At exactly the same time, large areas of rock on the southern continents located at 40° south had been polished and scratched by ground ice. These glacially striated surfaces were often overlain by thick accumulations of glacial sediments.

Wegener was trained as a meteorologist and studied ancient climates. The fact the tropical conditions had dominated locations 40° north of the equator, while at the same time freezing cold conditions and ground ice had dominated places located 40° south of the equator, did not make any sense to him. This confounded and confused other climatologists as well.

Wegener knew that the German explorer Alexander von Humboldt had noted the matching shapes of the circum-Atlantic continents in the late 18th century. Wegener also knew that geologists working in Africa, Australia, South America and India had suggested that these continents might have been connected in some way. This was because of the similarity of some of the sedimentary rock sequences and fossils that had been found across their regions. The southern hemisphere geologists had even proposed the name Gondwanaland for this hypothetical landmass.

Wegener solved his climate conundrum using the jigsaw-fit of continents concept in a revolutionary way. His starting points were that continents could move and had been joined together into a single continental mass at some point in the past. If this was accepted, he reasoned, the continents could also have moved around together as a single very large unit. Wegener reconstructed the continents into a single unit as suggested by their shapes.

The story goes that Wegener cut up a globe and joined all the southern and northern continents together to create his supercontinent and then moved the supercontinent around on a globe to test his ideas. The results must have astounded him.

First, the shape of the southern continent glacial deposits became circular, like the present-day Antarctic **ice sheet**. Second, the scratch marks the ice had left behind also pointed towards a common point of origin. Third, and most importantly, the centre of the 'southern glacial deposit circle' matched when placed over the south pole (Figure 6.26). The tropical environments recorded by the northern hemisphere continents coincided with the equator. The desert environments corresponded with the locations of the present-day northern and southern hemisphere deserts on either side of the tropical zone (Figure 6.27). The idea of continental drift solved Wegener's climate conundrum.

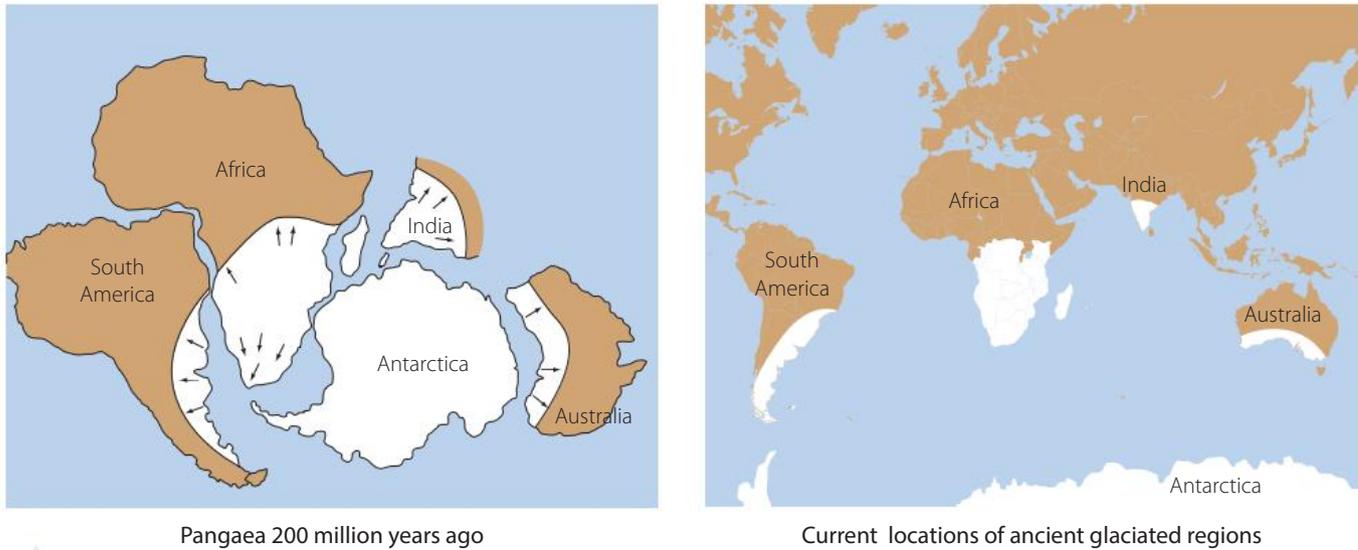
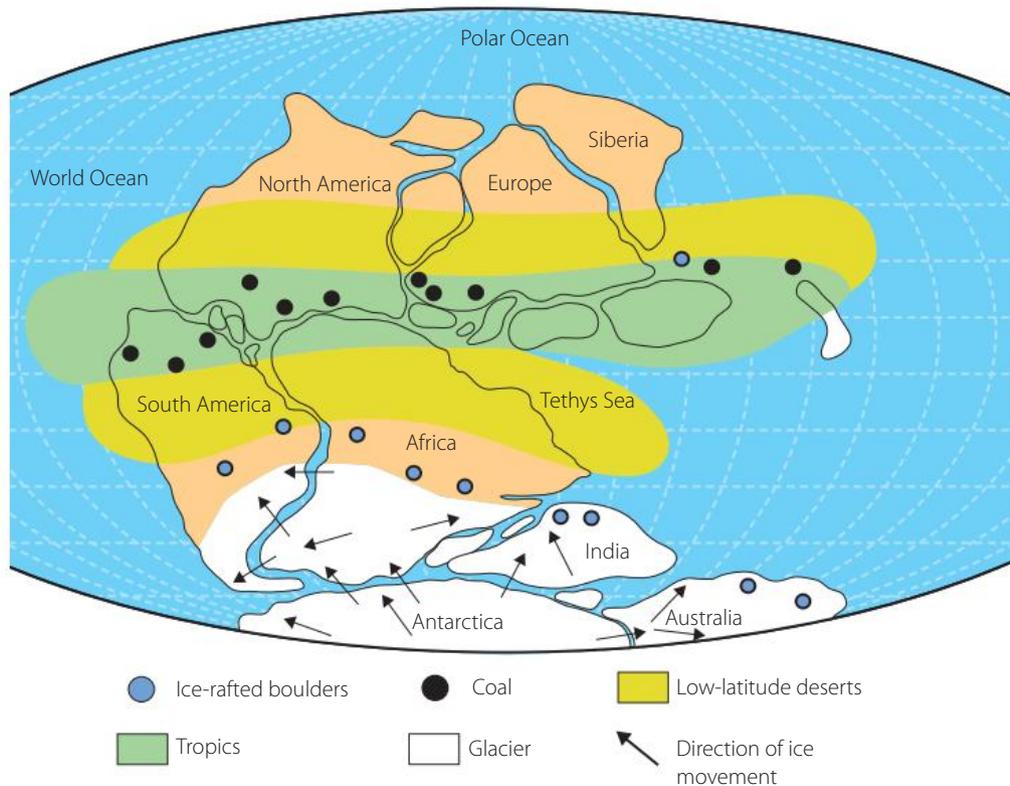


FIGURE 6.26 Wegener's jigsaw fit reconstruction produces a near circular ice sheet centred at the south pole.

FIGURE 6.27 The distribution of Late Palaeozoic climate zones using Wegener's continental drift hypothesis



Based on sketch by Alfred Wegener

Wegener's theory proposed that all the continents on Earth had originally been joined together into a single landmass. He suggested that the landmass had begun to disintegrate about 300 million years ago during the late Carboniferous and the continents had drifted away from each other. Antarctica had remained near the south pole while all the other continents had moved north.

Wegener also used the distribution of fossils, modern animals and geological structures as evidence to support his ideas. In particular, he suggested that the overlapping ranges of modern-day earthworms across continental edges indicated that the continents had been joined together.

Wegener stated that the continents were moving at speeds of about 1 m/year; this is about ten times faster than the speeds that have since been measured. Most geologists refused to accept a theory of continents that moved at spectacular speeds and did not have a credible driving mechanism.

Holmes's mantle convection

Most geologists of the time rejected Wegener's theory entirely. Arthur Holmes, an English physicist who had switched fields to become a geologist, thought that the continental drift model might actually be correct. He had established the first reliable method for dating rocks using the chemical uranium-lead method (page 96). In the late 1920s, Holmes suggested that mantle convection could provide a driving mechanism for continental motion.

Holmes had already rejected the contractionist model, which proposed that mountain building was the consequence of a continually cooling and shrinking Earth. Holmes had shown that the heat generated by radioactive decay was maintaining Earth's internal temperature and that Earth was not shrinking irreversibly as the contractionists suggested. Instead, Holmes proposed that the build-up of radioactive heat deep within the planet might generate giant **convection cells** that could drive lateral motion of the continents.

Holmes published his ideas between 1928 and 1930. He explained continental drift with several diagrams of Earth's interior (Figure 6.28). Mantle material was heated near the mantle-core boundary. This hot mantle would rise and circulate. When it cooled near Earth's surface, the mantle could cool and sink. The cycle repeated. Earth had several large circulating mantle convection cells and these were causing the continents to move.

Holmes's model explained the break-up of the continents, their separation and their motion. Continental drift was a by-product of a convecting and circulating mantle. Holmes's convection model for drift also explained the uplift of continents by the hot mantle, and continental collisions could also explain how continental mountain ranges might be formed.

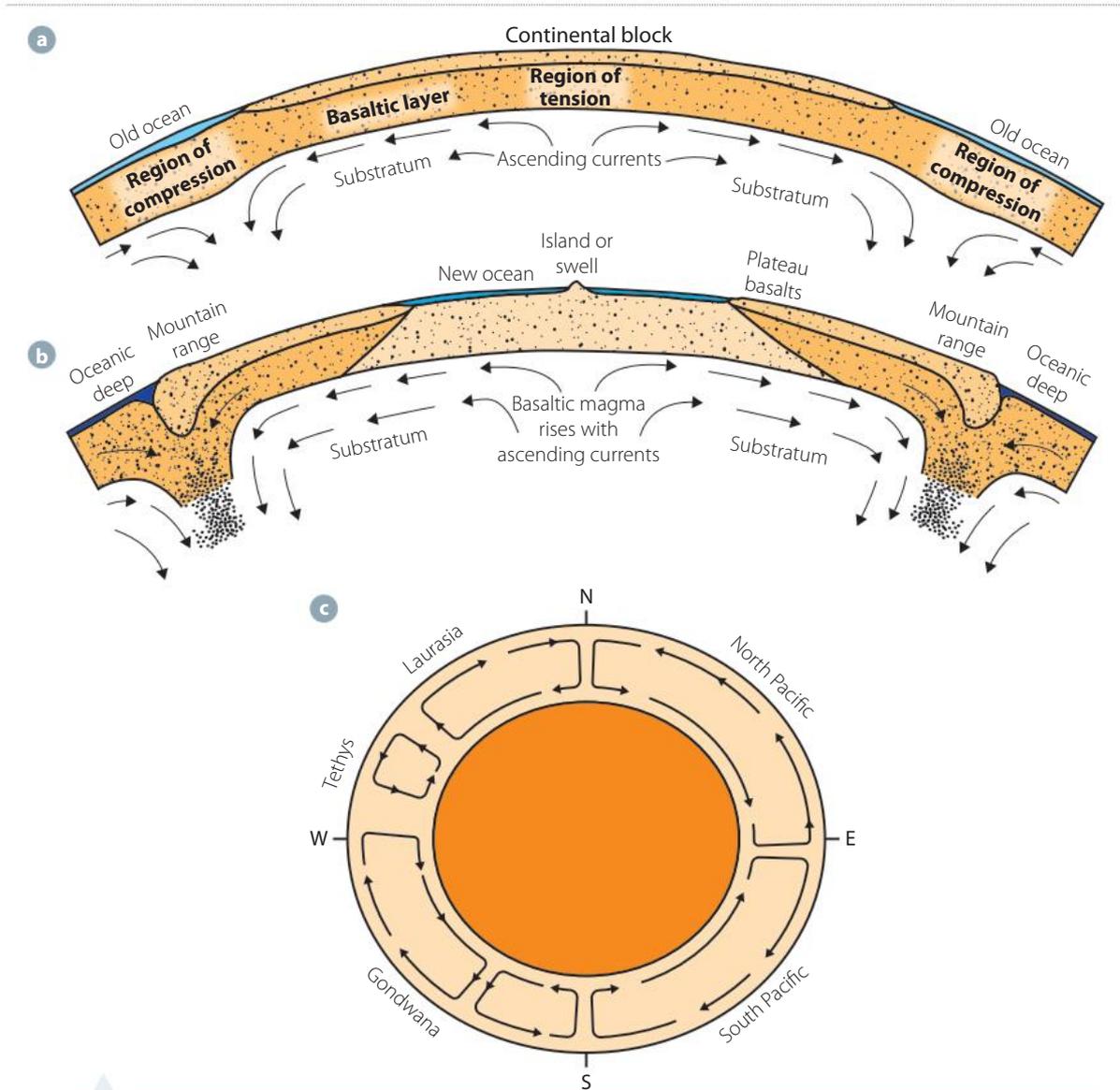
Careful examination of Holmes's diagrams reveals similarities to the diagrams currently used to depict sea-floor spreading at mid-ocean ridges and subduction of sea floor and ocean-continent subduction zones. His island swells correspond to mid-ocean ridges. The ocean deeps and mountain ranges correspond to trenches and subduction zones.

Holmes's explanation of drift was presented in the final chapter of his major textbook *Principles of Physical Geology*, published in 1944. This book bravely advocated the continental drift theory at a time when it was generally ridiculed by mainstream geologists. It was only Holmes's fame and general standing as one of the people who had determined the age of Earth that enabled him to gain support.

Holmes's model had a small group of dedicated followers. Many were southern hemisphere geologists who were familiar with the glacial striations the Carboniferous ice sheet had gouged in areas that were now hot deserts. In Australia, they also mapped and mined the coal formations deposited above the glacial sediments that had led Wegener to propose drift. Professor Sam Carey of the University of Tasmania was continental drift's strongest advocate during the 1950s and 1960s.

Holmes's diagrams present his mantle convection drift model well and anticipate plate tectonics by nearly 40 years. When plate tectonics became widely accepted in the early 1970s, his

Mantle convection is explained in Chapter 7.



Based on sketch by Arthur Holmes

FIGURE 6.28 Arthur Holmes's mantle convection models for **a** continental splitting, **b** continental drift and **c** mantle circulation

model of mantle convection was commonly used to explain why the lithospheric plates moved. By the 1980s, however, geologists and geophysicists realised that additional processes were probably required.

Plate motion is still not entirely understood. It is thought that mantle convection and gravitational processes combine to produce **ridge push** and **slab pull** (Figure 6.29). Old, cold oceanic lithosphere sinks in to the mantle and displaces mantle that has been heated near the core. The hot mantle rises, somehow driving the sea-floor spreading at mid-ocean ridges and volcanism at the hotspot volcanoes. More data and computer modelling of Earth's internal processes will eventually provide a full answer.

Models for plate motion mechanisms. Source: Steven Earle (2015) CC BY 4.0

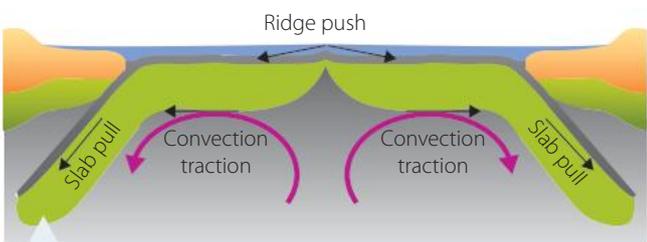


FIGURE 6.29 Ridge push, slab pull and convection mechanisms of plate motion. Compare this diagram to Arthur Holmes's convection model for new ocean formation in Figure 6.28.

Admiral Harry Hess and sea-floor spreading

Admiral Harry Hess was a marine geologist who commanded the US Navy transport ship the USS *Cape Johnson* during World War II. He made several transits of the Pacific Ocean and made sure that the ship's echo sounder was on and recording data on its paper chart recorder. After the war he served in the Naval Reserve and coordinated programs of marine surveying in the Pacific Office for the US Hydrographic Office and the Office of Naval Research.

In 1953 Marie Tharp and Bruce Heezen published a landmark study of the bathymetry of the Mid-Atlantic Ridge system. Hess studied their detailed maps of the extensive chain of undersea mountains that winds its way around the planet. Marine geologists, including Hess, were greatly surprised that Tharp's and Heezen's maps showed that the Mid-Atlantic Ridge and the abyssal plains were symmetrical in cross-section.

Hess realised that there might be a relationship between the Mid-Atlantic Ridge system and the set of great oceanic trench systems he had identified on the bathymetric maps of the Pacific Ocean. He reinterpreted all the bathymetric data and the known geology of the Pacific and Atlantic oceans. In 1960 he proposed that sea floor was created at the mid-ocean ridges, spread out towards the trenches and then descended beneath them into the mantle (Figure 6.30).

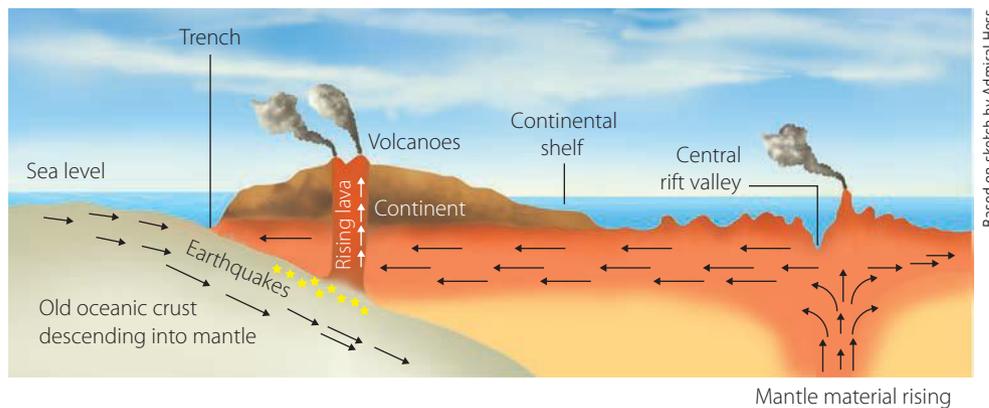


FIGURE 6.30
A sketch of Admiral Hess's 1960s sea-floor spreading model

Hess's model incorporated aspects of Holmes's mantle convection model. Hess proposed that the continents were carried along by laterally moving mantle. Rising currents were powerful enough to split continents and create the mid-ocean ridges and symmetrical ocean floors such as the Atlantic. Hess's sea-floor spreading model is the basis of the plate tectonic model of ocean lithosphere formation at divergent margins that we use today.

Vine, Matthews, Wilson and McKenzie

Three or four major scientific papers were critical breakthrough works that established and introduced the plate tectonics theory between 1963 and 1968. One paper was published in the prestigious journal *Nature* in 1963 by Fred Vine of the University of Cambridge and his supervisor Drummond Matthews. The paper is called *Magnetic Anomalies over Oceanic Ridges*. Their work led to the identification of the remnant magnetic striping of the sea floor and enabled the age dating of oceanic lithosphere using magnetic striping of the sea floor.

About the same time as Vine and Matthews identified the importance of sea-floor magnetic striping, the special nature of mid-ocean ridge transform faults was identified by Tuzo Wilson. In 1965, he was probably the first person to use the term 'plates' in the way that we think of them today. In 1966, Wilson also proposed that subduction of oceanic lithosphere could close ocean basins and bring the

How sonar is used to map the sea floor
Click your way through the animation

The Wilson cycle

continents back together in continent–continent collisions. Repetition of this process was suggested to be responsible for repeated episodes of mountain building over geological time. This process is often called the ‘Wilson plate tectonic supercycle’.

In 1967, Dan McKenzie and Bob Parker suggested the reason why sea-floor magnetic stripes were preserved in such good detail. This was because the sea floor generated by spreading at mid-ocean ridges moved away from mid-ocean ridges as rigid slabs. Their thinking on this topic had been influenced by a presentation given by Jason Morgan at a conference that McKenzie attended that year. By 1969, the term ‘plate tectonics’ was widely and commonly used.

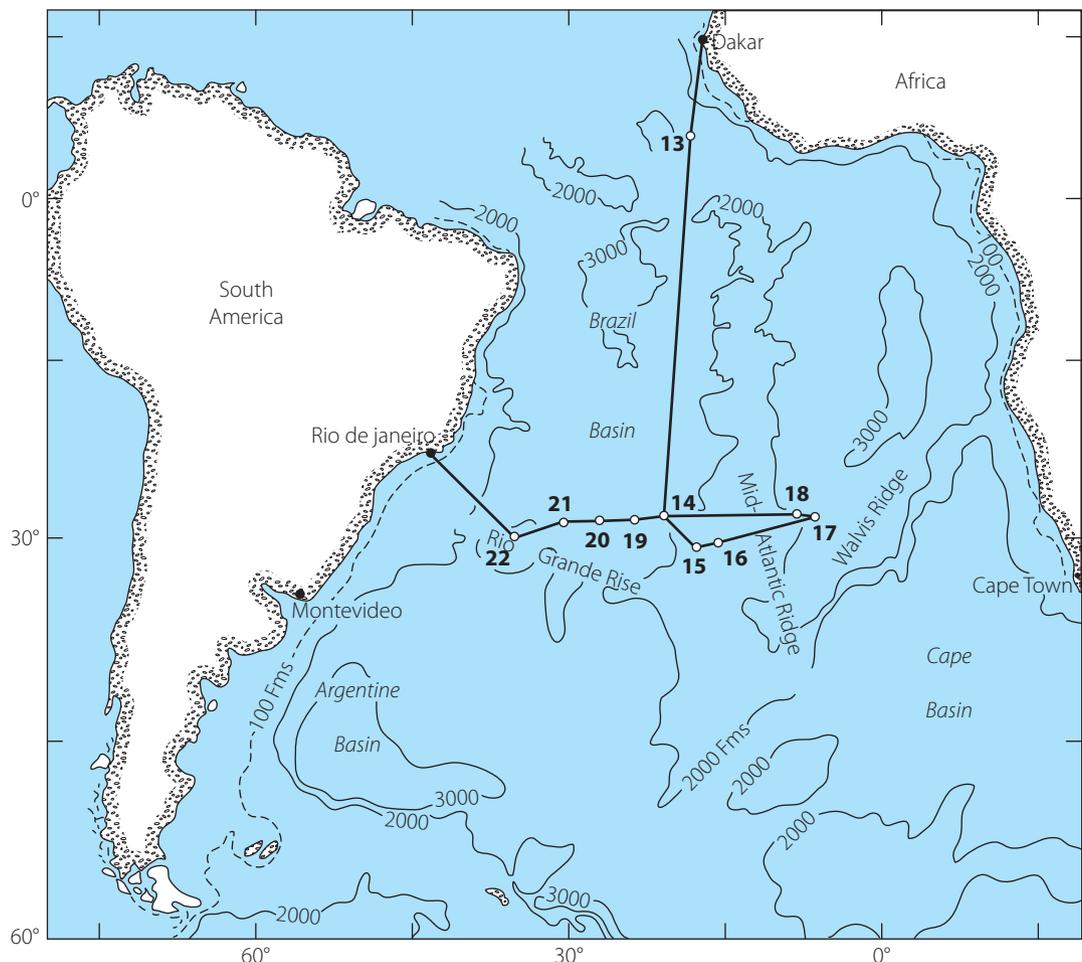
Glomar Challenger

The Deep Sea Drilling Program started in 1968 with the construction of the drillship *Glomar Challenger*. This program gathered evidence that confirmed that the sea-floor basalts were formed at mid-ocean ridges and that this newly formed lithosphere was transported away from the mid-ocean ridges. The third voyage of the drillship *Glomar Challenger* was to the South Atlantic Ocean. The scientific and technical crew collected drillcores on a line across the South Atlantic Ridge located between Capetown in South Africa and Rio de Janeiro in Brazil (Figure 6.31).

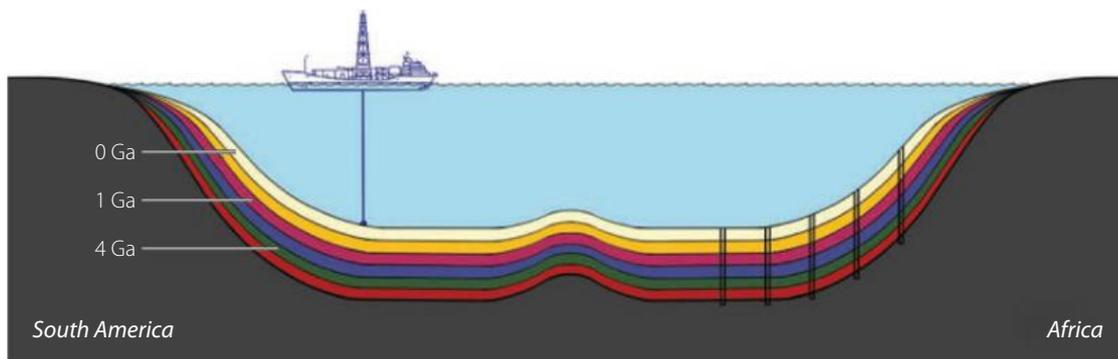
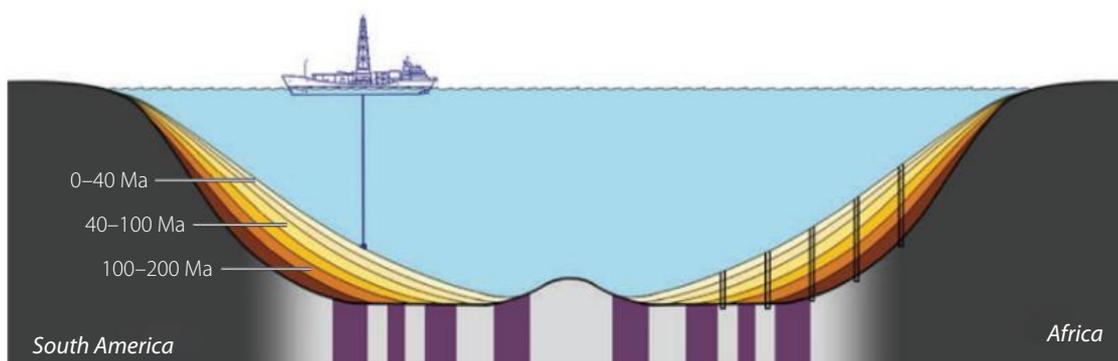
The aim of this voyage was to drill a set of holes at increasing distances away from the South Atlantic mid-ocean ridge. If the age of the sediment located just above the basalt basement increased with distance from the ridge, this would support Hess’s sea-floor spreading hypothesis and confirm the ages assigned to the sea floor in magnetic striping studies (Figure 6.32).

FIGURE 6.31

Location map of the DSDP Leg 3 drill sites
Fms = fathoms;
1 fm ≈ 1.83 m



Maxwell, Arthur E., Richard P. Von Herzen, James E. Andrews, Robert E. Boyce, E. Dean Millow, Kenneth J. Hsu, Stephen E. Percival, and Tsunemasa Saito. "Introduction." *Initial Reports of the Deep Sea Drilling Project Vol. 3* (1970): p. 7–9. doi:10.2973/dsdpp.proc.3.101.1970

Fixed Earth – ancient ocean**Drifting Earth – young ocean****FIGURE 6.32**

Schematic diagram showing the two competing models for the geology of the Atlantic Ocean tested on DSDP Leg 3.

Ga = billion years;
Ma = million years.

As it turned out, the ages of the basalt sediment samples exactly matched the sea-floor magnetic stripe ages. This provided the strongest evidence yet in support of plate tectonics and continental drift. Cores were drilled to basaltic basement at nine sites progressively further west from the mid-ocean ridge (Figure 6.33). This was the evidence that convinced the scientific community that the theory of plate tectonics was valid.

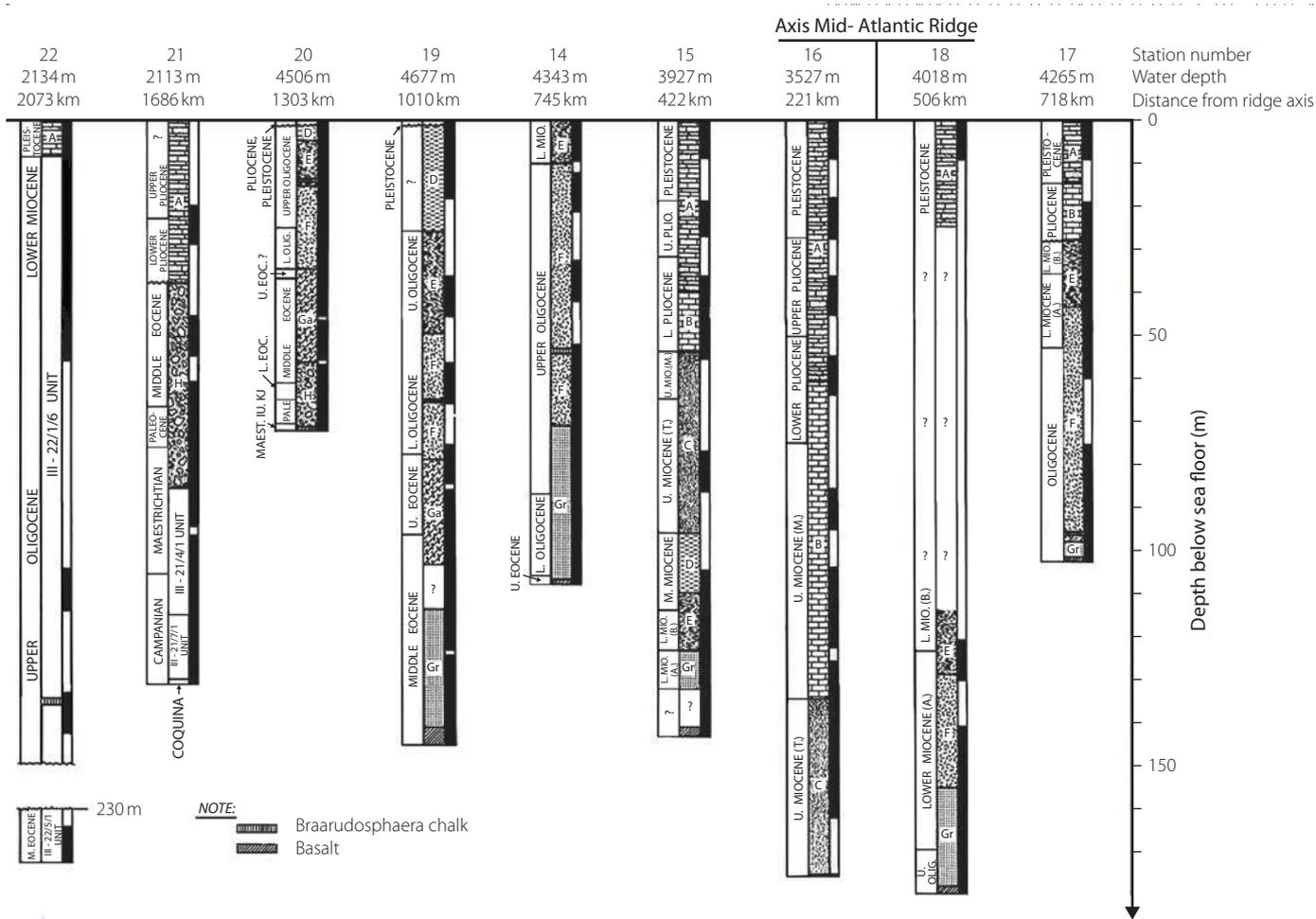
As the theory predicted, the age of sediments at the bottom of these cores increased smoothly away from the ridge. Material recovered from just above the basalts at site 16 near the ridge was 10 million years old. Material recovered from just above the basalts at site 21 was 80 million years old. Good basalt samples that could be dated to confirm the magnetic stripe sea-floor ages were collected later during DSDP Legs 5, 6 and 12. In 1983, DSDP Leg 69 collected basalts from the north-west Pacific where some of the oldest sea floor on Earth is located. Figure 6.34 shows cores collected on later surveys.

Wegener was right after all. Continents did split, drift and move. Hess's, Vine's, McKenzie's, Morgan's and Wilson's models of moving lithospheric plates, sea-floor spreading, subduction and continental collision were widely accepted by geologists all over the world. The geology textbooks were rewritten. Geologists and geophysicists had developed a better theory that is easily understood and is used today to explain and understand most large-scale geological processes and events.

It is important to recognise that the theory of plate tectonics is still not complete. It is continually being refined because the mechanisms that drive the plates across the globe are still not properly understood. We know that old, cold subducted lithosphere sinks to the mantle core boundary where it pushes hot buoyant mantle back up towards the surface. Understanding just how these two processes force the lithospheric plates to move is still a work in progress. Geophysicists and seismologists are still trying to solve this part of the plate tectonic puzzle. They use computer models and seismological data to determine just how it is that interplay of gravity and convective heating drives the surface motion of the plates.



Plate tectonics



Maxwell, Arthur E., Richard P. Von Herzen, James E. Andrews, Robert E. Boyle, E. Dean Milow, Kenneth J. Hsu, Stephen F. Percival, and Tsunemasa Saito. "Summary and Conclusions." Initial Reports of the Deep Sea Drilling Project Vol. 3 (1970): p.441-471. doi:10.2973/dsdp.proc.3.113.1970

FIGURE 6.33 Core logs from the DSDP Leg 3 drill sites



Science Photo Library/Tom Kleindinst, Woods Hole Oceanographic Institution, Visuals Unlimited

FIGURE 6.34 a Rock core samples and b sediment cores collected on JOIDES Resolution Legs 352 and 353

INVESTIGATION 6.3

Evaluating the contributions to the theory of plate tectonics

A primary- or secondary-sourced investigation of the developments that led to the proposal and acceptance of the theory of plate tectonics.

AIMS

- A** To gather, process and analyse primary- or secondary-sourced information about the people who developed the theory of plate tectonics
- B** To construct a timeline that identifies when the key contributions that led to the theory of plate tectonics were made and the person or team who made that contribution

METHOD

Part A: Collect, consider and assess information

- 1** Use a variety of primary and secondary sources in your investigation. These may include scientific journals, websites textbooks, encyclopedias, biographies, historical accounts, popular science magazines, newspaper articles and experts in the field. A variety of scientific search engines such as Scopus, ScienceDirect and Web of Science can be accessed at some public libraries and these may assist in your search.
- 2** Use this information to complete the following table. You are asked to evaluate each person's contribution. To do this you need to make a judgement as to whether their contribution was a critical piece of evidence to support the theory.
- 3** Provide a complete reference list to show the sources that you used.

RESULTS

SCIENTIST(S)	DATE OF THEIR WORK	WHAT DID THEY CONTRIBUTE TO THE THEORY OF PLATE TECTONICS?	EVALUATE THEIR CONTRIBUTION TO THE ACCEPTANCE OF THE THEORY

Part B: Construct a timeline

Once you have completed Part A, complete the following steps.

- 4** On a sheet of A3 paper or a large piece of cardboard, draw a timeline to an appropriate scale (for example 1900 to the present day).
- 5** Add the names of the people from your results table, as well as the major figures identified in this chapter, and summarise their contributions for your timeline.
- 6** Group the distinct periods together under broad headings, for example pre-Drift, post-Drift, before Sea-floor spreading, after Hess and so on.
- 7** Make sure you have considered each of the main concepts or sources of evidence used to develop the theory of plate tectonics and linked these to the scientists responsible.





DISCUSSION

- 1 Describe the major stages in the development in the theory of plate tectonics.
- 2 List the information or data that was used to support both the continental drift hypothesis and the theory of plate tectonics.
- 3 Evaluate the relationships between the continental drift hypothesis and the theory of plate tectonics. Are they similar or quite different ideas?
- 4 Are all the timelines produced by your classmates the same? Explain these differences if they exist.
- 5 Identify two or three pieces of the evidence that supports plate tectonics that you think are the most convincing. Discuss your choice with your classmates.
- 6 Assess the quality of the information you used to develop your timeline. Is it accurate and reliable? (pages 16–17.)

KEY CONCEPTS

- Alfred Wegener proposed the continental drift hypothesis in 1912. This idea was the forerunner of the theory of plate tectonics.
- Continental drift was based on the jigsaw-fit of continents.
- Continental drift also suggested that all of the continents had been joined together into a single large land mass in the Late Palaeozoic.
- Harry Hess proposed the sea-floor spreading model in 1960. He suggested that new sea floor was created at the mid-ocean ridges and that old sea-floor descended into the mantle at the deep ocean trenches.
- The theory of plate tectonics was developed by a group of 30 to 40 people between 1955 and 1968. The main breakthroughs were:
 - detailed mapping of the shape of the sea floor
 - understanding the significance of sea-floor magnetic striping
 - age dating of the sea floor based on sea-floor magnetic stripe studies
 - more convincing reconstructions demonstrating the jigsaw-fit of the continents based on more detailed maps of the continental edges
 - the discovery of terrestrial plant and animal fossils such as *Lystrosaurus* fossils in Antarctica
 - earthquake distribution studies that identified the plate boundaries.
- The Deep Sea Drilling Program collected sea-floor sediment and basalt samples that confirmed that the sea floor is progressively older the more distant it is from the mid-ocean ridges.
- The theory of plate tectonics is not yet complete.

CHECK YOUR UNDERSTANDING

6.3

- 1 Who proposed the continental drift hypothesis?
- 2 What scientific problem did continental drift solve?
- 3 Who first proposed convection currents as a mechanism for continental drift?
- 4 Outline the main features of Harry Hess's model of sea-floor spreading.
- 5 In 1967, which two scientists proposed that plates moved as rigid slabs?
- 6 Who proposed the plate tectonic supercycle?
- 7 Why is the theory of plate tectonics considered to be a collective effort rather than the work of an individual?
- 8 What type of data was collected on the *Glomar Challenger*?
- 9 What role did the work of Matthews and Vine play in establishing the theory of plate tectonics?
- 10 How was the data collected on the *Glomar Challenger* used to support the theory of plate tectonics?

6 CHAPTER SUMMARY

- ▶ The theory of plate tectonics states that Earth's crust and brittle upper mantle are combined into a single rigid layer of material. This layer is called the lithosphere.
- ▶ The lithosphere is divided into plates.
- ▶ Oceanic lithosphere is composed of oceanic crust and mantle and continental lithosphere is composed of continental crust and upper mantle.
- ▶ Oceanic and continental lithospheric plates are named for the continents they transport as they move.
- ▶ The theory of plate tectonics is supported by many different sets of evidence, including:
 - the jigsaw-fit of the continents
 - the location of fossils of large, extinct, terrestrial animals on several continents that are now separated by oceans
 - geological boundaries that match across continental borders
 - the shape and age of the sea floor
 - age dating of hotspot volcanoes
 - age dating of sea-floor basalt and sediment drill core samples.
- ▶ Alfred Wegener proposed the continental drift hypothesis in 1912. This idea was the forerunner of the theory of plate tectonics.
- ▶ The theory of continental drift was based on the jigsaw-fit of continents.
- ▶ Continental drift also suggested that all of the continents had been joined together into a single large land mass in the Late Palaeozoic.
- ▶ Harry Hess proposed the sea-floor spreading model in 1960. It suggested that new sea floor was created at the mid-ocean ridges and that old sea floor descended into the mantle at the deep-ocean trenches.
- ▶ The theory of plate tectonics was developed by a group of 30 to 40 people between 1955 and 1968. The main breakthroughs were:
 - detailed mapping of the shape of the sea floor
 - understanding the significance of sea-floor magnetic striping
 - age dating of the sea floor based on sea-floor magnetic stripe studies
 - more convincing reconstructions demonstrating the jigsaw-fit of the continents based on more detailed maps of the continental edges
 - the discovery of terrestrial plant and animal fossils such as *Lystroraurus* in Antarctica
 - earthquake distribution studies that identified the plate boundaries.
- ▶ The Deep Sea Drilling Program collected sea-floor sediment and basalt samples that confirmed that the sea floor is progressively older the more distant it is from the mid-ocean ridges.
- ▶ The theory of plate tectonics is not yet complete.

6 CHAPTER REVIEW QUESTIONS



Review quiz

- 1 What are the main components of continental lithosphere?
- 2 What is the asthenosphere?
- 3 Why do earthquakes help us identify the boundaries of the lithospheric plates?
- 4 Where is oceanic lithosphere formed?
- 5 Where is oceanic lithosphere subducted?
- 6 Name the type of sea floor where old oceanic lithosphere commonly occurs.
- 7 Name two geological features associated with divergent plate boundaries.
- 8 Name the set of geological features commonly associated with convergent plate boundaries.
- 9 Use the Internet to locate a map showing the age of the sea floor or use Figure 6.18.
 - a How are these ages determined?
 - b Where is the oldest sea floor in the South Atlantic Ocean located?
 - c Where is the youngest sea floor in the North Atlantic Ocean located?
- 10 Use the Internet to locate a map showing the location of the major lithospheric plates or use Figure 6.2.
 - a Identify a part of the Pacific lithospheric plate that is composed of continental lithosphere.
 - b What types of lithosphere are present in the African Plate?
 - c Where are the majority of Earth's deep-ocean trenches located?

- 11** Use the Internet to find a map showing the location of the lithospheric plates and how they are moving.
 - a** Determine how fast the Australian Plate is moving.
 - b** In what direction is the Australian Plate moving?
 - c** Determine the speed and direction of motion for several of the other large and small lithospheric plates.
- 12** Locate and name the geological feature that forms the southern boundary of the Australian Plate.
- 13** Use the Internet to locate a map showing the age of the sea floor to determine when Australia separated from Antarctica.
- 14** Make a sketch of a subduction zone that shows its major geological features.
- 15** Outline how magnetic striping is used to determine the age of the sea floor.
- 16** Evaluate the fossil evidence used to support the theory of plate tectonics. Explain why the occurrence of *Lystrosaurus* and *Cynognathus* fossils in Antarctica is particularly important evidence.
- 17** Explain how chains of hotspot volcanoes provide evidence that confirms the theory of plate tectonics and helps us determine the speed at which plates move.
- 18** Name two scientists associated with the continental drift hypothesis and outline their contributions to establishing this concept.
- 19** Name two scientists associated with the theory of plate tectonics and outline their contributions to establishing this concept.
- 20** The theory of contractionism and the theory of plate tectonics each provide explanations for the formation of mountain belts and the occurrence of earthquakes.
 - a** Which of these two theories provides a more convincing explanation for mountain building and earthquake occurrence?
 - b** Outline the reasons for your choice.
- 21** Geologists rejected Wegener's theory of continental drift in the 1920s because it lacked a convincing mechanism for the motion of the continents. On the other hand, geologists accepted the theory of plate tectonics soon after it was proposed, despite the fact that a convincing explanation for lithospheric plate motion was not presented.
 - a** Assess whether or not you think it was reasonable for geologists to have quickly accepted plate tectonics to be a valid hypothesis.
 - b** Consider the evidence that Wegener presented for drift. Was the geological community's rapid rejection of continental drift a reasonable response?

7 Plate boundaries

OUTCOMES

In this chapter you will learn about:

- the processes that produce divergent and convergent plate boundaries [CCT ICT L](#)
- modelling divergent and convergent plate boundaries [CCT ICT L](#)
- the distinctive geological and topographic features that are developed at both divergent and convergent plate boundaries
- the processes that produce transform plate boundaries
- where examples of the different types of plate boundaries can be found
- using geological maps to identify plate boundaries.





In Chapter 6 you learnt that the surface landscape of the planet has been formed by the interaction of lithospheric plates. The history of these interactions extends back in time to the Archaean, approximately 3200 million years ago. The theory that plate tectonics began at that time is supported by rock data from south-western Greenland.

Valuable mineral deposits are associated with plate boundaries. Geological events such as earthquakes, volcanic eruptions and tsunamis are also known to be associated with plate boundaries. The Ring of Fire to the north and east of Australia is where the Pacific Plate meets the Australian, Philippine Sea, Eurasian, North American and South American plates (Figure 7.1).

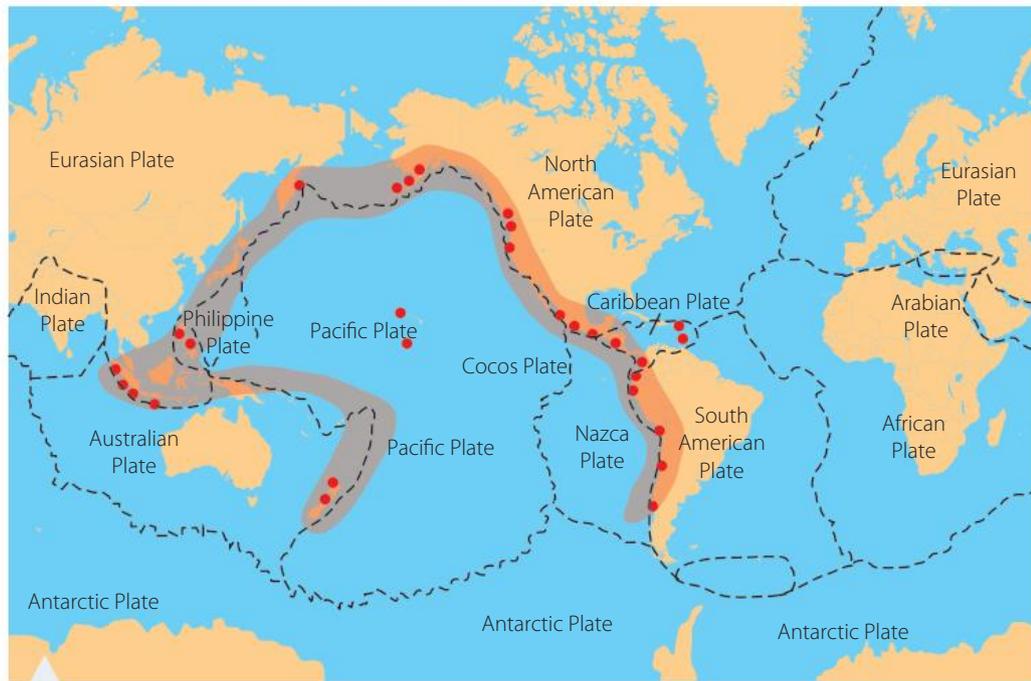


FIGURE 7.1 Ring of Fire, where the Pacific Plate meets the Indian–Pacific, Eurasian, North American and South American plates. The red dots indicate locations of geological events such as earthquakes and volcanic activity.

7.1 Divergent plate boundaries

Refer to Chapter 2 for more about the compositional layers of Earth and Chapter 4 for more information about the half-life of elements.

A **divergent plate boundary** is a region where two plates are moving away from each other. As the plates move apart, molten mantle beneath rises to the surface and creates new crust.

Processes that form divergent plate boundaries

Plates move away from each other as a result of the transfer of heat energy from Earth's core to Earth's surface. This heat energy is a combination of leftover heat from the formation of the planet and heat generated by the decay of radioactive isotopes in the mantle and core. The reason that there is still heat left over from the formation of Earth 4.55 billion years ago is that the mantle and crust provide exceptionally good insulation. Additionally, radioactive decay of many elements can continue for extended periods of time because many elements have a long **half-life** (Table 7.1).

TABLE 7.1 Half-life of some different elements

ELEMENT	HALF-LIFE (YEARS)
Uranium-235	700 000 000
Potassium-40	1 251 000 000
Uranium-238	4 500 000 000
Thorium-232	14 050 000 000
Rubidium-87	48 800 000 000
Neodymium-144	229 000 000 000

You will learn more about heat energy and convection in Chapter 8.

Convection in water

Magma in Earth's mantle is heated by this energy. As the magma gains heat energy, the particles in the magma move further apart, meaning it decreases in density. As a result, it rises. Heat is lost at the surface, cooling the magma. As the magma cools, the particles move closer together and this increase in density causes it to sink. This happens over and over, setting up a **convection cell** (Figure 7.2).

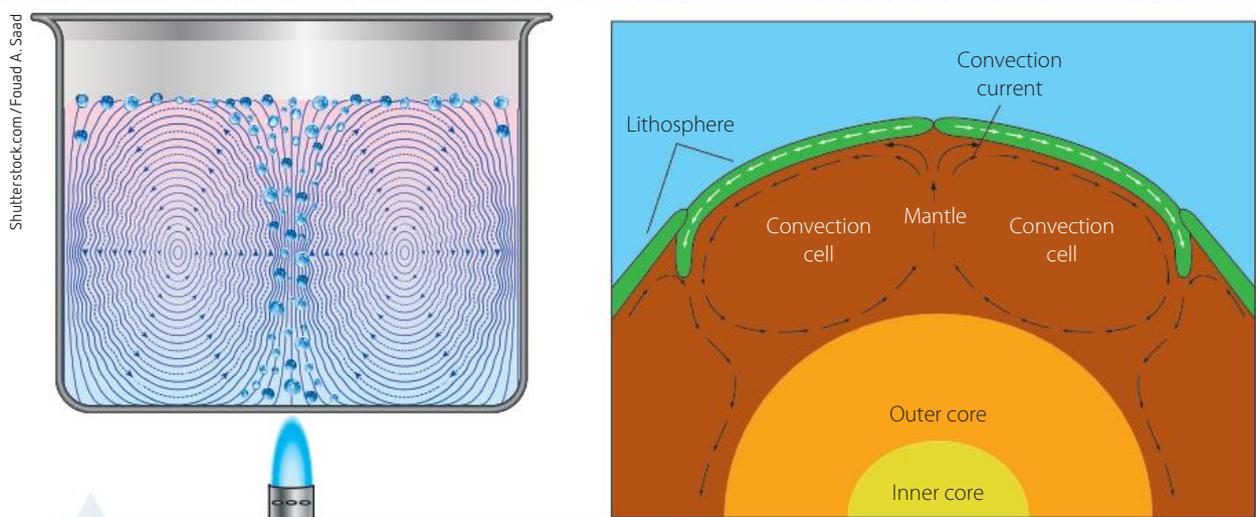


FIGURE 7.2 a Convection cells in a beaker of water b Convection cells in Earth's mantle

Rising convection currents in the mantle push up on the bottom of the lithosphere. This lifts the lithosphere and the magma flows laterally, or sideways, under it. Plate material is dragged in the direction of flow. The plate sitting on top of the flowing magma is stretched until it is thin enough to break apart (Figure 7.3). Magma rising up through the break forms new crust.

Modelling convection

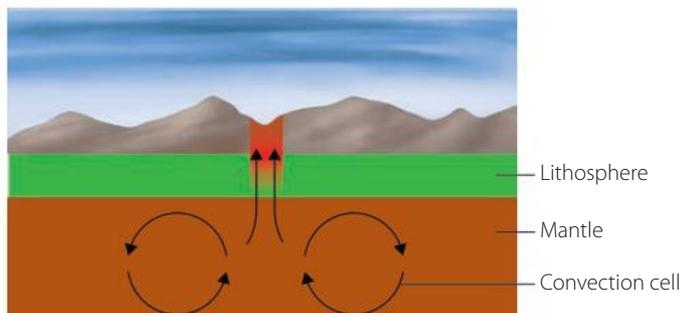


FIGURE 7.3 How divergent movement in the mantle creates a divergent boundary in the lithosphere



Forming a divergent plate boundary

Observe the processes involved in the formation of a divergent plate boundary on the sea floor.



Basalt erupting

Watch each of these short videos of basalt eruptions. Make a list of the types of features you observe.

You will meet normal faults on page 180.

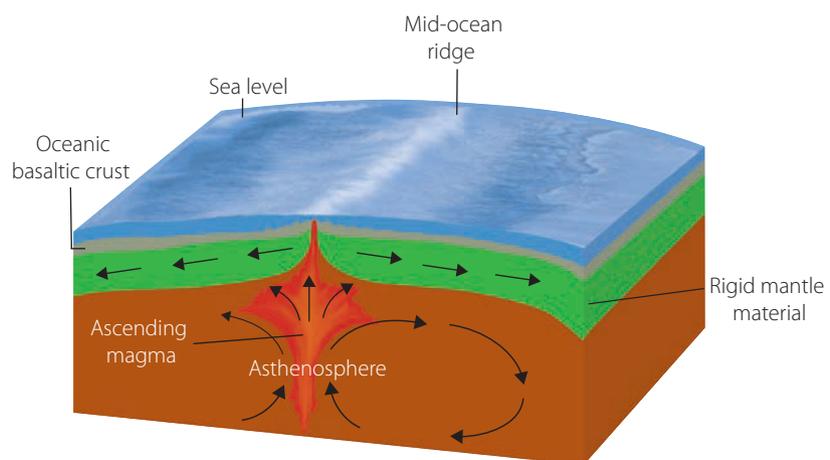
Divergent boundaries in oceanic lithosphere

In Chapter 6 you learnt about the work of Harry Hess and the mapping of the sea floor. This work led directly to his theory of sea-floor spreading proposed in the early 1960s. Because most of the divergent boundaries in oceanic lithosphere occur below sea level, it is difficult to observe them without actually descending to the ocean floor.

Mid-ocean ridge systems are found in all oceans and have been formed as a result of rising heat from the mantle. Oceanic lithosphere is much thinner than continental lithosphere, with an average thickness of 80–100 km. At oceanic spreading ridges, the lithosphere can be as thin as 10 km, and it is more severely affected by the rising heat. At all divergent plate boundaries, there is crustal thinning due to the combination of heat and the tension from the frictional drag of the mantle as it moves laterally away from the plate boundary. The heat being delivered to the base of the lithosphere causes it to expand and swell so that the ocean ridge can be up to 3 km higher than the deep ocean basins to either side. Being forced upwards and stretched sideways causes the crust and the upper mantle attached to it to become thinner, and if the rocks are brittle, they will break. This leads to a central rift being formed in the top of the ridge.

As the rocks of the ridge crest are faulted, any movement along these faults will reduce pressure on the upper mantle immediately below the central ridge. The reduction in pressure causes some of the mantle material to undergo **partial melting**, which produces basalt. This basalt **melt** is able to move upwards along the faults and make its way to the surface of the ocean floor. As the basalt cools from the top down, a succession of gradually coarser rocks form, such as dolerite and gabbro. These have the same chemistry as the basalt but with larger crystals. This process continuously forms new basaltic crust (Figure 7.4).

FIGURE 7.4
Formation of a mid-ocean ridge



Divergent boundaries in continental lithosphere

Continental lithosphere is much thicker than oceanic lithosphere, typically 150 km thick. Like oceanic lithosphere, the continental lithosphere is heated by the mantle and swells, but not to the extent seen in the oceanic lithosphere. Continental lithosphere is therefore more likely to behave in a brittle fashion and fractures more readily. This results in the formation of a **rift valley** in direct response to crustal thinning. The rift valley is always bounded on both sides by normal faults, meaning the central area of the rift valley is lower than the regions to either side (Figure 7.5). This can often form a corridor for major rivers, such as the Rhine River in Europe (Figure 7.7), or regions where linear lakes can form, such as in east Africa.

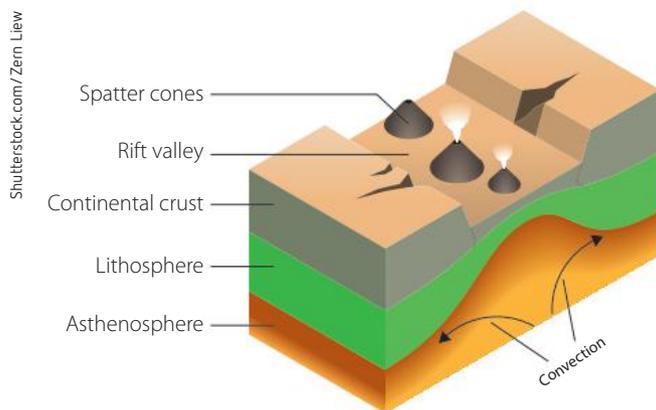


FIGURE 7.5
Structure of a continental rift valley showing boundary faults and volcanic centres

As in the central rift of the mid-ocean ridges, the reduction in pressure on the hot upper mantle material produces basalt magmas that move along the zones of weakness forming the boundary of the rift valley. A line of basaltic volcanoes can form along the length of the rift, ranging in size from small spatter cones only a few metres high to major volcanic mountains such as Mount Kilimanjaro in Kenya, which is 4900m from base to summit (Figure 7.6). Because the lava is basaltic and very fluid, the angle of the sides of these volcanoes is small.



FIGURE 7.6 Mount Kilimanjaro in Kenya, showing the small angle of the volcano's slopes

INVESTIGATION 7.1

Modelling rift valley formation

AIM

After reading the investigation, write an aim for it.

MATERIALS

- 2 wooden boards of A4 size and at least 2 cm thick
- Plaster of Paris, or damp coarse sand if the plaster of Paris is too difficult to use
- Cling wrap
- Digital camera (optional)

METHOD

- 1 Place the two wooden boards together with their long sides touching.
- 2 Cover the surface of the wooden boards with cling wrap so that the plaster of Paris is free to move.



Critical and creative thinking



- » 3 Mix enough plaster of Paris to form a layer 1 cm thick covering the join between the boards and extending at least 10 cm out from the join on each side.
- 4 Let the plaster set for about 2–3 minutes.
- 5 Slowly pull the boards apart from each other until there is a gap of approximately 10 cm.
- 6 Record any change in the surface of the plaster over the next 10 minutes.

RESULTS

Record your results using photographs or diagrams.

ANALYSIS OF RESULTS

- 1 Describe your results.
- 2 Where did the cracking occur in relation to the boards?
- 3 What was the height variation between the centre of the rift and the plaster that was still sitting on the boards?

CONCLUSION

How did this investigation assist you in understanding how rift valleys form?

KEY CONCEPTS

- A divergent plate boundary is a region where two plates are moving away from each other.
- Divergent plate boundaries are formed when heat energy from the centre of Earth heats magma, causing convection cells to form. The hot magma rises and lifts the lithosphere and flows sideways under it. This lateral flow drags the plates in the direction of the flow.
- Basalt is the most common rock formed at a divergent plate boundary.

CHECK YOUR UNDERSTANDING

7.1A

- 1 What is a divergent plate boundary?
- 2 Distinguish between a rift valley and a mid-ocean ridge.
- 3 Draw a labelled diagram to show how a divergent plate boundary is formed. Include the following terms in your labels: magma, convection, lithosphere, rift.
- 4 Contrast continental lithosphere with oceanic lithosphere.
- 5 How does the thickness of continental lithosphere and oceanic lithosphere affect the formation of divergent plate boundaries?
- 6 Construct a sentence to explain what happens at mid-ocean ridges using the following terms: basalt, melt, dolerite, gabbro, new basaltic crust.

Topographic and geological features of divergent plate boundaries

Divergent boundaries in continental lithosphere can be identified by topographic and geological features such as rift valleys and basalt eruptions. Continent–ocean boundaries are characterised by mid-ocean ridges, fissure eruptions, shallow earthquake activity, creation of new ocean sea floor and widening ocean basins.

Rift valleys

When a divergent plate boundary occurs in continental lithosphere, a rift valley is formed. The sides of a continental rift zone are bounded by normal faults, so the floor of the rift drops down to form a **graben** (German for trench). A graben is typically bounded on both sides by elevated plateau areas called **horsts** (German for heap) (Figure 7.7). Rift valleys are typically narrow and deep.

Volcanism along the rift valley is basaltic in nature. However, because the rift is above water, the result is fissure volcanoes or shield volcanoes. The basaltic lava that is extruded from both of these types of volcano is very fluid. Fissure volcanoes erupt vast amounts of the fluid lava, which often forms volcanic ‘fire curtains’ as it erupts, before rapidly away downhill from the fissure. Icelandic volcanoes erupt in this way. Shield volcanoes erupt in this way. Shield volcanoes have very slight slopes because of the fluid nature of the basalt, and they form major features in the landscape of the rift valley. Mount Kilimanjaro in Kenya is the best example of this type of volcano along a continental rift valley (Figure 7.6). When the surface of the fluid lava cools and solidifies, the lava beneath it continues to move. This causes the surface to fold in a way that looks like coils of rope. Hawaiians call this surface feature *pahoehoe*.

Because the rift valley forms a low point in the landscape, water is moved under gravity into the rift valley. In Africa, the rift valley is defined by a series of linear lakes – Lake Victoria, Lake Nyassa and Lake Malawi. In Europe, the Rhine rift confines the Rhine River into a narrow valley (Figure 7.7b).

As plates pull apart, there is frequent shallow earthquake activity, usually less than 30km deep. There is an earthquake somewhere in the world approximately every 30 seconds.

Mid-ocean ridges

The Mid-Atlantic Ridge is the best known of all the mid-ocean ridge systems. This ridge system forms a linear mountain chain running down the centre of the Atlantic Ocean and is up to 1600km across. The ridge crest is 2–3km higher than the deep sea-floor ocean basins to each side. Usually, the elevation of topographic features is measured from sea level, but this system does not work for heights above the ocean floor. The height of the top of the ridge is measured as a height above the ocean floor to either side of the ridge.

The mid-ocean ridge is the most common form of divergent plate boundary. The rock type at this plate boundary is mafic in composition because it has been formed from the partial melting of the upper mantle. Fine-grained rocks at the surface are called basalt; medium-grained rocks formed in dyke systems beneath the basalt are called dolerite; and the coarse-grained rock at the base of the oceanic crust is gabbro. The only major difference between the rocks is their grain size.

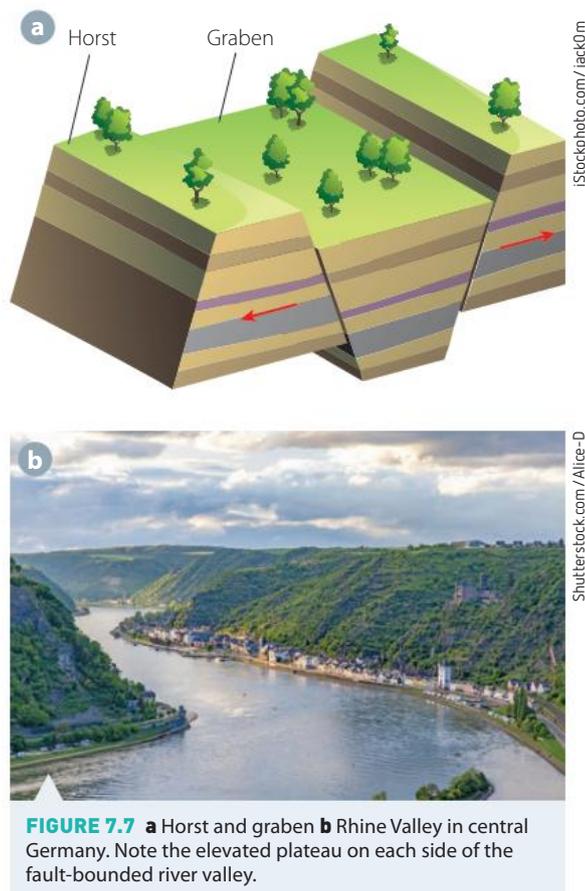


FIGURE 7.7 a Horst and graben b Rhine Valley in central Germany. Note the elevated plateau on each side of the fault-bounded river valley.



Basalt is typically molten at 1200°C while ocean temperature on the sea floor is typically 2°C. The surface of the extruded basalt crystallises on contact with the cold ocean water but the interior is still fluid, so basalt extruded from cracks in the sea floor builds up in pillow-shaped masses. A pillow basalt (Figure 7.8) is strong evidence that the basalt was erupted directly into a watery environment. The extruded basalt forms new oceanic crust, which spreads out because more crust is continuously made. This process forms **ocean basins**.



FIGURE 7.8 Pillow basalt from an underwater eruption

Shutterstock.com/Gudjon E. Olafsson

Normal faults

Normal faults enable the lithosphere to take up more horizontal space and are always associated with diverging plate boundaries. The rocks of the lithosphere behave in a brittle manner and split at right angles (normal) to the direction of the tension being applied. The movement is vertical, causing a section of the lithosphere, known as the hanging wall, to drop down relative to the area on the other side of the fault, known as the footwall, as shown in Figure 7.9.

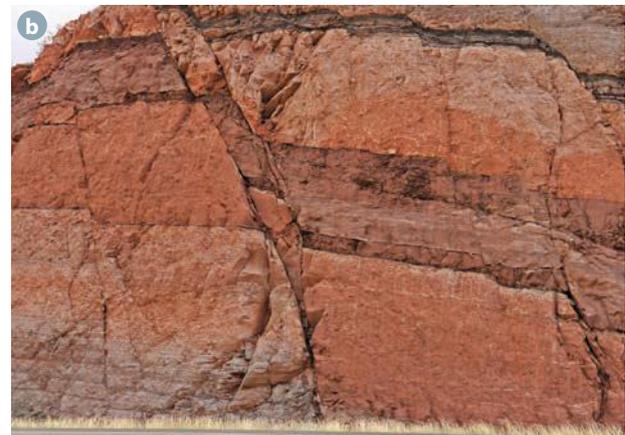
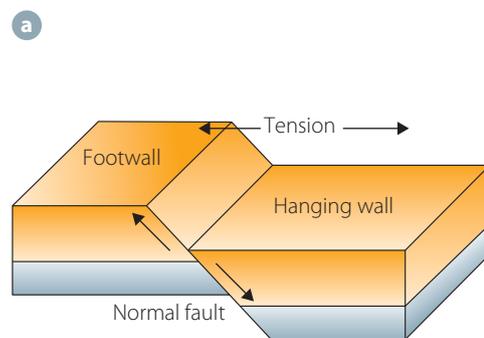


FIGURE 7.9 **a** A normal fault occurs when lithospheric rocks snap under tension. **b** A normal fault near Moab, Utah

Shutterstock.com/Breck P. Kent

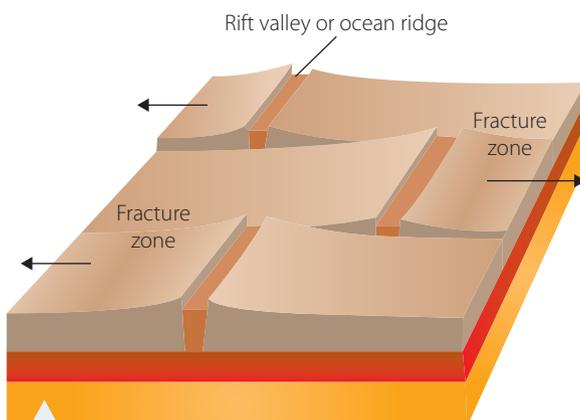


FIGURE 7.10 A transform fault can offset a rift valley or ocean ridge

Transform faults

Transform faults have little to no vertical movement on the fault. This makes them very different from other fault types. The movement along the fault is mainly horizontal and allows the spreading ridge or rift valley to be offset or to change direction (Figure 7.10). Transform faults are discussed in more detail in section 7.3.

Locating divergent plate boundaries

A rift valley is produced when a divergent plate boundary is located in continental lithosphere (Figure 7.11). If the plate boundary is located in the oceanic lithosphere, a mid-ocean ridge is formed.

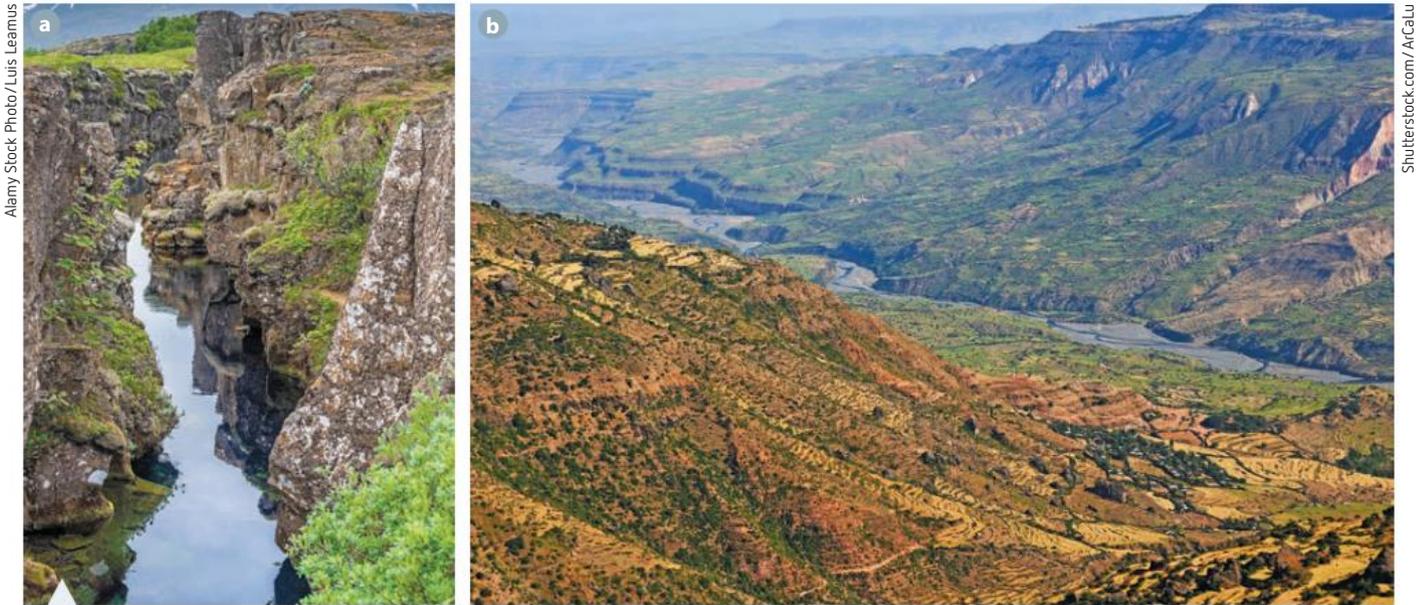


FIGURE 7.11 **a** Thingvellir National Park in Iceland showing the rift between the North American and Eurasian plates **b** The Great Rift Valley in Tanzania where the African Plate is splitting into two.

Figure 7.12 shows the locations of rift valleys and mid-ocean ridges. You will notice that the Mid-Atlantic Ridge passes through Iceland. This has formed the Thingvellir Rift Valley (Figure 7.11a). The Central Indian Ridge passes through north-east Africa, forming the Great Rift Valley (Figure 7.11b).

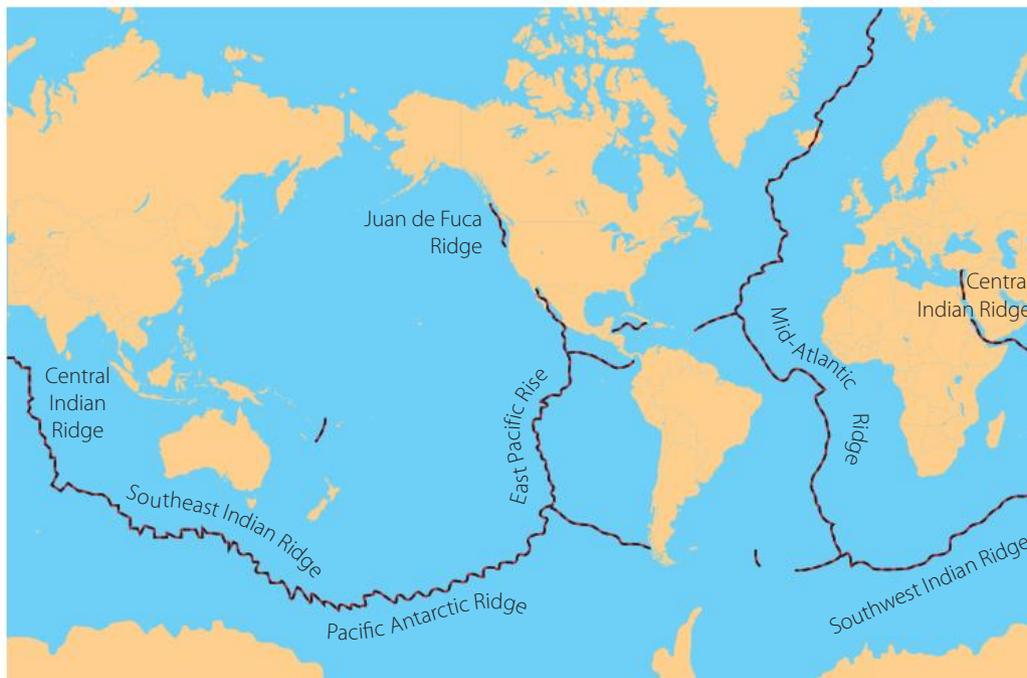


FIGURE 7.12 Locations of divergent plate boundaries in the lithosphere and the oceanic lithosphere

INVESTIGATION 7.2



Literacy



Information and communication technology capability



Literacy



Map of the world and plate boundaries

Locating divergent plate boundaries

AIM

To use a geological map of the world to locate divergent plate boundaries

METHOD

- 1 Download and print the map of the world from the worksheet 'Map of the world and plate boundaries'.
- 2 Use the Internet, an atlas or other sources to locate the information that you need.
- 3 Using a red pen or pencil, carefully draw on the map the location of all the divergent plate boundaries.
- 4 Locate and name the major ridge systems that have been mentioned so far in this chapter.
- 5 Create a key to show what the red lines indicate.
- 6 Keep this map because you will be using it again in Investigations 7.6 and 7.9.

KEY CONCEPTS

- Mid-ocean ridges are mountain systems that form on the ocean floor at divergent plate boundaries.
- Rift valleys can occur on continents and are caused by the movement of the underlying mantle material pulling continental crust apart.
- Rift valleys are low areas in the landscape and so often contain water in the form of linear lakes or major rivers.
- Rift valleys are bounded on both sides by normal faults.
- A normal fault is when a vertical section of the lithosphere drops down relative to the area on the other side of the fault.
- Mid-ocean ridges and rift valleys can change direction due to transform faults.
- A transform fault allows horizontal movement when two plates slide past each other.
- Mantle material partially melts to produce basalt, which moves to the ocean floor through faults, producing new sea floor.
- The continual production of new sea floor causes sea-floor spreading.

CHECK YOUR UNDERSTANDING

7.1B

- 1 What is formed when divergent plate boundaries move apart in continental lithosphere?
- 2 What is formed when divergent plate boundaries move apart in oceanic lithosphere?
- 3 List three differences between a rift valley and a mid-ocean ridge.
- 4 Name two places where major rift valleys occur.
- 5 Name three mid-ocean ridges.
- 6 Draw a diagram to distinguish between a graben and a horst. How do these relate to rift valleys?
- 7 Distinguish between the two types of fault associated with divergent plate boundaries.
- 8 Create a table to summarise the features associated with divergent boundaries.

7.2

Convergent plate boundaries

A **convergent plate boundary** is formed by the collision of two plates that are moving towards each other. The movement occurs as a result of the original movement of the plates away from the spreading ridge and the effect of gravity **subducting** a plate, or forcing it below another plate.

There are three different types of convergent plate boundaries: ocean–ocean, ocean–continent and continent–continent (Figure 7.13). In all three cases, there is **crustal shortening** or reduction in the area of Earth's crust as the plates collide. This crustal shortening is most marked in the continent–continent plate boundary because the continental lithosphere is too buoyant to subduct to any great degree.

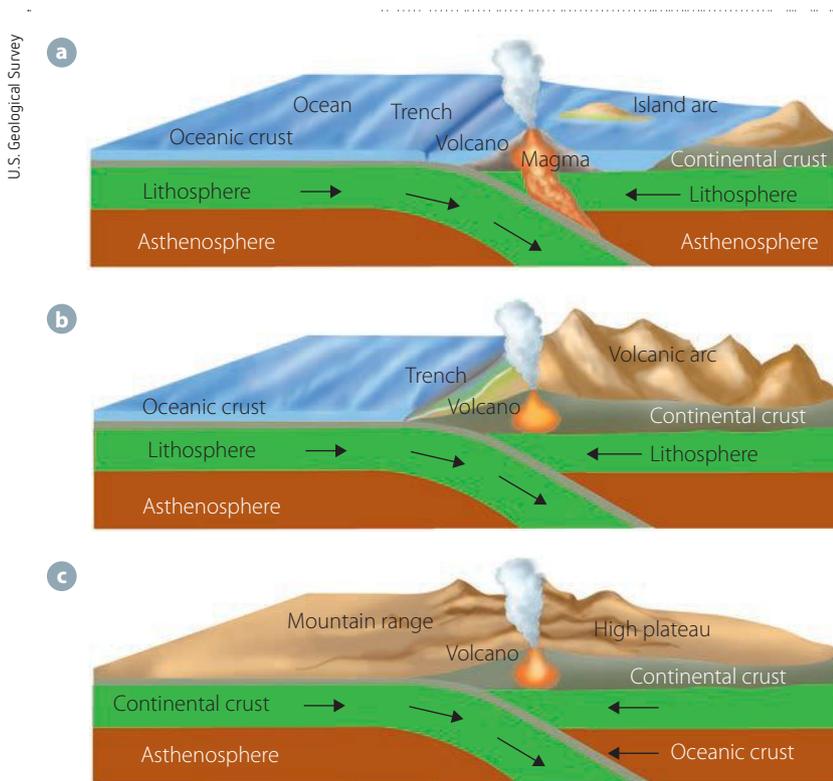


FIGURE 7.13

The three different types of convergent plate boundaries: **a** ocean–ocean **b** ocean–continent and **c** continent–continent

Ocean–ocean convergent boundaries

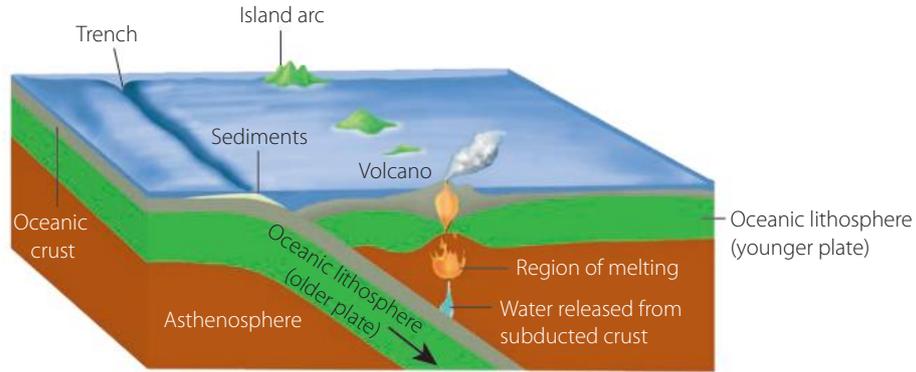
As an oceanic plate moves away from a mid-ocean ridge, it loses heat to the water above it. As this cooling continues, the oceanic lithosphere gradually thickens because mantle material adheres to its underside. This **underplating** means that the plate becomes thicker as it ages. When two oceanic plates collide, the older, thicker plate is more likely to be subducted.

Silica-based and calcium-based sediments build up on the surface of oceanic plates. Because these sediments build up at a steady rate over time, older oceanic crust will have thicker sea-floor sediments. There will also have been some chemical alteration of minerals within the basalts that have been in contact with the ocean. The most common chemical alteration is the addition of water to the structure of minerals, such as olivine and pyroxene, as they have weathered. Some of the feldspar minerals, particularly the plagioclase group, will have undergone partial alteration to clay.

As the older plate starts to subduct, friction with the overriding plate will cause some of the ocean floor sediments to be scraped off. Over time, this mix of ocean-floor sediments folds and faults into a large sedimentary mass (Figure 7.14). This sedimentary mass is known as an **accretionary wedge**.

FIGURE 7.14

An ocean–ocean plate collision. Notice the collection of sediments at the site of subduction. This is the accretionary wedge.



INVESTIGATION 7.3

Modelling accretionary wedge formation



Critical and creative thinking

You will need to work in groups of three to complete this investigation.

AIM

To model the formation of an accretionary wedge

MATERIALS

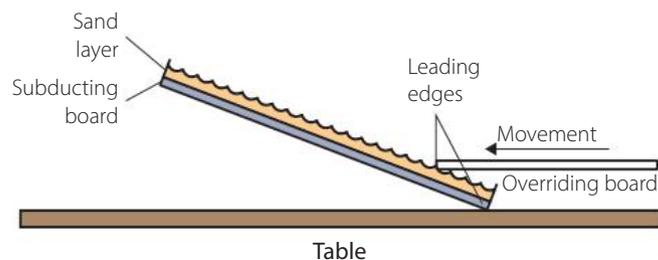
- 2 wooden boards of A4 size and at least 2 cm thick
- Coarse sand
- Fine sand
- Spray bottle of water
- Digital camera

Note: Fine finishing sand is usually pale in colour while coarse sand is most commonly crushed sandstone and is darker. Using sands of different colours will make it easier to observe and record the changes within the modelled accretionary wedge.

METHOD

- 1 Cover one of the boards with a 1-cm layer of coarse sand with a 1-cm layer of fine sand on top. As each layer is applied to the board, spray the sand with water to make it damp. This board will be the subducting board.
- 2 Keeping the leading edge of the subducting board in contact with the table, raise the trailing edge so the board is at a slight angle, as shown in Figure 7.15.

FIGURE 7.15



- » 3 While one student holds the subducting board in place, a second student is to slowly push the overriding board towards it.
- 4 Use the digital camera to record any change in the surface layer of sand as the two boards are pushed together.

RESULTS

Record your results using photographs or diagrams. Label the subducting plate, overriding plate and the accretionary wedge.

ANALYSIS OF RESULTS

- 1 What happened to the layering within the sand at the leading edge of the boards?
- 2 What was the increase in the thickness of the sand at the edge of the overriding board?

CONCLUSION

Summarise your findings regarding the formation of structures in an accretionary wedge. How did this model assist in your understanding of accretionary wedge formation?

Trenches

High pressures are exerted on the mix of sediments in the accretionary wedge. High pressure and low temperature metamorphism is a common feature within the wedge. With time, the subducting plate also pulls down the leading edge of the overriding plate, creating a linear **trench** of often exceptionally deep water (Figure 7.16). The average depth of the ocean worldwide is approximately 3100m, but trench areas can be much deeper. For example, the deepest part of the Mariana Trench is the Challenger Deep, at approximately 11 000 m.

When the subducting plate descends past a depth of 100km, the upper surface of the basalt and remaining oceanic sediments begins to melt. This partial melting gives rise to a magma that has a much higher silica, carbon dioxide and water content than the magma that formed the original basalt. This molten material rises towards the surface and forms a chain of volcanic islands called an **island arc**. When the island arc is relatively young it will be a chain of individual volcanic islands, such as in the Aleutian Islands (Figure 7.17), but over time, adjacent islands can join together to form larger island groupings with a number of active volcanoes, as seen in Japan and Indonesia.

The magma with its enriched silica and volatile (water and carbon dioxide) content behaves very differently from basalt magmas. Often described as andesitic magma because the most common volcanic rock formed is andesite, high-silica magma is much more viscous and has a lower temperature than basalt magmas. These factors combine to cause very **explosive** volcanic eruptions. Some of these eruptions have caused large numbers of deaths either directly or by affecting climate (Table 7.2). There have been three recorded cases where volcanoes fed by this type of magma have produced eruptions so violent that they were able to affect global climate for up to three years after the eruption.

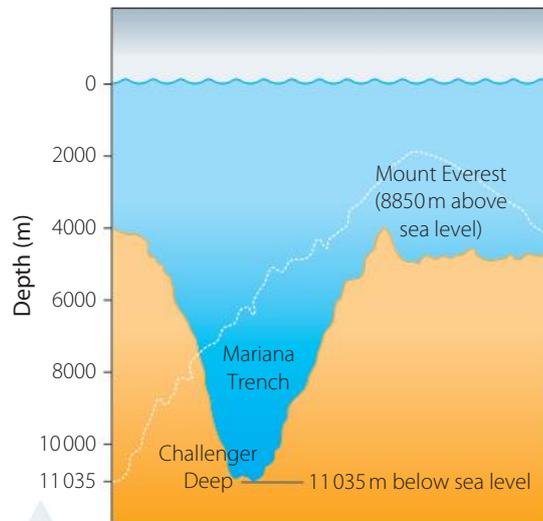


FIGURE 7.16 The highest and lowest points on Earth. Mount Everest would fit into the Challenger Deep with about 2 km of water still above it.

FIGURE 7.17
The relationship between the Aleutian Island chain and nearby continents



TABLE 7.2 Island arc volcano eruptions and number of deaths

ISLAND ARC VOLCANO AND YEAR OF ERUPTION	NUMBER OF DEATHS
Tambora, Indonesia, 1815	100 000+
Krakatau, Indonesia, 1883	36 000
Mt Pelee, Martinique, 1902	29 000
Mt Unzen, Japan, 1792	15 000
Mt Kelud, Indonesia, 1586	10 000

The region between the island arc and the trench is known as the **fore-arc basin**. It receives sediments from the volcanic material on the island chain, the accretionary wedge sediments and shallow-water marine sediments such as corals that will eventually become limestone. The distance between the trench and the development of the island arc is determined by the angle with which the descending plate moves into the mantle. If it is a fairly steep angle, the distance between the trench and the island arc will be relatively short, as seen in the Aleutian Islands (Figure 7.17). However, if the angle of descent is relatively

shallow, there can be a larger distance between the trench and the island arc, as seen in the region along the Tonga-Kermadec trench system. On the other side of the islands is the **back-arc basin**. Volcanic material and shallow-water marine deposits occur here but without the deep-water sediments found in the accretionary wedge.

Ocean–continent convergent boundaries

When an oceanic plate collides with a continental plate, it is the oceanic plate that is subducted (Figure 7.18). This is because oceanic crust has an average density range of $3.0\text{--}3.2\text{gcm}^{-3}$ while continental crust has an average density range of $2.6\text{--}2.8\text{gcm}^{-3}$. Enormous forces push the denser plate down into the mantle, generating extreme temperatures. Volcanic

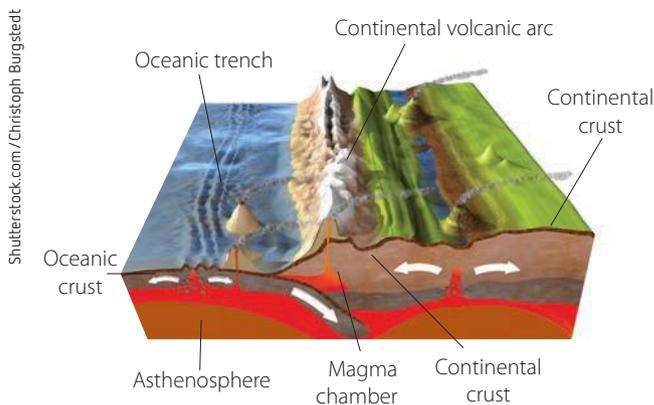


FIGURE 7.18 Cross-section showing the collision between an oceanic and a continental plate

activity usually occurs where there are subduction zones, such as in Indonesia.

As the oceanic plate subducts, it produces an ocean trench close to the edge of the continental plate, which will have a very narrow continental shelf. The continental shelf is part of the continental lithosphere that is submerged beneath shallow waters at the edge of the continent. A continental shelf lies off the east coast of New South Wales.

Many earthquake disasters have occurred on ocean–continent plate boundaries. In 2004, a tsunami resulted when an earthquake occurred 160 km

off the west coast of northern Sumatra, approximately 4500 km north-west of Australia. The earthquake was triggered by a rupture along the fault line where the Indian Plate was being subducted under the Burma Plate. Accumulating stresses caused the Burma Plate to snap upwards over a length of 1200 km. The displaced water caused the devastating tsunami. The estimated death toll of 275 000 people occurred across 14 countries.

Earthquakes will most often occur on the upper surface of the descending plate slab. This area is known as the **Benioff-Wadati zone** (Figure 7.19). Mapping of the foci of these earthquakes has enabled seismologists to map the descending plate.

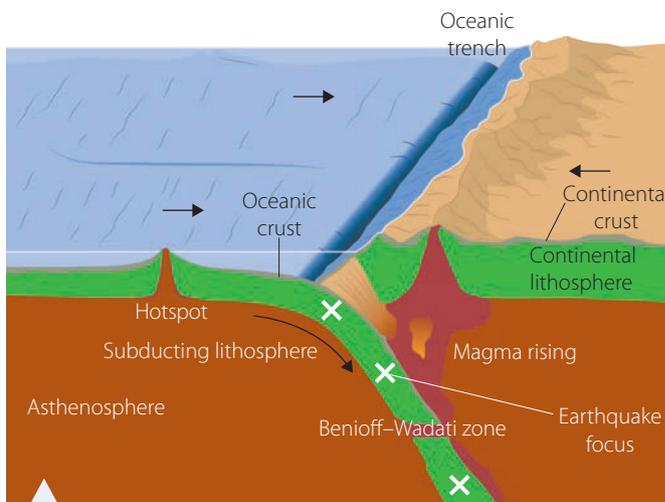


FIGURE 7.19 Benioff-Wadati zone of increased earthquake activity

You might like to investigate the New South Wales continental shelf further for a depth study.

Continent–continent convergent boundaries

Convergent boundaries formed by the collision of two continental plates have different rock types and structures from other types of collisional boundaries.

Where continental plates collide, as shown in Figure 7.20, there is always a subduction zone between them where oceanic lithosphere has been subducted over time. This means that there is a large and very thick accretionary wedge on the leading edge of the overriding plate. This accretionary wedge material will sit geographically close to sediments that have formed over time in very deep water in the oceanic trench. The approaching continental plate will have a wide continental shelf with typical shallow-water marine sediments up to a few kilometres thick.

As the two continental masses approach closely enough for the sediments to start to interact, subduction effectively ceases. The sediments have a density similar to continental lithosphere and so do not subduct to any great extent; rather, they start to fold and fault to accommodate the continued movement of the plates. This process is occurring as the subcontinent of India is being pushed towards the north-east into Asia, producing the Himalayas. With the ending of subduction, volcanoes on the overriding plate gradually cease to erupt and quickly erode.

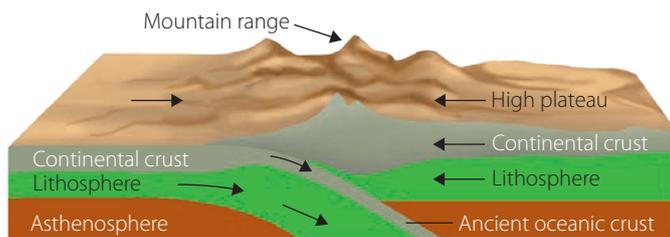


FIGURE 7.20
Two continental plates colliding

INVESTIGATION 7.4

Modelling the collision of two continental plates

AIM

To model the structures that occur in rocks as two continental plates collide



Critical and creative thinking

MATERIALS

- 2 wooden boards of A4 size and at least 2 cm thick
- 3 different colours of playdough or modelling clay
- Rolling pin
- Plastic knife
- Baking paper (30 cm × 30 cm)
- Digital camera
- Sticky tape

METHOD

- Working in groups of two or three, roll out each colour of modelling clay into an 8 cm × 8 cm square.
- Securely sticky tape each end of the baking paper to the table. This is your work space. Place one square of modelling clay on the sheet of baking paper. Place the other two squares on top to make a stack.
- Use the knife to trim the outer edges of the modelling clay stack so that there is a flat surface on each edge.
- Photograph the 'before' modelling-clay stack.
- Place the two wooden boards on top of the baking paper on either side of the modelling clay.
- Have one student in charge of each board. Gently start to push the boards towards each other until the modelling clay stack has reduced in width by half.
- Photograph the 'after' modelling-clay stack.

RESULTS

Record your results using photographs or diagrams.

ANALYSIS OF RESULTS

- Describe how the layers of modelling clay changed shape.
- Did you observe any change in thickness of the layers before and after?

CONCLUSION

How did this investigation model the collision between two continental plates? Can you suggest any improvements to the model?

KEY CONCEPTS

- The three types of convergent boundary are ocean–ocean, ocean–continent and continent–continent.
- Older oceanic lithosphere becomes thicker with age through a process called underplating.
- An accretionary wedge is formed as an oceanic plate subducts under a continental plate.
- Volcanoes form as an oceanic plate subducts beneath a continental plate.
- Oceanic lithosphere can be tracked as it is subducted by means of the earthquakes generated by friction between the subducting and overriding plates.
- Chains of islands in an arc shape are an indicator of an ocean–ocean plate collision.
- Subduction ceases and folding and faulting occur, forming mountain ranges, when two continental plates collide.

- 1 What is a convergent plate boundary?
- 2 Define subduction and underplating.
- 3 State the three different types of convergent plate boundaries.
- 4 Explain the make-up of an accretionary wedge and how it forms.
- 5 Use a series of diagrams to show where and how a trench forms.
- 6 Why does subduction cease when two continental plates collide? What forms instead?
- 7 What does an island arc indicate?
- 8 Which plate subducts when an oceanic plate collides with a continental plate? Explain why.
- 9 Contrast high-silica magma with basalt magma.

Topographic and geological features of convergent plate boundaries

Specific topographic and geological features such as mountain ranges, trenches and reverse faults and folds occur at convergent plate boundaries.

Oceanic–continental mountain ranges

The collision between an oceanic plate and a continental plate causes a coastal mountain chain to form. The leading edge of the continental plate crumples in the collision. Due to the density difference between oceanic and continental lithosphere, the continental lithosphere is forced upwards. This crumpling of continental lithosphere forms a broad mountain chain that runs parallel to the deep-ocean trench (Figure 7.19). The descending plate undergoes partial melting at a depth of around 100 km and produces an intermediate-chemistry magma rich in volatile components. This material makes its way up through the overlying crust, often absorbing some of the continental rocks along the way, further increasing the silica content of the magma. If the passage to the surface is delayed for too long, the molten material can start to crystallise and intrusive bodies of diorite and syenite (types of intermediate-chemistry igneous rocks) are formed that become part of the base of the mountain chain. When the magma does reach the surface, the resulting volcanoes are always explosive and produce large volumes of ash or powdered rock that can then flow away from the crater. Karymsky, in Russia, is one such volcano (Figure 7.21).

The mountain range formed is composed of two sections: a volcanic mountain chain closer to the coast (often referred to as the magmatic arc) and a fold mountain chain further inland. The fold mountain chain is characterised by **reverse faulting** and heavily folded material. In this region there is often extensive metamorphism due to the huge forces acting on the rocks.

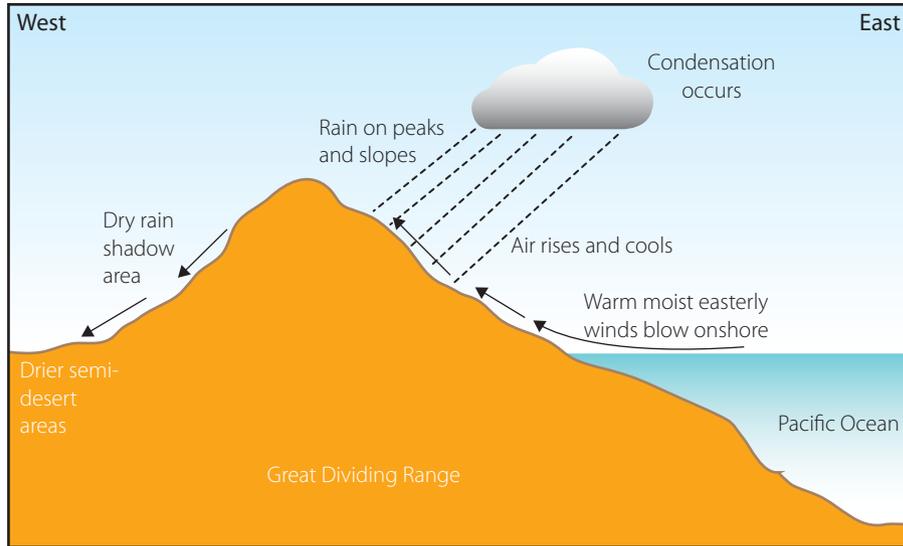
There is a strong **orographic** effect on any winds blowing from the ocean to the land, often leading to extensive rain shadows and desert areas behind the mountain range. Examples of this are the Atacama Desert in Chile, the High Desert plateaus of northern California and the Great Dividing Range along the Queensland and New South Wales coastlines (Figure 7.22). The large amount of rain, as well as snow at higher elevations, that falls on the windward side of the mountains means that they are often a source of large rivers.



FIGURE 7.21 Karymsky volcano, Kamchatka, Russia, showing an ash explosion

You will learn more about reverse faulting on page 192.

FIGURE 7.22
The Great Dividing Range causes a rain shadow on the western side



Continental–continental mountain ranges

A collision between two continental plates causes a linear mountain range to be formed within the centre of a continent. Geologists use this information to assist in determining which parts of a present-day continent came from earlier continents. Radioactive dating (Chapter 4) makes it possible to determine when parts of a large continent were assembled from its component parts. The best-known example of this type of mountain range is the Himalayan–Alpine belt (Figure 7.23), which started to be formed approximately 75 million years ago and runs from Asia to Europe.

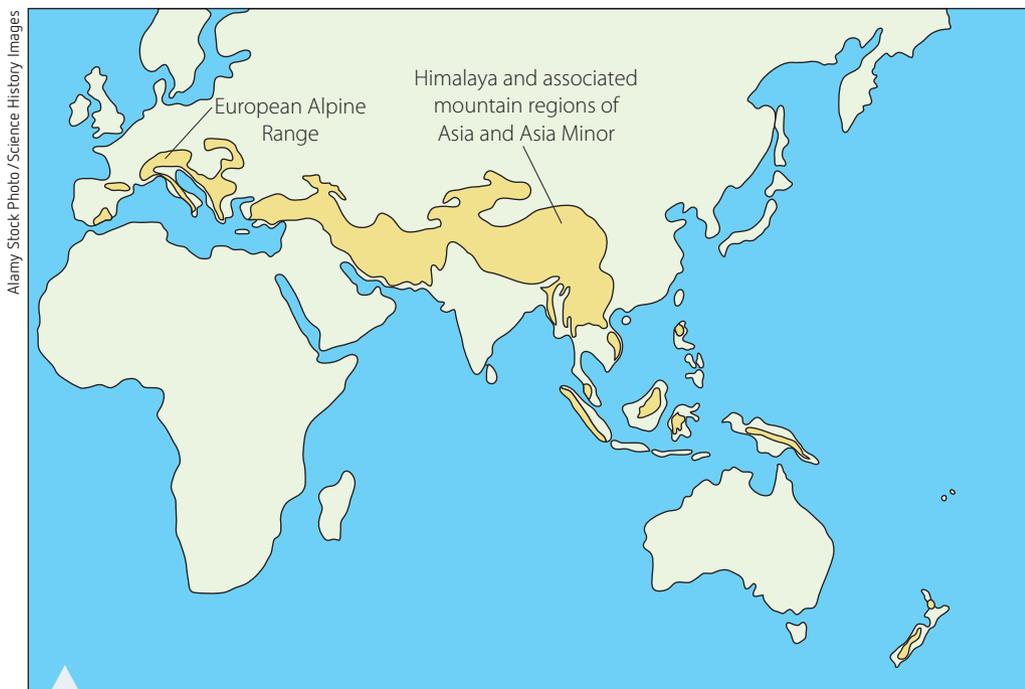


FIGURE 7.23 The Himalayan–Alpine belt

The overall effect of the folding and reverse faulting is that the sediments gradually pile up on each other, becoming increasingly thicker. As this thickening occurs, the sheer weight of rocks forces the lower part of the emerging mountain range deeper. This brings the lowermost rocks in the folded mass into contact with the much hotter mantle material from underneath the crust. At this point, a combination of frictional heating from the folding and the heat coming from the mantle starts partial melting of some of the sediments. Water caught up in the structure of the sediments causes the rocks to melt at a much lower temperature than if there was no water present. (Dry quartz melts at about 650°C but if as little as 1% water is added then the melting temperature of the quartz can be as low as 350°C.) Because this melt is formed from the sediments of the sea floor, it often contains large components of quartz and clays. The quartz and the clay form a molten mass that has a relatively high silica content, typically above 65% silica, which means it is very viscous. This high viscosity means that the molten material, now generally called granite, moves slowly as it travels up through the crust. On a few occasions, the magma may get close enough to the surface to erupt. This is the exception, because the majority of granite bodies cool within the crust before they reach the surface. The granites help to weld the sediments together, along what geologists call a **suture line** along a major fault zone.

The folded sediments and resulting granites usually form a broad mountain range. As the mountains push higher as a result of the plates continuing to converge, they will intercept rain-bearing winds and clouds and affect rainfall patterns in the region. These mountain ranges will also give rise to large river systems that flow from their flanks, such as the Ganges and Brahmaputra rivers in India and the Danube in Europe. Evidence of older suture regions found as linear mountain chains in the centre of continents, such as the Ural Mountains in Russia, provide evidence of the direction of collision. Even very old mountain chains that are little more than hills, such as the Peterman Ranges and the MacDonnell Ranges in central Australia, provide information about the assemblage of the Australian continent many millions of years ago.

Oceanic trenches

An oceanic trench, or deep-ocean trench, is a linear depression in the ocean floor where water depth is much greater than in other areas of the ocean (Figure 7.24). An oceanic trench will occur wherever oceanic lithosphere is subducting beneath another plate.

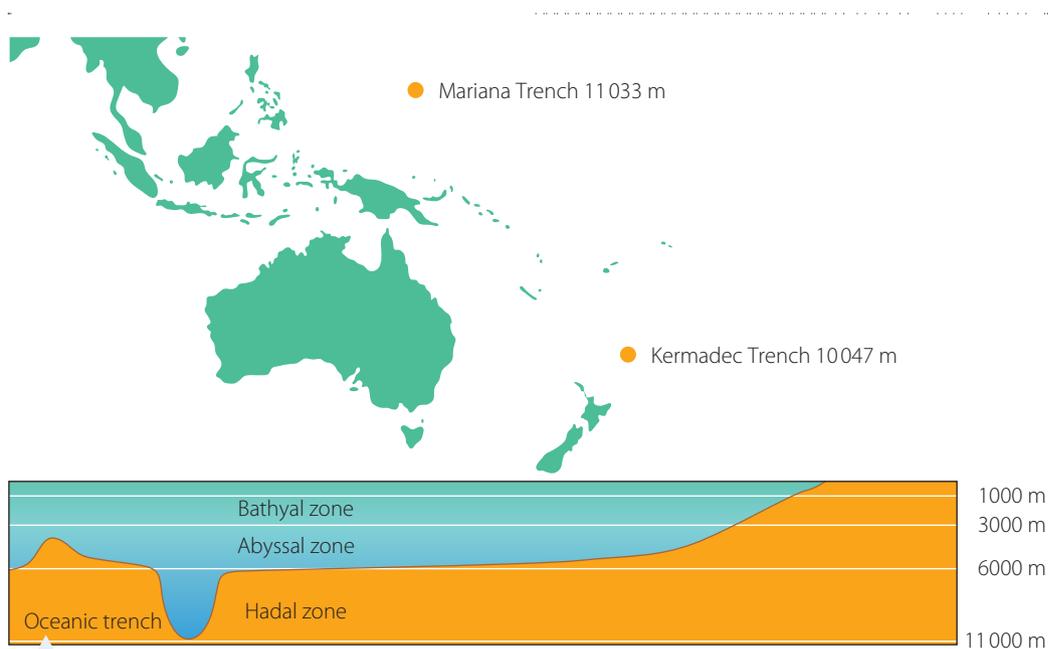


FIGURE 7.24 Location of the two nearest trench areas to Australia, and the cross-section of a trench system

Reverse faults and folds

Folding is a way that crustal rocks change shape as they are slowly pushed together. The degree of folding is also a method of determining the intensity of the collision, with simple open folds as shown in Figure 7.25 indicating the first stages of the collision.

FIGURE 7.25
Simple open folds in
sedimentary rocks



Alamy Stock Photo/blackwinkel

As the plate collision continues, more complex folding occurs until the folds become larger and more tightly pushed together, as shown in Figure 7.26.

FIGURE 7.26
Tightly folded rocks



Shutterstock.com/Matauw

With even more pressure applied, the folds become increasingly folded back on themselves. They can even be broken off and can slide along a low-angle fault for many kilometres in a structure known as a **nappe** (Figure 7.27).



FIGURE 7.27
Tightly folded marine
sediments in the Swiss
Alps

If the folding becomes too intense or the pressure is applied too quickly, a reverse fault will be formed. In a reverse fault, the land is compressed to the point where one block is pushed up on top of the other (Figure 7.28). It is a form of crustal shortening. A reverse fault is the opposite of a normal fault.

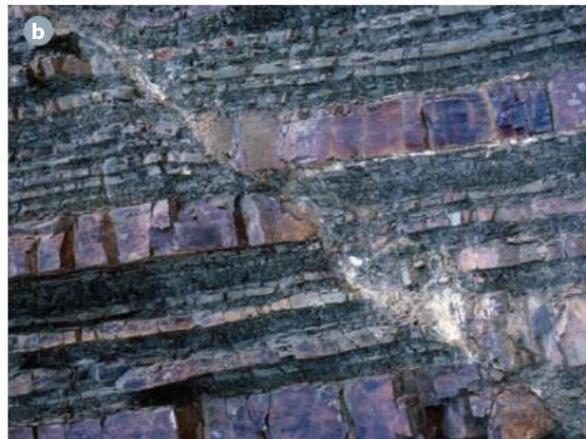
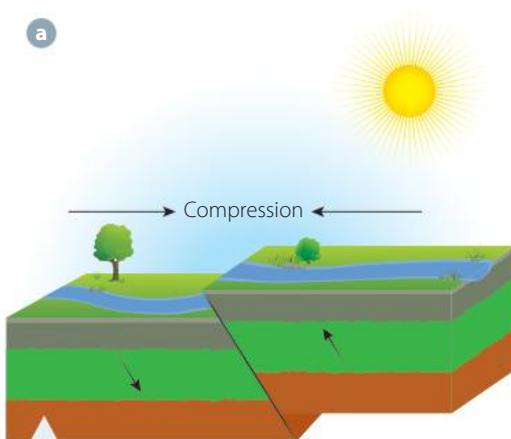


FIGURE 7.28 **a** In a reverse fault, the hanging wall rises relative to the footwall. One block of rocks is pushed on top of another, the opposite of a normal fault. **b** These strata show the movement clearly.

INVESTIGATION 7.5

Comparing convergent plate boundaries

You may be familiar with using tables in spreadsheets to manipulate numerical data. A well-designed table is an excellent way to organise information for study or in response to an exam question that requires you to compare two or more features.

Construct a table to compare the features of each of the three types of convergent plate boundaries. Include information on types of plate involved, volcanism (if any), rock types, geological structures, earthquakes and their depth, and topographic features associated with each type of boundary.



Locating convergent plate boundaries

The Andes mountain range in South America is an example of a convergent plate boundary. It is a result of the Nazca Plate (oceanic) subducting beneath the South American Plate (continental). The Tibetan Plateau is the result of an ongoing collision between the Indian and Eurasian continental plates that started around 75 million years ago.

INVESTIGATION 7.6



Information and communication technology capability



Literacy

Locating convergent plate boundaries

AIM

To use a map of the world to locate convergent plate boundaries

METHOD

- 1 Locate the world map that you used in Investigation 7.2.
- 2 Use the Internet, an atlas or other sources to locate the information that you need.
- 3 Using a blue pen or pencil, carefully draw on the map the location of all the convergent plate boundaries. Devise a technique to show which plate, if any, is the subducting plate.
- 4 Locate and name the mountain ranges that have been mentioned in this chapter so far.
- 5 Add the blue line to the key.
- 6 Keep this map because you will be using it again in Investigation 7.9.

KEY CONCEPTS

- Linear mountain chains at one side of a continent indicate an oceanic plate subducting beneath the continental plate.
- Continent–continent plate collisions produce broad mountain chains, often in the middle of a continent.
- Volcanoes at collision zones are highly explosive as a result of the high silica and water content of the magma supplied from the subducting oceanic plate.

CHECK YOUR UNDERSTANDING

7.2B

- 1 List the features of an ocean–ocean plate collision that allow it to be identified easily.
- 2 List the features of an ocean–continent plate collision that allow it to be identified easily.
- 3 List the features of a continent–continent plate collision that allow it to be identified easily.
- 4 Describe the type of faulting that is most commonly associated with collision boundaries.
- 5 What is the name of the arrangement of earthquakes that defines the outline of the descending plate in a subduction zone?
- 6
 - a Why are volcanoes at subduction zones particularly explosive?
 - b Why are volcanic eruptions not associated with a continent–continent collision zone?

7.3

Transform plate boundaries

Transform faults were first described in the early 1960s by Canadian geologist John Tuzo Wilson. His explanation allowed sea-floor spreading ridges to be offset incrementally along their length and accounted for the curved nature of the mid-ocean ridges recorded from sonar depth soundings. Transform offsets have also been identified in terrestrial rift valleys such as the East African Rift system and the Rhine Valley in Germany. Transform faults tend to cut the main direction of the rift system at right angles, with little or no vertical displacement. Because the plate segments on either side of the transform fault are moving in opposite directions, they are often the location of numerous shallow (less than 100 km depth) earthquakes.

INVESTIGATION 7.7

Modelling transform faults cutting a spreading ridge

AIM

To model how a curved spreading ridge can form

MATERIALS

- Baking paper (approximately 60 cm)
- 10 wood strips (4 cm wide, 15 cm long and at least 2 cm thick)
- Coarse sand
- Spray bottle of water
- Ruler
- Sticky tape
- Digital camera

METHOD

- 1 Tape a sheet of baking paper to the table.
- 2 Place the 10 wooden strips together on the baking paper, as shown in Figure 7.29, so that their long edges sit side by side.

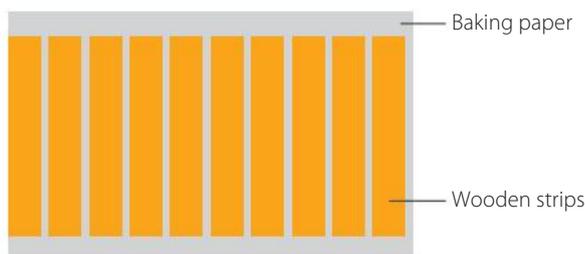


FIGURE 7.29

- 3 Place a layer of coarse sand over 80% of the area covered by the wood strips.
- 4 Spray the sand with the water so that it is damp but not completely wet.



Critical and
creative thinking

- » 5 Using a ruler edge, make a depression in the sand, twice the width of the ruler, that cuts across the boards at right angles. Take a photo from above.
- 6 Keeping the wooden strip on the left-hand side fixed in position, slide the second wooden strip 2 cm past it lengthwise along the paper.
- 7 Repeat this movement and direction for the next three strips.
- 8 Move the remaining strips the same distance in the opposite direction. Take a photo from above.
- 9 Record any change in the surface of the sand as you move each strip of wood.

RESULTS

Describe any changes that you observed in the ruler depression.

ANALYSIS OF RESULTS

- 1 How did this investigation account for the curved nature of a spreading ridge observed by John Tuzo Wilson?
- 2 What is meant by a transform fault?
- 3 Did you have any problems performing this investigation? What changes could you suggest to improve this model?

CONCLUSION

Account for the use of models to assist in understanding geological phenomena.

Processes that formed transform plate boundaries

Movements at spreading plate boundaries and collisional plate boundaries have substantial vertical components. They happen at roughly the same rate, so that the amount of oceanic and continental lithosphere remains the same. If Earth were flat and not a sphere, then spreading and subduction

could operate as the only plate tectonic movements. However, the planet is spherical and rotational movement is needed to accommodate movement over the surface of the sphere. Transform boundaries are necessary to allow for that rotation. When transform plate boundaries move past each other, the fracture zone that is formed is known as a transform fault. This movement can be significant, as shown in Figure 7.30.

When plate components move past each other, the only heat energy generated is frictional. This is not enough heat to lead to any metamorphism of the rocks on either side of the plate boundary. However, the pressures exerted can be immense and rocks along the transform fault can be crushed to a fine powder. This is generally called **fault gouge**. The formation of fault gouge actually allows more ease of movement between the two sides of the fault because it is the remains of the rocks that had previously been locked together.



FIGURE 7.30 This fence was displaced 2.5 metres near the San Andreas fault during the April 1906 earthquake.

INVESTIGATION 7.8

Modelling a transform plate boundary

AIM

To model how a transform plate boundary can form

MATERIALS

- 2 wooden boards of A4 size and at least 2 cm thick
- Plaster of Paris, or damp coarse sand if the plaster of Paris is too difficult to use
- Cling wrap
- 10 toothpicks or matches
- Digital camera

METHOD

- 1 Cover each wooden board separately with cling wrap.
- 2 Place the two wooden boards together against their long sides.
- 3 Mix enough plaster of Paris to form a 1-cm thick layer covering the join between the boards and extending at least 10 cm out from the join.
- 4 Let the plaster set for about 2–3 minutes.
- 5 Break the toothpicks or matches in half and use them to make a fence line that crossed the join.
- 6 Slowly push the boards in opposite directions for approximately 10 cm.
- 7 Use the digital camera to record any change in the surface of the plaster.

RESULTS

Describe the changes that you observed.

ANALYSIS OF RESULTS

- 1 Where did the cracking occur in relation to the join between the boards?
- 2 Was there any change in shape in the plaster sitting on the boards?
- 3 Was any new crust at the boundary created by this movement?

CONCLUSION

How did your model assist you in understanding transform faults? Can you suggest any ways to improve the model?

Locating transform plate boundaries

The San Andreas fault in California is a transform fault (Figure 7.31). The transform fault system in California is not simply plates sliding past each other. The surfaces along the transform fault are not smooth and they interlock for a period of time. The forces pushing the plates on either side of the transform fault do not stop, even when a section of the transform fault has locked up. Once the stress of the forces pushing the plate segments in opposite directions exceeds the strength of the rocks that have caused the lock-up, an earthquake is inevitable. The longer the stress builds up around the lock-up, the larger the earthquake will be.



FIGURE 7.31 Aerial view of the San Andreas fault cutting across the Carrizo Plain in California

A second aspect of the plate boundary is that the two plates change direction slightly along the length of the transform boundary. This is because Earth is a sphere and not a flat plane. This slight change in direction has caused a large number of secondary fault systems to propagate out from the plate boundary, making this region one of the most seismically active regions on Earth. These secondary fault systems also interact with each other, and there is a series of small mountain ranges parallel to the Californian coastline that have been formed as a result.

INVESTIGATION 7.9



Information and communication technology capability



Literacy

Locating transform plate boundaries

AIM

To use a map of the world to locate transform plate boundaries

METHOD

- 1 Locate the world map that you used in Investigations 7.2 and 7.6.
- 2 Use the Internet, an atlas or other sources to locate the information that you need.
- 3 Using a green pen or pencil, carefully draw onto the map the location of all the transform plate boundaries.
- 4 Locate and name the transform fault lines that have been mentioned so far in this chapter.
- 5 Add the green line to the key.

KEY CONCEPTS

- A transform fault is the fracture zone formed when two plates slide horizontally past each other.
- Rocks can be locked together at transform boundaries, preventing movement.
- Locked-up boundaries can become unlocked suddenly when the forces on them overcome the strength of the rocks, causing earthquakes.
- The San Andreas fault in California is a transform fault.

CHECK YOUR UNDERSTANDING

7.3

- 1 What is a transform plate boundary?
- 2 List three places where major transform plate boundaries occur.
- 3 Describe the type of movement that occurs at a transform plate boundary.
- 4 What occurs as two transform plate boundaries move past each other?
- 5 Explain why earthquakes occur at transform plate boundaries.
- 6 Account for why the shape of Earth is responsible for transform plate boundaries.

7 CHAPTER SUMMARY

- ▶ A divergent plate boundary is a region where two plates are moving away from each other.
- ▶ Divergent plate boundaries are formed when heat energy from the centre of Earth heats magma, causing convection cells. The hot magma rises and lifts the lithosphere and flows sideways under it. The lateral flow drags the plates in the direction of the flow.
- ▶ Basalt is the most common rock formed at a divergent plate boundary.
- ▶ Rift valleys can occur on continents and are caused by the movement of the underlying mantle material pulling a continent apart.
- ▶ Linear lakes or major rivers regularly form within rift valleys because the valleys are low regions in the landscape.
- ▶ Rift valleys are bounded on both sides by normal faults.
- ▶ Mid-ocean ridges are mountain systems that exist on the ocean floor at divergent plate boundaries.
- ▶ Mid-ocean ridges and rift valleys can change direction due to transform faults.
- ▶ A transform fault is horizontal movement when two plates slide past each other.
- ▶ A normal fault occurs when a vertical section of the lithosphere drops down relative to the area on the other side of the fault.
- ▶ Mantle material partially melts to produce basalt, which moves to the ocean floor through faults and produces new sea floor.
- ▶ The continual production of new sea floor causes sea-floor spreading.
- ▶ The three types of convergent boundary are ocean–ocean, ocean–continent and continent–continent.
- ▶ Older oceanic lithosphere becomes thicker with age through a process called underplating.
- ▶ Oceanic lithosphere can be tracked as it is subducted due to the earthquakes generated by friction between the subducting and overriding plates.
- ▶ Chains of islands in an arc shape are an indicator of an ocean–ocean plate collision.
- ▶ Volcanoes form as an oceanic plate subducts beneath a continental plate.
- ▶ When two continental plates collide, subduction ceases and folding and faulting occur, forming mountain ranges.
- ▶ Linear mountain chains at one side of a continent are an indication of an oceanic plate subducting beneath the continental plate.
- ▶ Continent–continent plate collisions produce broad mountain chains, often in the middle of a continent.
- ▶ Volcanoes at collision zones are highly explosive due to the high silica and water content of the magma that comes from the subducting oceanic plate.
- ▶ A transform fault is the zone formed when two plates slide horizontally past each other.
- ▶ Rocks can be locked together at transform boundaries, preventing movement.
- ▶ Locked-up boundaries can become unlocked suddenly when the forces on them overcome the strength of the rocks, causing earthquakes.
- ▶ The San Andreas fault in California is a transform fault.

7 CHAPTER REVIEW QUESTIONS



- 1 Distinguish between divergent, convergent and transform plate boundaries.
- 2 Explain how convection contributes to movement at plate boundaries.
- 3 Account for the heat that drives convection in the mantle.
- 4 Copy the table and place these terms in the correct column to show which type of boundary they are associated with: mid-ocean ridge, transform fault, reverse fault, trench, fold, rift valley, mountain range, normal fault

DIVERGENT PLATE BOUNDARY	CONVERGENT PLATE BOUNDARY

- 5 Outline the differences between a divergent plate boundary on the ocean floor and one found in continental lithosphere. Describe any size differences between them.
- 6 Draw a cross-section of a rift valley showing the types of faults on both sides of the valley. Use half-arrows to show the relative direction of movement.
- 7 List the specific differences in the types of volcanic structures on sea-floor spreading ridges and in continental rift valleys. Explain why these differences occur.
- 8 Draw cross-sections of an ocean–ocean collision zone and an ocean–continent collision zone. In your cross-sections, make sure that you show the thickness of the lithosphere. Include a vertical scale and use arrows to show the relative motion of the two plates.
- 9 Give reasons why the chemistry of the magma generated at an ocean–ocean and ocean–continent plate boundary is very different from the chemistry of the rocks that make up the oceanic lithosphere.
- 10 Volcanic eruptions at collision boundaries are by far the most violent, with the potential to affect global climate. What factors account for the violence of these eruptions?
- 11 Earthquakes along subducting ocean plate slabs can occur as deep as 700 km. Describe the characteristics of the descending slab that mean that earthquakes do not generally occur below 700 km depth.
- 12 When two continental plates collide, a linear mountain chain is formed in the middle of the new continent. Using a program such as Google Earth, identify and name five linear mountain chains that are found away from any plate boundaries. Suggest the direction of collision of the plate fragments that caused the linear mountain chains.
- 13 Produce a flow chart that outlines the steps in the formation of a mountain chain such as the Himalayas.
- 14 Earthquakes along transform boundaries are often very damaging. Why do earthquakes along this type of boundary happen at short time intervals and why can they be so damaging?
- 15 Account for the necessity of transform faults to enable spreading ridges to be curved.
- 16 Mountains caused by plate collisions produce varied and unique environments. Explain how the interaction between the mountain chain and the atmosphere affects these environments.
- 17 Account for why basalt is associated with divergent plate boundaries and granite is associated with convergent plate boundaries.
- 18 In central New South Wales, a limestone layer showing shallow-water corals and shells is overlain by andesitic volcanic rocks. Within 10 km there are different rocks that are heavily folded and faulted and indicate a deep-water environment. Justify the suggestion of a geologist that the area was once part of an island arc system.
- 19 High in the Himalayas, it is possible to find shallow-water marine fossils, often at heights above 4000 m. Assess this in relation to what you know about the process involved in the formation of the Himalayas.
- 20 The coastline of New South Wales is characterised by a narrow continental shelf that drops away into relatively deep water within a short distance of the coast. Inland is the remains of a linear mountain chain that has volcanic rocks and sediments intermixed with granites. Much of this mountain chain has been extensively folded and faulted and it has undergone significant metamorphism. Identify the type of plate boundary that used to exist along the east coast of the southern half of Australia. Justify your choice on the basis of the evidence in the rocks.
- 21 Compare the topographic features found at each of the three types of plate collision zone that you have studied. Place your answer in a well-structured table.
- 22 Is there any evidence of basaltic volcanism along the Rhine Rift in Germany similar to that observed along the East African Rift?

Answer the following questions.

- 1 Name three geographic locations where typical examples of the following types of plate boundaries can be found.
 - a divergent plate boundaries
 - b convergent plate boundaries
 - c transform plate boundaries
- 2 Contrast the different types of mountains produced at convergent plate boundaries.
- 3 Contrast the different types of volcanic rocks typically erupted at a divergent plate boundary and an ocean–continent convergent plate boundary.
- 4 Produce a labelled cross-section of a divergent plate boundary showing geological and topographic features. The cross-section must include both vertical and horizontal scales.
- 5 Explain the different depths of earthquake foci at both convergent and divergent plate boundaries.
- 6 Draw cross-sections of both normal and reverse faults and identify at which type of plate boundary you would expect to find each type of fault.
- 7 Explain the role of seismology in identifying the boundaries of the tectonic plates.
- 8 Go to the weblink Plate boundary map. Download and print the map. Using different coloured highlighters or markers, colour the location of divergent, convergent and transform plate boundaries on the map.
- 9 A large number of copper-lead-zinc-gold mines have been developed within ancient sequences of andesitic lava. Identify the plate tectonic setting in which these volcanic lavas were probably erupted, and name three geographic areas where you would explore to find new copper-lead-zinc-gold mineral deposits.
- 10 Geophysical data has been routinely collected to identify mineral deposits and plate tectonic boundaries, as well as to understand the processes of plate tectonics.
 - a Name two types of geophysical data that have been collected for both mineral exploration projects and investigations of plate tectonics.
 - b Describe how the two types of geophysical data you identified in part a have been used for both these purposes.
 - c Explain why geophysical methods are a useful remote-sensing tool for both mineral resource geologists and the earth scientists who investigate the processes of plate tectonics.



Plate boundary map

DEPTH STUDY SUGGESTIONS

- Investigate the plate boundaries surrounding the Pacific Ocean. Detail the earthquake and volcanic risk factors associated with each of the boundary types.
- Investigate the earthquakes and volcanic activity in and around the Mediterranean Sea and relate these to the plate tectonic framework in the region.
- Investigate the role of deep-sea drilling ships like the *JOIDES Resolution* in plate tectonics investigations.
- Research the assemblage of the New England Fold Belt (NEFB) in northern New South Wales. You will need to find the timing of the formation of the NEFB, what plate tectonic framework was in operation across the time it took the NEFB to be assembled and the source of the sediments that fed into the region during formation. What are the types of ore deposits found within the NEFB and how were they formed?
- Research the assemblage of the Lachlan Fold Belt (LFB) in central and western New South Wales. You will need to find the timing of the formation of the LFB, what plate tectonic framework was in operation across the time it took the LFB to be assembled and the source of the sediments that fed into the region during formation. What are the types of ore deposits found within the LFB and how were they formed?
- Research the closing of the Tethys Ocean. What geological resource has been formed in the sediments of this once-vast ocean? What are the current remnants of the Tethys Ocean and where are they located? What was the plate tectonic framework in operation that led to the demise of the Tethys Ocean?

» MODULE THREE

TRANSFORMING ENERGY

- 8 Energy
- 9 Geological change
- 10 Heat, the atmosphere and hydrosphere

8 Energy

OUTCOMES

In this chapter you will learn about:

- convection and how it occurs [CCT](#)
- the role of solar radiation in photosynthesis and ecosystems
- solar radiation and the processes of the water cycle
- how gravity and heat generate movement
- the role of gravity and heat in tectonic processes on Earth, other planets and moons [N](#)
- convection and slab pull as determining a plate's speed. [CCT ICT](#)





Christopher Huxley



FIGURE 8.1 Spinifex pigeon resting on a conglomerate boulder

What do the spinifex pigeon and the Mount Currie conglomerate (Figure 8.1) have in common? One thing is where they are found: Kata Tjuṯa in Central Australia. Another thing they share is the need for energy to exist. Scientists use energy to explain change. The bird obtains energy for life from the plants in the arid environment where it lives. The plants obtain their energy from the Sun through the process of photosynthesis. The conglomerate exists because of the energy that powered the **tectonic** processes that created the giant fans

of sediment shed from an ancient and long-eroded mountain range 600 million years ago. Energy is also a concept used by the Anangu people, whose country includes Kata Tjuṯa. They believe that the rocks of Kata Tjuṯa contain spirit energy of the Dreaming.

8.1 Role of energy in Earth processes

Our planet is dynamic: it is constantly changing. Some changes are rapid and others are slow. An undersea landslide can move thousands of cubic kilometres of sediment over minutes or hours. The building of a mountain range like the Himalayas takes tens of millions of years. What all the processes that operate in and around Earth have in common is **energy**. Energy is required to cause change. When a change of any type occurs, we can describe the change as involving energy being **transformed** (changed from one form to another) or being **transferred** (moved from one place to another). When a skateboard rider rolls up a slope, the energy of their motion (kinetic energy) decreases as they slow down. That energy is transformed into gravitational potential energy as they get higher up the slope. In the skateboard wheels, small changes in shape transfer **heat energy**, which moves into the air or the surface the wheels roll over.



What is energy?

Sources of energy

The energy that drives Earth's systems come from two main sources: solar radiation and the internal heat of Earth.

Solar radiation

The Sun is the primary source of the energy that drives processes in the atmosphere, hydrosphere and biosphere. Solar energy drives our climate, determines the distribution of water and provides energy for living organisms in the form of photosynthesis. Photosynthesis transforms and stores solar energy in a form that living things can use. Measurements from satellites show that the rate at which sunlight delivers energy to the top of the atmosphere is approximately 342 W m^{-2} (watts per square metre).

The internal heat of Earth

Heat in Earth has two main sources: heat generated during Earth's formation and ongoing heating from radioactive decay. Each of the sources accounts for about half of the heat originating in Earth. Some heat may also be generated when molten material solidifies at the boundary between the outer core and inner core, and by tidal forces within Earth. Geophysicists estimate that the total heat flow from Earth is a rate of $4.4 \times 10^{13} \text{ J s}^{-1}$ (44TW or terawatts).

You will learn more about the role of solar energy in driving ocean currents and the atmosphere in Chapter 10.

When Earth formed, a great deal of heat was generated. **Accretion** and later differentiation of the planet transformed gravitational potential energy into heat. The temperature gradient within the lithosphere is higher than that in the mantle, averaging $25\text{--}30^\circ\text{km}^{-1}$. Heat flow at plate boundaries is higher. Minerals in the lithosphere have only one-half to one-third the thermal conductivity of minerals in the mantle. Lithospheric rocks also contain more radioactive material, which generates heat as it gives out radiation. This is called **radiogenic** heat.

Our understanding of heat in Earth continues to change. In the 19th century, Lord Kelvin calculated the age of Earth as 20–1000 million years, assuming a rate of constant cooling. He did not know of radiogenic heat or the role of plate tectonics in heat loss. Recent experiments using molten iron under extreme temperatures and pressures indicate that the temperature at the surface of the inner core is approximately 6000°C . This is higher than the accepted value of 5100°C . Other research investigating the mantle's cooling history suggests that the mantle temperature has fallen by only approximately 150°C in the last 2.5 billion years.

Radioactive heating in the lithosphere and mantle contributes heat to the solid Earth. Uranium, thorium and potassium isotopes, together with their breakdown products, generate heat when they decay. Minerals containing these isotopes are common in both granites and basalts.

Twenty terawatts ($20 \times 10^{12}\text{ W}$) of radioactive heating flows from Earth's surface. Of this, 8TW is from uranium-238 decay, 8TW is from thorium-232 decay and 4TW is from potassium-40 decay.

Over geological time, the number of radioactive isotopes with short half-lives has declined. Potassium-40, for example, probably contributes one-tenth of the heat that it did when the planet formed. Long-lived elements such as uranium-238 and thorium-232 have maintained a fairly constant rate of heat generation during Earth's history.

Figure 2.5 on page 34 illustrates how the temperature of Earth changes with depth.

How energy is transferred

Heat energy can be transferred. When a hot liquid cools, we say heat has flowed from the liquid to its surroundings. In any material, particles constantly vibrate or move. This vibrational energy of a substance is referred to as its **temperature**. The higher the vibrational energy, the higher the temperature.

Energy is transferred from one place to another by radiation, conduction and convection. In many systems, all three methods of energy transfer may be present and act together. Consider water heating in a saucepan (Figure 8.2). Heated air above the water rises through convection. The saucepan handle becomes warm as heat moves into it by conduction. A person might also feel heat from the flame as it radiates heat.

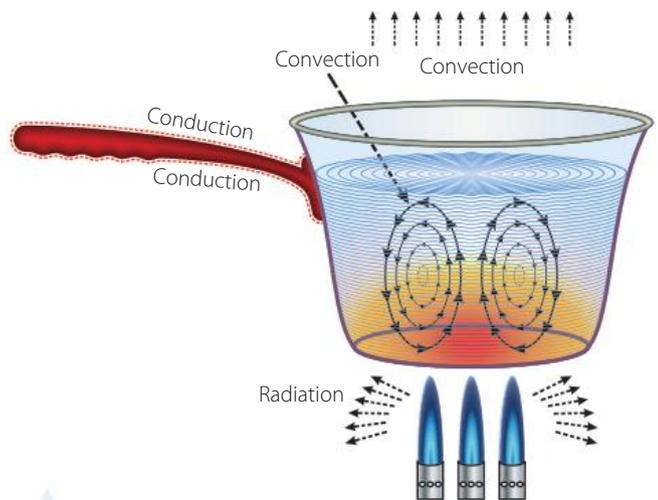


FIGURE 8.2 Heat can be transferred by conduction, convection and radiation.

Radiation

Radiation is the transfer of energy by electromagnetic waves. Electromagnetic waves can travel through the vacuum of space and are absorbed by matter. Electromagnetic waves radiated from the Sun include both infrared radiation, which warms Earth, and visible light, which is used by plants during photosynthesis.

Conduction

Conduction is the way energy is transferred by contact. Conduction occurs mainly between solids but can also occur between solids, liquids and gases. The vibrations of particles in a hot area are transferred to adjacent lower energy particles, increasing their vibration and their energy. This process continues until the heat is evenly shared between the substances in contact. The speed of conduction depends on the materials involved. Metals conduct heat well, but most earth materials conduct heat slowly. Heat transfer in the inner core, across boundaries and through the lithosphere, occurs by conduction (Figure 8.3).

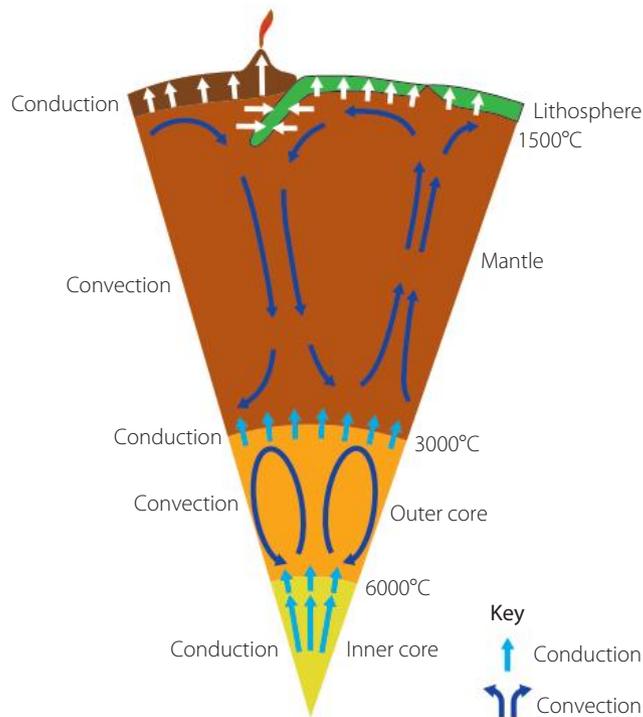
Convection

You learnt about the magnetic field in Chapter 6.



Convection

FIGURE 8.3
Heat transfer within Earth



KEY CONCEPTS

- Energy required to drive Earth processes comes from the Sun and from heat within Earth.
- Heat in Earth comes from its formation and the decay of radioactive elements.
- Energy can be transferred from place to place or transformed into other forms.
- Energy is transferred by radiation, conduction and convection.

CHECK YOUR UNDERSTANDING

8.1

- 1 Define the following terms: energy, temperature.
- 2 Distinguish between energy transformation and energy transfer.
- 3 Which Earth processes are driven by energy from the Sun?
- 4 Describe the origins of the heat within Earth.
- 5 What are the most important energy transfer processes found in Earth?
- 6 Summarise the major differences between:
 - a conduction and radiation
 - b convection and conduction
 - c convection and radiation.

8.2

Convection moves energy and matter

To understand how convection works, we will examine a simple model (Figure 8.4). In this model, the fluid cools from above and is heated from below. This creates two layers: a hot thermal boundary layer at the base, and a cold thermal boundary layer at the top.

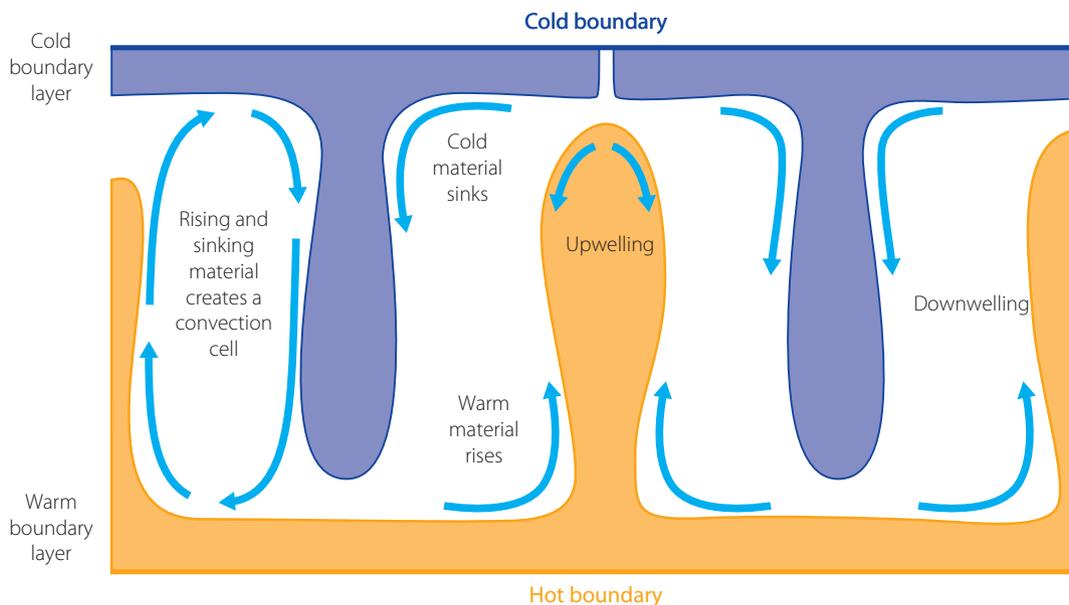


FIGURE 8.4

Heating and cooling at boundaries can create unstable boundary layers.

Heat moves from the lower boundary into the fluid by conduction or radiation. As the particles vibrate faster, the space between them increases, and so the warmed fluid expands. This expansion makes the material in the warm boundary layer less dense than the cooler fluid above it. If the heating is uneven, or something disturbs the warming fluid, a body of the warm fluid will rise through the cooler fluid. A hot mass of mantle rising from the core boundary in Earth is called a **mantle plume**. It may generate doming and volcanic activity within a plate. Plumes are thought to play a role in the **tectonics** of other bodies in the solar system.

At the cold thermal boundary, heat is removed from the fluid. As heat moves from the fluid, the fluid in the cold boundary layer cools, becomes more dense and sinks. Oceanic lithosphere shows this behaviour. It cools and becomes denser with age. If it sinks into the mantle, a subduction zone is formed.

The vertical movement of the heated or cooled fluid creates horizontal motion. At both boundaries, surrounding fluid flows into the space the moving fluid leaves (Figure 8.4). As a result of these motions, heat is carried towards the cold thermal boundary and cooler fluid moves towards the warm thermal boundary. Horizontal flow between these processes forms a cyclic flow and this cycling of convecting material is called a **convection cell**.

The speed of convection depends on a number of factors. The **viscosity** of the fluid, the depth of the convecting layer and the heat difference between the boundaries all influence the rate of fluid movement. In the mantle below the lithosphere, for example, material convects at a speed of about 2 cm year^{-1} . At greater depths, the rate is slower because the higher pressure inhibits movement. In the atmosphere, the convection of air in a **cumulonimbus** cloud moves at a speed greater than 10 m s^{-1} .

Convection cells were discussed on page 205.

INVESTIGATION 8.1



Investigating convection

INTRODUCTION

Convection is a method of heat transfer that is widespread in the solid Earth, hydrosphere and atmosphere. Scientists study convection by directly measuring convection in a system, and they also use models. In this investigation, a model of simple convection will be used to examine some features that affect how convection operates.

AIM

To demonstrate convection currents and to describe some factors that affect convection

MATERIALS

- Concentrated potassium permanganate solution
- 250 mL beaker
- Alcohol thermometer
- Tripod
- 4–6 matches
- Tongs
- Pipette
- Large ice cube
- Digital camera



WHAT RISKS ARE THERE IN DOING THIS INVESTIGATION?

Potassium permanganate solution stains and can cause irritation

HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

Wear safety glasses and a lab coat. If the solution comes into contact with skin, wash it immediately with water. If the chemical contacts an eye, immediately flush the eye with water.

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

METHOD

Part A: Convection with a hot lower boundary

- Pour approximately 200 mL of cold water into a 250 mL beaker.
- Measure and record the temperature of the water.
- Place the beaker carefully on a tripod and leave the beaker until the water is still.
- Use the pipette to draw up some of the potassium permanganate solution.
- Slowly insert the pipette vertically into the beaker and very slowly squeeze a small amount of the potassium permanganate onto the bottom of the beaker to form a small purple-coloured deposit.
- Withdraw the pipette carefully so as to disturb the water as little as possible.
- Light a match and hold it under the beaker below the purple area for two seconds.
- Observe what happens. You might use the camera to record what happens.
- In your results, use a diagram to record what you see.
- Repeat steps 5–7 but hold the match under the beaker for four seconds.
- Record what you see and note the differences with the first trial.

Part B: Convection from a cold upper boundary

- Empty the water from the beaker.
- Pour approximately 200 mL of warm water into the 250 mL beaker.



- » 14 Place the beaker carefully on the tripod and again leave the beaker until the water is still.
- 15 Next, use the tongs to carefully place an ice cube in the water near one side of the beaker. Let the water settle.
- 16 Use the pipette to slowly squeeze a small amount of the potassium permanganate solution onto the upper surface of the floating ice cube.
- 17 Observe what happens as the potassium permanganate enters the water.
- 18 In your notes, use a diagram to record what you see.

RESULTS

Record your observations as carefully labelled diagrams and a set of dot point observations.

ANALYSIS OF RESULTS

- 1 Analyse your results to describe how the water containing the potassium permanganate moved when it was heated.
- 2 Compare the effect of heating the base of the beaker for a short time with the effect of longer heating.
- 3 Contrast what happened in Part B with what you saw in Part A.

DISCUSSION

- 1 Use the idea of density changes to explain what you observed.
- 2 Explain why the movement of the rising water changed as it approached the surface of the beaker.
- 3 Explain the movement of the dyed water near the edge of the ice cube.
- 4 How would changing the temperature of the water in Part B affect the movement of the dyed water?
- 5 Which model best represents convection driven by the heat from Earth's core? Explain your decision.
- 6 How might this experiment be extended to investigate other aspects of convection?

CONCLUSION

Summarise the process of convection in terms of heating, cooling and density differences.

Convection in the mantle

Studying mantle convection is not easy. The mantle is a spherical shell, and this shape makes modelling difficult. There may be different compositional zones in the mantle that can affect convection. Seismic tomography, electrical conductivity and gravity data are used to test models of mantle convection. Physical scale models and sophisticated computer simulations are used to understand how the mantle might move.

The idea of tectonic plates acting as a cold thermal boundary of mantle convection is relatively recent. It suggests that plate motion and the resulting tectonics are due more to surface cooling than to heating from the core–mantle boundary. Indeed, some scientists argue that mantle plumes rising from the core–mantle boundary are not necessary to explain hotspots and intraplate volcanism. Other scientists strongly disagree with this.

Another area of debate concerns how convection works in the mantle. One model suggests that convection cells operate within the whole mantle. Another model describes a layered convection, with separate convection systems operating above and below a 660km transition zone where minerals change form due to pressure. Some scientists argue that whole-mantle and layered convection may occur at different times in Earth's history. The general view today is that convection occurs in the whole mantle.

KEY CONCEPTS

- Convection is caused by temperature differences and gravity.
- Gravity and heat create convection in the mantle and the motion of lithospheric plates.

- 1 Construct a flow chart to describe how convection works.
- 2 Summarise the factors influencing convection in the mantle.
- 3 Outline two different views about the nature of convection in the mantle.

8.3 Solar radiation and life

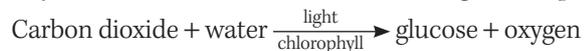
Light sustains the **biosphere**. Light from the Sun is captured by some living organisms and converted into other forms of energy that can be used by these and other living organisms. Scientists have estimated that life uses light to store 550–640Pg (petagrams) of carbon dioxide each year. The process that does this is photosynthesis.

A petagram is 10^{15} grams or 10^9 tonnes.

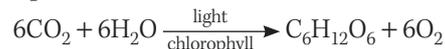
The nature of photosynthesis

Photosynthesis occurs in the cells of green plants, some protists and bacteria. Photosynthesis is the process through which light energy is converted into stored chemical energy. This stored chemical energy is used as food for most living things. The exceptions are some bacteria and **Archaea**, such as those living near hydrothermal vents and fumaroles. Most of these organisms use chemical reactions, instead of light, to make nutrients; this is called **chemosynthesis**. Organisms capable of making their own nutrients are termed **autotrophs** and organisms that obtain their nutrients from the autotrophs or their remains are termed **heterotrophs**.

Photosynthesis is summarised in the following word equation:



As a chemical equation it looks like this:



Photosynthesis can be considered a two-system process. First, energy in sunlight is absorbed in plants by chemical pigments located in **chloroplasts**. The most important pigments are chlorophyll a and chlorophyll b, which absorb red and blue wavelengths of light (Figure 8.5). Other pigments, such as beta-carotene and phycocyanin, absorb other parts of the visible spectrum. It is mainly the green part of the light spectrum that is not absorbed. This light passes through leaves or is reflected and scattered; as a result, plants' leaves appear green.

The light energy is used to form energy-carrying molecules called ATP. Because light is necessary for these processes, they are known as light reactions. In the second part of the process, ATP is involved in reactions in which carbon dioxide (CO_2) and hydrogen ions (H^+) extracted from water (H_2O) molecules are used to make glucose ($\text{C}_6\text{H}_{12}\text{O}_6$). Glucose molecules store chemical energy. These reactions are referred to as dark reactions because they do not require light energy. Figure 8.6 illustrates these two steps.

Oxygen gas, derived from the water molecules, is a by-product of light reactions. The first organisms to make oxygen through photosynthesis were simple photosynthetic organisms called cyanobacteria. The production of oxygen some 3.5–2.7 billion years ago fundamentally changed Earth's biosphere in two major ways.

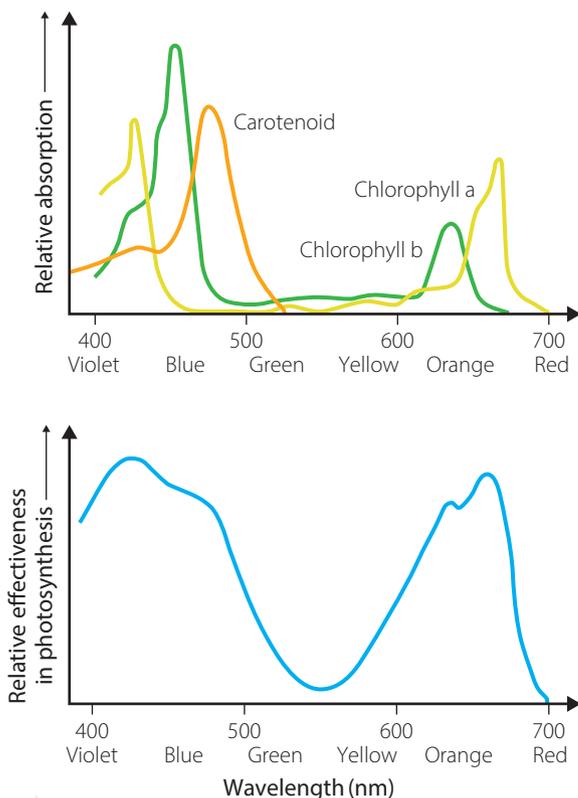


FIGURE 8.5 The absorption of light and relative effectiveness of photosynthesis at different light wavelengths

Oxygen was highly toxic to many types of anaerobic organism, which became extinct, and new oxygen-tolerant organisms evolved. Ozone, formed from oxygen, blocks ultraviolet light. The formation of the ozone layer enabled life to spread from the ocean to the land. Without ozone, harmful ultraviolet light would reduce the survival of organisms exposed on land.

Light availability

Not all the light entering Earth's atmosphere arrives at the surface. The amount of energy entering the atmosphere from the Sun is 1361 W m^{-2} . Of this, about 30% is reflected back into space, about 20% is absorbed by the atmosphere, and the rest of the light is absorbed by Earth's surface. These values are averages, with the amount of light reaching the surface dependent on factors such as latitude, cloud cover, surface reflection (albedo), altitude, aerosols and pollutants.

Photosynthesis does not capture all the energy in sunlight. Only half of the visible light reaching the surface can be captured in the chloroplasts of plants. As a consequence, only 1–2% of radiant energy from the Sun is ultimately trapped in the biosphere.

Light availability in the ocean

Absorption of light by water affects where photosynthetic organisms are found. On land, plants have ready access to light. For land plants, conserving water is critical. In lakes and the ocean, light for photosynthesis is available only in shallow areas and close to the surface of the deep ocean. The reason is that water absorbs light, and the red light used in photosynthesis is absorbed particularly strongly. In the ocean, small photosynthetic organisms, the phytoplankton, are restricted to the first metre or so of the ocean. They may extend as deep as 100m if the water is particularly clear. This thin layer of photosynthetic cells contributes 50–80% of the oxygen entering the atmosphere.

Solar energy captured through photosynthesis provides the energy for ecosystems where there is no light. Phytoplankton, and the organisms that feed on them, die and sink into the deep ocean. Decomposition occurs, but some organic material reaches the abyssal plains of the ocean. There, animals process the organic material for their energy requirements. Because energy-rich food is rare in the deep ocean, a range of adaptations occur in the animals to optimise how energy is utilised and harvested.

Energy and ecosystems

Light plays a critical role in maintaining ecosystems. An **ecosystem** consists of both the living and non-living components of an environment. In an ecosystem, the living (biotic) components interact with the non-living (abiotic) components. Energy stored in photosynthesis is used to support all the living things in an ecosystem. In photosynthesis, simple inorganic compounds are transformed into glucose, which can then be used to create other carbohydrates, complex amino acids and proteins. These compounds store energy and have a higher energy state than the other chemicals in their surroundings. Animals and micro-organisms consume the organic material produced by plants and use the energy stored in it to power their own life processes. In a very productive ecosystem, 60–80t of organic material is produced in a hectare every year. The efficiency of converting solar radiation into stored energy is about 1.0% in forests and about twice that for crops.

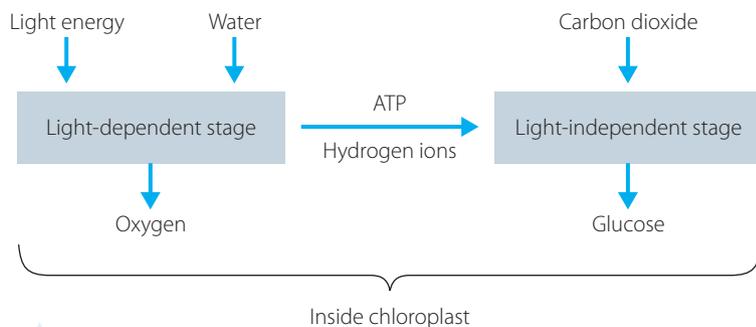


FIGURE 8.6 Photosynthesis is a two-stage process.

Photosynthesis and chemosynthesis

NASA: Carbon dioxide controls Earth's temperature

The Deep Sea

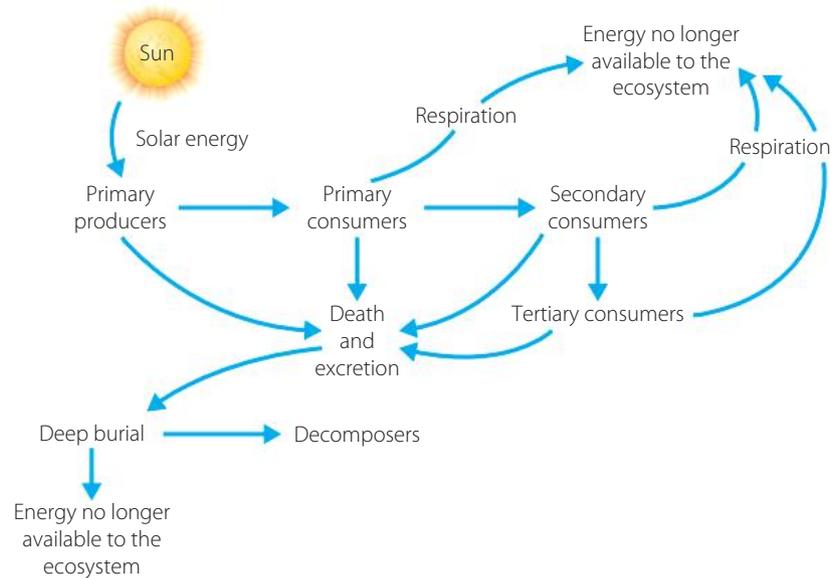
Use the information provided to summarise the physical characteristics of the deep ocean and the adaptations of animals found there.

Energy is gradually lost as it flows from one organism to another. This can be shown in a food chain (Figure 8.7). The number of steps an organism is from the start of the food chain is referred to as its **trophic level**. Each trophic level in an ecosystem is dependent on the previous one for its energy. Less than 10% of energy in one trophic level is transferred to the next. Most energy is used in maintaining the normal functioning of cells (respiration) and is lost from the food chain. As a result, the number of trophic levels found in an ecosystem is rarely more than four (Figure 8.8).

FIGURE 8.7
A simple food chain



FIGURE 8.8
Energy flow through an ecosystem. Most energy leaves the ecosystem as a result of respiration.



KEY CONCEPTS

- Light from the Sun provides energy for living things through the process of photosynthesis.
- A limited amount of light from the Sun is captured in photosynthesis.
- Energy stored in plants provides energy for other living things in ecosystems.
- Energy is lost in ecosystems, mainly through respiration.

CHECK YOUR UNDERSTANDING

8.3

- 1 Where do ecosystems obtain the energy needed to support life?
- 2 In point form, outline the process of photosynthesis.
- 3 Describe some of the factors affecting the availability of light to plants.
- 4 Why is photosynthetic activity in water restricted to the top 10–80m?
- 5 Identify the main reason for energy loss in ecosystems.

8.4 Solar radiation and the water cycle

Water is found in all the components of Earth and is collectively known as the **hydrosphere**. Water exists in the atmosphere, the ocean, the **cryosphere**, the upper parts of the lithosphere and the biosphere. The **water cycle** is a model that describes the movement of water between the different spheres of Earth (Figure 8.9).

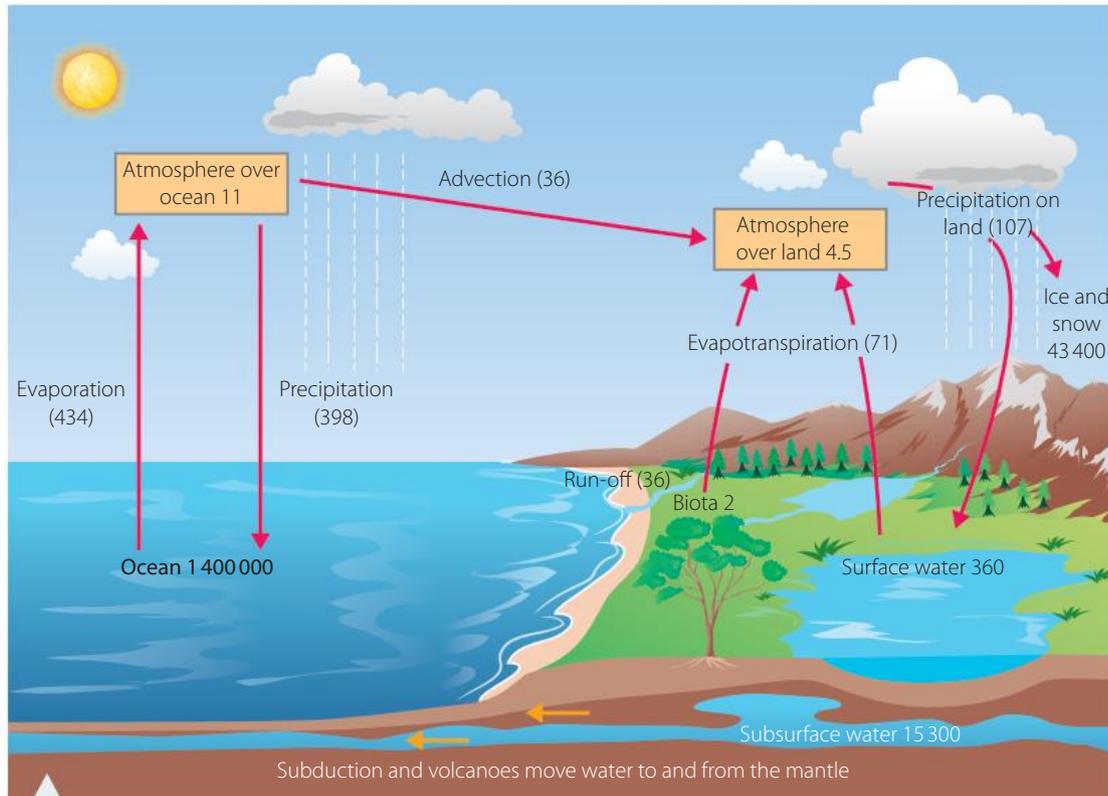


FIGURE 8.9 Processes of the water cycle. Boxes represent stores. The numbers are mass in units of 10^{12} tonnes. The numbers in brackets represent rates of exchange in units of 10^{12} tonnes per year.

Processes of the water cycle

Evaporation is the conversion of a liquid to a gas. Water molecules with enough kinetic energy can escape from the surface of liquid water into the atmosphere and carry energy away as they leave. The evaporation rate increases with increasing temperature or decreasing pressure. Evaporation cools a surface where it occurs. About 17 billion litres of water evaporates into the atmosphere every second.

Precipitation is the deposition of water, ice or snow from the atmosphere to Earth's surface. Water vapour cools to form small droplets of liquid or ice crystals in the atmosphere. When they are large enough, gravity causes them to fall. An important energy change occurs when droplets fall. Gravitational potential energy is transformed into kinetic energy as the droplets fall, and the impact of precipitation on bare ground causes erosion. Precipitation also has the effect of moving cold material from the atmosphere to Earth's surface.

Transpiration is the process by which water evaporates from the surface of plant leaves. Transpiration is a physical process and plants exhibit a range of adaptations to reduce the rate at which they lose water. Transpiration and evaporation are sometimes discussed together and described as **evapotranspiration**.

Advection is a term used to describe the transfer of heat or material by the flow of a fluid. This may seem to be the same as convection, but advection is just transfer in a flow, usually horizontal, whereas convection involves density differences.

Convection, discussed on page 205, is a key process in moving heat.

In Chapter 10, we will examine the distribution of water on the planet in more detail.

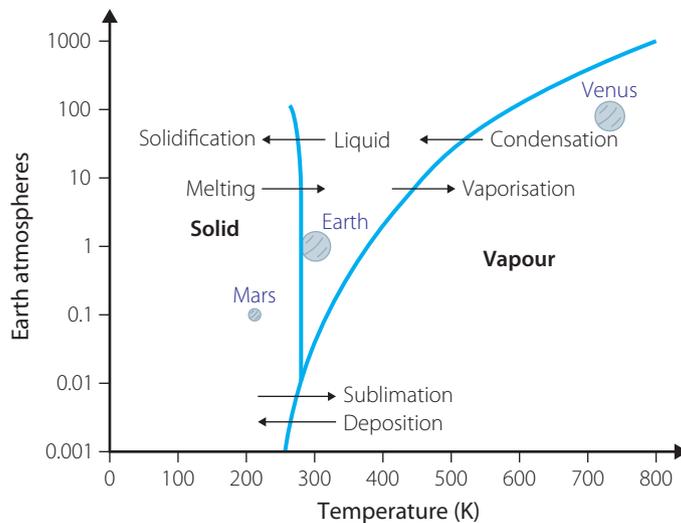
Run-off describes the movement of water across Earth's surface. Run-off may occur in river channels, creek lines, or across flat surfaces. Water may seep into the ground; this is referred to as **percolation**. The cause of run-off is gravity. Water flows from a place of high gravitational potential energy to a place of lower energy. The transformation of the gravitational potential energy into kinetic energy is reflected in the speed of the water flow.

Temperature, pressure and the nature of water

Water can change state relatively easily with changes of temperature and/or pressure. Figure 8.10 shows the effect of temperature and pressure on the state of water and the transitions from one state to another.

FIGURE 8.10

The effect of temperature and pressure on the physical state of water. The vertical scale is pressure in multiples of a standard Earth atmosphere. The temperature scale is in kelvin (K). The average conditions found on Earth, Mars and Venus are also shown.



Solar radiation moves water

The amount of sunlight that reaches Earth's surface affects the relative temperature of different parts of Earth and determines how water behaves.

Latitude and heating

The amount of heating generated by sunlight at Earth's surface depends on latitude. Areas near the equator are heated more strongly by sunlight than areas close to the poles (Figure 8.11). At low latitudes, near the equator, light arrives at the surface almost at right angles to the surface, but at high latitudes nearer to the poles, the light strikes the surface at a greater angle. This means that the light is spread out over a greater area and less heat is delivered to the surface.

Absorption and scattering of light in the atmosphere also affect surface heating. Some wavelengths of light are absorbed by molecules such as carbon dioxide and water in the atmosphere. Light is also scattered by particles in the air. At high latitudes the light travels a longer path through the atmosphere and less light reaches the surface, creating less heating. Clouds and aircraft contrails (condensation trails) can also reflect light and reduce the amount of heating at the surface.

Light is reflected from land and water surfaces (Figure 8.12). **Albedo** is the ratio of light reflected to light that reaches the surface, expressed as a decimal. The average albedo of Earth is 0.35 but it varies widely according to the type of surface involved. Ocean water absorbs most light that falls on it and can have an albedo as low as 0.06. Vegetation generally has a low albedo, with green grass having a higher albedo (0.25) than forests (0.08–0.18). Fresh snow and ice have high albedos.

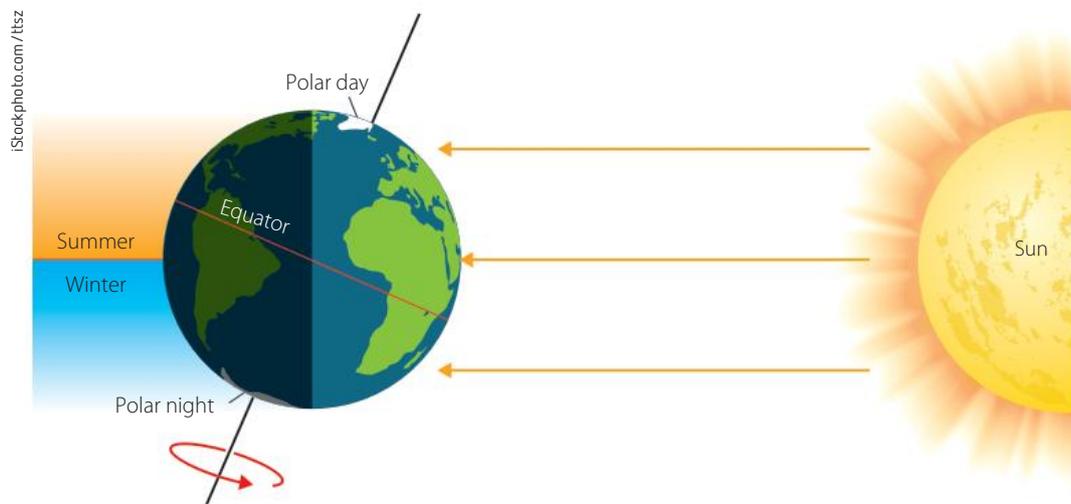


FIGURE 8.11
The amount of light reaching Earth's surface is affected by the angle at which the light strikes the surface.

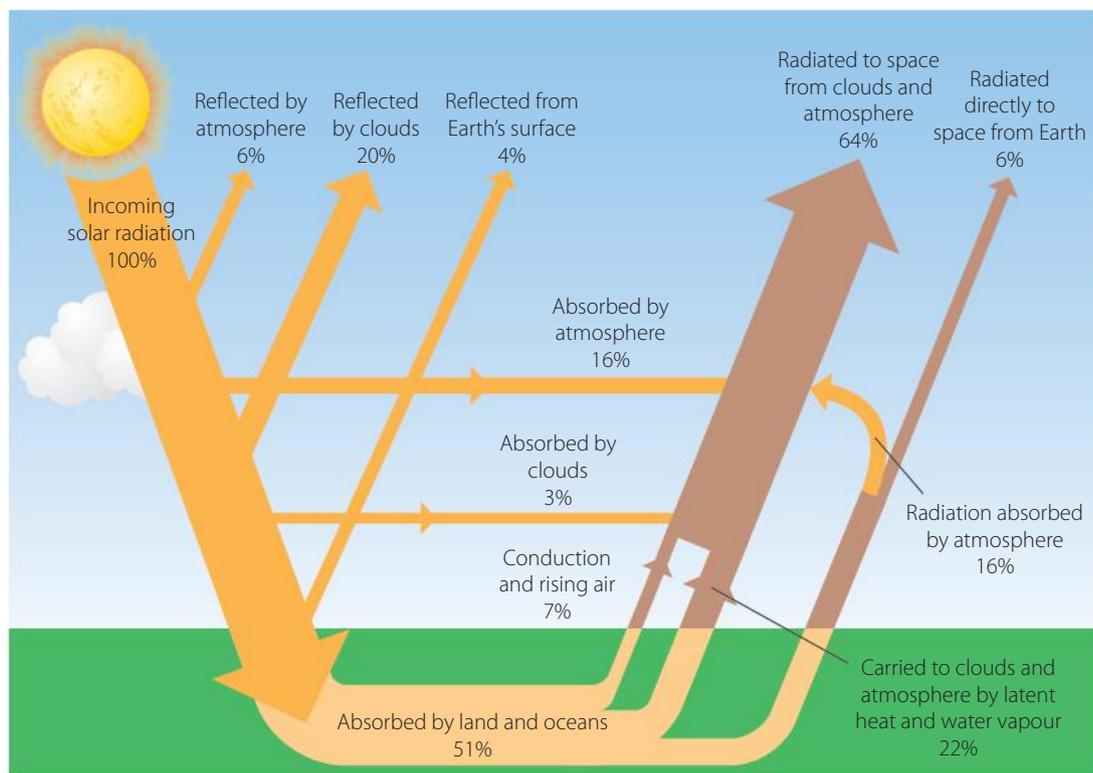


FIGURE 8.12
Earth's energy budget for solar radiation

The tilt of Earth's axis gives rise to seasons in higher latitudes. Depending on the season, days can be very long or very short, and these differences in day length also affect heating at the surface.

Convection in the atmosphere

Variations in heating of the surface of Earth cause the atmosphere to move by convection (Figure 8.13). Heating at the equator causes warm air to rise, while cooling at high latitudes near the poles leads to cold air descending. These processes cause air to flow towards the equator near the surface and to flow towards the poles at high altitudes.

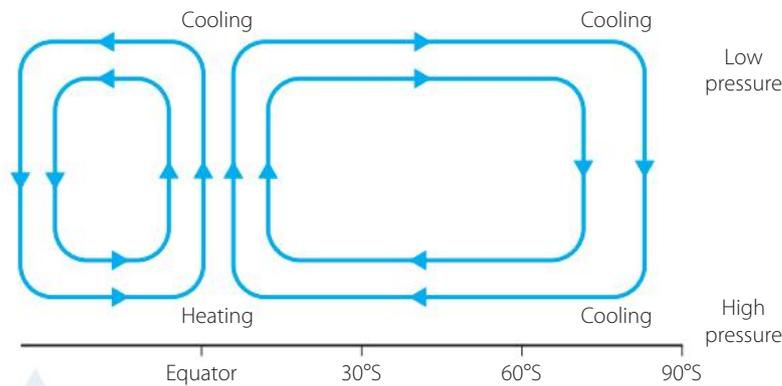


FIGURE 8.13 A simple model of air and heat circulation in the atmosphere

KEY CONCEPTS

- Variations in heating and cooling lead to water movement.
- Earth is unusual in having water exist in solid, liquid and gas phases.
- The gain or loss of energy causes water to change state and to move.

CHECK YOUR UNDERSTANDING

8.4

- 1 What is the water cycle?
- 2 Draw a diagram to illustrate the cyclic movement of water to and from the ocean via ice and snow.
- 3 Outline four of the processes that are involved in moving water in the water cycle.
- 4 Describe the processes shown in Figure 8.9.
- 5 Explain how heat affects the state in which water is found on Earth.

8.5

Gravity, heat and the movement of plates

Studying other planets and moons in the solar system is one way of improving our understanding of plate tectonics and how energy shapes Earth. Scientists learn by carrying out field work, conducting experiments and modelling Earth using computers. By analysing tectonic structures on other planets, scientists are able to test models they have developed and also learn something of how processes may have operated in the past.

Since the 1960s, spacecraft have visited other parts of the solar system. Venus, cloaked in thick clouds, has been mapped using Earth-based radio telescopes, radar on spacecraft such as Magellan, and a wide range of instruments including a **spectrograph** and a magnetometer on the Venus Express. Slight variations in the path of satellites orbiting a planet caused by small gravity variations have been used to understand more about the internal structure of Venus.

Earth's unique tectonics

It seems that only Earth has plate tectonics at present. If plate tectonics operates, or operated, on other planets we would expect to see the volcanic arcs and trenches of subduction and the fracture zones of sea-floor spreading. Recent research suggests that Europa (a moon of Jupiter) may have a form of plate tectonics operating in its icy surface, but the plate margin features familiar to us on Earth are rare or absent elsewhere in the solar system.

 Critical and creative thinking

 **Exploring the planets**

Use the Smithsonian site to learn more about the planets and moons of the solar system.

 ws

Comparing tectonics on three planets

Tectonics on other worlds

Tectonics is the study of geological structures and how they form. Some tectonic features do not require plate interactions to form. Structures such as folds and faults are created by **stress** and **strain** in rocks. The stresses that cause the deformation may be caused by a combination of gravity and heat. Four tectonic features that are found on planets and moons in the solar system are impact structures, horst- and-graben structures, volcanoes and volcanic domes.

Impact structures are created when large bodies strike a surface at high velocity. On Earth, such bodies are referred to by geologists as **bolides**.

A bolide may be a meteorite or a comet. The bolide impact creates a crater with a raised wall and sometimes a central raised area. Mars has more than 600 000 craters larger than a kilometre across. Australia has about 30 identified craters, perhaps the most famous being Wolfe Creek Crater (Kandimala) in Western Australia (Figure 8.14). It is thought that the crater was formed approximately 300 000 years ago by an object estimated to have had a mass of 50 kt.

Crust under tension can fracture to form rifts and horst-and-graben structures. Rising mantle material can create domes in the lithosphere and create tension in the upper surface, leading to faulting. The Global Surveyor and Mars Express missions have allowed scientists to map in detail a remarkable horst-and-graben structure on Mars called Acheron Fossae. The structure has been interpreted as rifting related to magma pushing up and fracturing the lithosphere before blocks of crust settled under gravity, forming high and low areas.

Volcanic activity is how planets and moons lose heat. On Earth, within plates, we find volcanoes, **calderas** and **large igneous provinces (LIPs)**. Calderas are round depressions formed when a magma chamber empties rapidly, causing a volcano to collapse. Lake Toba, on Sumatra in Indonesia, is located in a caldera. It formed 74 000 years ago when 2800 km^3 of material was erupted. Large igneous provinces (LIPs) erupt more quietly and over longer periods. Basaltic lavas may flow for a million years, covering hundreds of square kilometres.

Volcanoes and extensive lava flows are common on other rocky planets and moons. On Mars, Olympus Mons stands 26 km high (Figure 8.15). It is a shield volcano (Chapter 9), like other volcanoes on the raised Tharsis Dome. The northern hemisphere of Mars is notable for the lack of impact craters. Basaltic lava flows have covered the surface, erasing such structures. Venus has 1600 large shield volcanoes, more than any other planet, and probably more than 100 000 in total. They appear uniformly spread over the planet. A particular type of volcano found on Venus is the pancake dome (Figure 8.16). The volcano is broad and flat and thought to be composed of silica-rich rock.

The tectonic patterns we find among the planets are found on moons too. Io, the third largest moon of Jupiter, is very volcanically active. A great deal of heat is generated as rocks are deformed by the gravity of nearby Jupiter. It is characterised by mountains and caldera structures called **paterae**. The relationship between areas of uplift and volcanic activity suggests that thermal uplift resulting from strong convection within the moon explains the tectonic features.

Cooling and the possibility of plate tectonics

Why Earth is the only planet in our solar system with plate tectonics is due in part to how it has cooled. Larger planets have relatively small surface areas compared to their volumes. This means they radiate heat from their surfaces more slowly than smaller planets and cool more slowly. The outer surface of a cooling planet needs to be flexible and capable of being broken in order for plates to form.



Alamy Stock Photo/Russotwins

FIGURE 8.14 Wolfe Creek meteorite crater. The crater is about 60 m deep and over 800 m in diameter.



Meteorite craters in Australia

Make a labelled drawing of the features you would expect to find in a meteorite crater.



Information and communication technology capability



Tangled terrain in Acheron Fossae

Use the weblink to provide three types of information about the Martian surface obtained using remote sensing.

You will learn more about LIPs in Chapter 9.



Information and communication technology capability



NASA solar system exploration

Use the weblink to explore the features of planets and moons in the solar system.

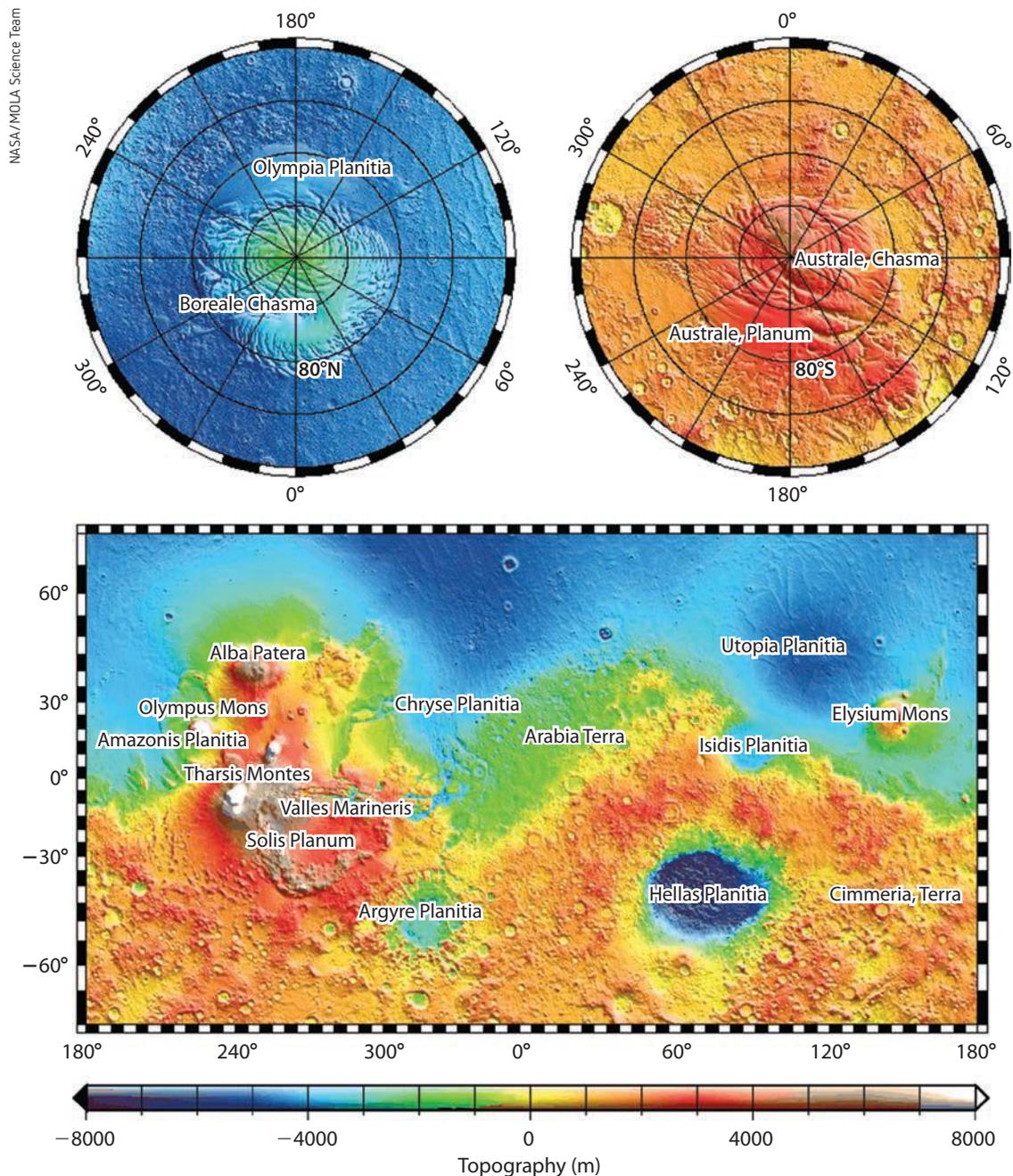
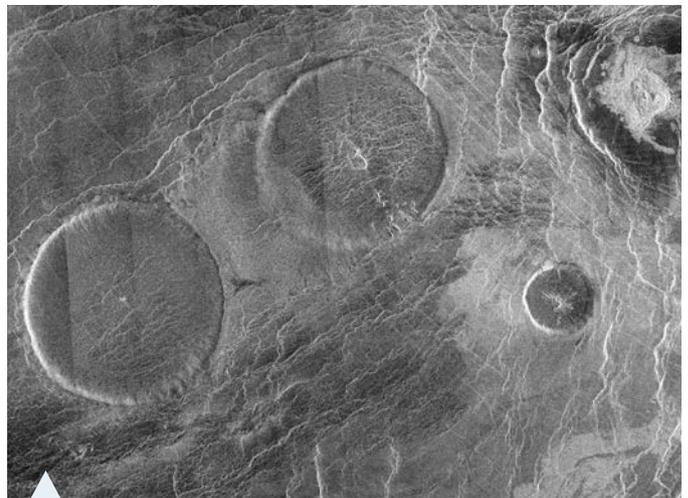


FIGURE 8.15 Features of Mars. This NASA image was created using data from laser elevation measurements made by the Mars Orbiter spacecraft.

On planets that have cool surfaces, such as Mars, the lithosphere is immobile. The viscosity of silicate rock in the lithosphere and mantle changes dramatically as temperature falls. Loss of heat at the surface causes the formation of a cold, rigid boundary layer unlike the underlying mantle. If the upper boundary layer, sometimes referred to as the **lid**, is cold and rigid, convection is restricted to the mantle. This is the situation on planets such as Mars and moons such as Io and the Moon. On Mars, the size of the volcano Olympus Mons suggests that the surface does not move relative to the hot mantle beneath it that provided the continuous supply of lava that built the volcano.

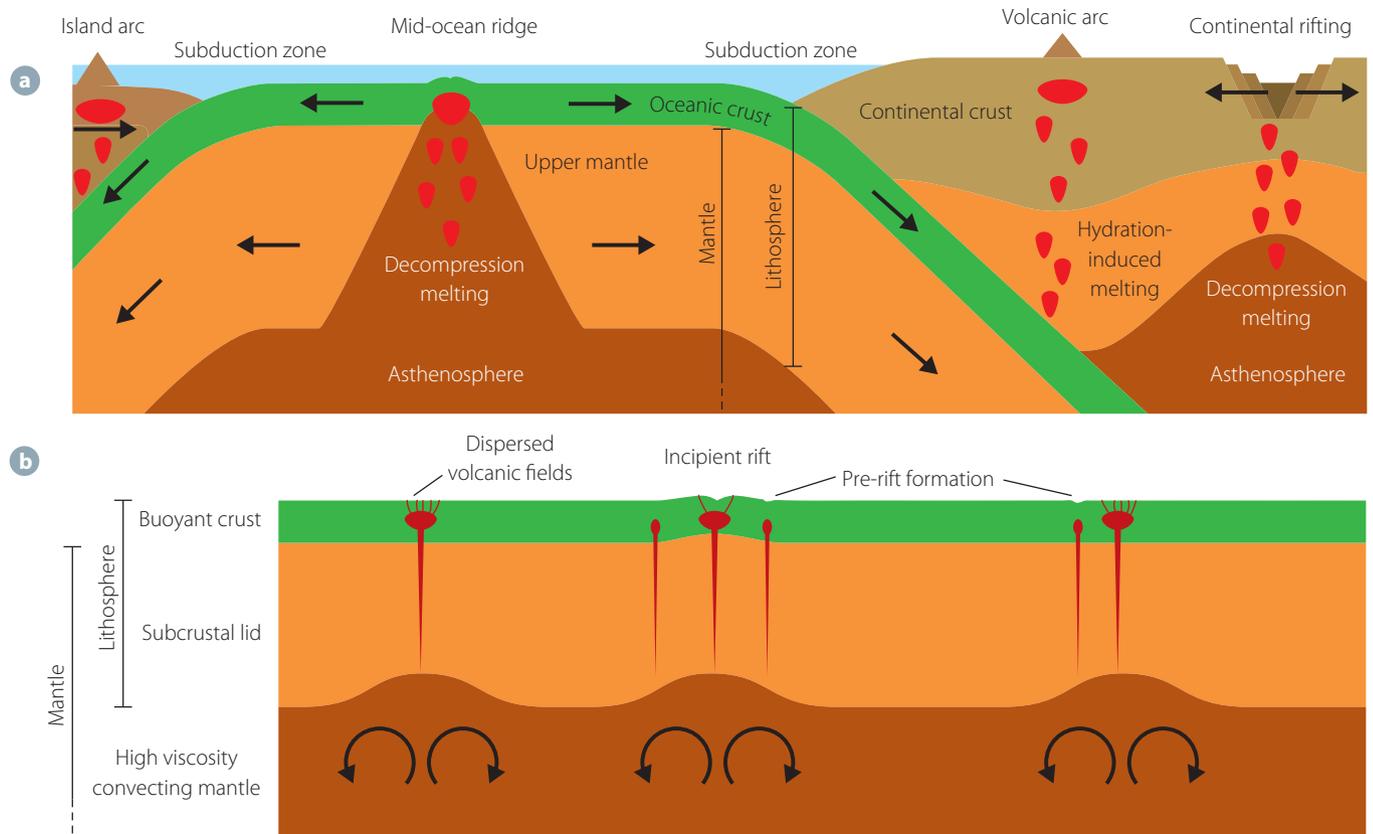
On Earth, the upper boundary layer, the lithosphere, is involved in convection. Oceanic lithosphere founders, or sinks, into the mantle when it thickens and cools. As it sinks, the foundering lithosphere drags attached lithosphere behind it, moving the plate. At boundaries where plates diverge, new material from the mantle replaces subducted material. In this way, the lid or lithosphere is resurfaced and replaced (Figure 8.17a).

A third model is a planet with a rigid lid that is periodically overturned. Venus is similar in size to Earth but it has an atmosphere that restricts the loss of heat from the surface. Venus has a surface temperature of 462°C and the atmospheric pressure is more than 90 times that on Earth. Gravity studies suggest that on Venus the lithosphere is approximately 550 km thick, but it is a much more volcanically active planet than Earth. Hot mantle material finds its way through the thick lithosphere, doming the surface and creating fractures as well as volcanic structures (Figure 8.17b). Studies have suggested that Venus may have its surface broken up into parts that jiggle against each other without necessarily subducting. The edges of some volcanic provinces suggest that subduction might occur, but the combination of plume-generated volcanism with subduction is not something we find on Earth.



Courtesy NASA/JPL-Caltech

FIGURE 8.16 Carmentis Farra – pancake domes on Venus. The larger domes are approximately 65 km in diameter but are only about 600 m high.



Idealised sketch summaries of **a** terrestrial plate tectonics and **b** a stagnant lid regime on Venus. From Airey, M. W., T. A. Mather, D. M. Pyle, and R. C. Ghail (2017), The distribution of volcanism in the Beta-Atla-Themis region of Venus: Its relationship to rifting and implications for global tectonic regimes. *J. Geophys. Res. Planets*, 122, 1626–1649. doi:10.1002/2016JE005205

FIGURE 8.17 **a** Tectonics on Earth creates horizontal motion. **b** On a planet like Venus, motion in the crust is vertical. The two drawings are not drawn to the same vertical scale.

Gravity and heat create motion

Gravity and heat create both horizontal and vertical motion in Earth's lithosphere. We have already seen how heat can create motion in the process of convection. A hot buoyant area of the mantle can cause the crust to bulge and form a dome. In the process, the upper cold crust may fracture, creating normal faults and rifts. More will be discussed about convection and horizontal plate motion in the next section.

The crust of Earth reacts to changes in several different ways. Pressure resulting from burial may cause brittle rocks to fracture and other rocks to fold. Soil and rock may creep down a slope or move suddenly as part of a landslide. The angle of a slope and the strength of a material will determine whether it will overcome friction and slide. The addition or removal of loads on the crust also causes vertical change.

Vertical motions within the crust are caused by gravitational forces. The crust may sink under the weight of ice sheets kilometres thick and then rebound when the weight is removed. Basins deepen as sediment fills them and old mountains remain relatively high despite millions of years of erosion. Large igneous provinces may add kilometres of igneous rock to the thickness of the crust, causing the crust to subside. All these processes can be understood in terms of **elastic** bending in the lithosphere and a process called **isostasy**.

Isostasy

Isostasy refers to a process in which the forces of weight and buoyancy adjust to create an **equilibrium**. It is a term derived from two Greek parts: 'isos' meaning equal, and 'stasis' meaning standing. If we consider a block of wood that is still but floating in water, it must experience two equal but opposite acting forces. One of those forces is weight. Weight is the force of gravitational attraction on a mass. If weight acted alone on the floating block, it would sink. Opposing the weight is a buoyancy force.

Buoyancy is due to the increasing pressure in a fluid as the depth increases. The pressure at the base of the floating block is greater than the pressure at the surface, so the block experiences an upwards force, an upthrust. The size of the buoyancy force is described by Archimedes' principle: an object partially or wholly immersed in a fluid experiences an upward force equal to the weight of the fluid displaced by the object.

Isostasy allows scientists to explain adjustments in the crust. Studies have shown that the crust in Scandinavia has risen 275m since the ice cover of the last ice age disappeared some 10000 years ago. A thousand years earlier, up to 3000m of ice covered the crust, exerting a considerable weight on the crust and causing the crust to subside. As the ice melted, the weight on the crust decreased and isostasy caused the crust to rise. The area continues to rise at approximately 1 cm year^{-1} .



Buoyancy simulation

Use the Phet Interactive to explore the factors involved in isostasy.

INVESTIGATION 8.2

Modelling movement due to heat and gravity



INTRODUCTION

This investigation models isostatic adjustments and how heat may influence the way isostasy works.

AIM

To model movement caused by gravity and heat

HYPOTHESIS

An equilibrium between buoyancy and gravitational forces changes if the weight force or buoyancy changes. »

» MATERIALS

- 2 long specimen tubes with lids
- 100 mL measuring cylinder
- 250 mL beaker
- 50 mL beaker
- Pair of tweezers
- 30 cm ruler
- Disposable pipette
- Marking pen
- 200 mL vegetable oil
- 3 × 10 g masses

WHAT RISKS ARE THERE IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Splashes to the eye	Ensure correct use of the pipette. Wear eye protection, and bathe the eye with water if liquid comes into contact with an eye.



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

METHOD

- 1 Measure 200 mL of water with the measuring cylinder and pour it into the 250 mL beaker.
- 2 Half-fill the 150 mL beaker with water.
- 3 Using the water in the 150 mL beaker, pour water into one of the specimen tubes until it is approximately 2 cm deep.
- 4 Place the specimen tube in the 250 mL beaker and adjust the water level in the tube until it floats with 4 cm of the tube above the water.
- 5 Place the lid on the specimen tube and use the marking pen to mark where the water in the beaker comes to on the side of the specimen tube.
- 6 With the 30 cm ruler, measure the height of the specimen tube above the water surface and record it in a results table like the one below.
- 7 With the tweezers, carefully place a 10 g mass on the lid of the specimen tube.
- 8 Using the ruler, again measure the height of the specimen tube above the water surface and record the height.
- 9 Repeats steps 6 and 7 twice more. Be careful to place the masses in such a way that the specimen tube floats upright.
- 10 Now, remove one of the masses, measuring and recording the height of the specimen tube. Repeat the measurement after removing a second mass.
- 11 Next, carefully remove the specimen tube and empty the water from the beaker.
- 12 Measure 200 mL of oil with the measuring cylinder and pour it into the 250 mL beaker.
- 13 Repeat steps 4 to 8.

RESULTS

- 1 Make a labelled scientific diagram showing the setup of the floating specimen tube in the beaker.
- 2 Make written observations of the specimen tube as you load and unload it.
- 3 Copy the table below and use it to record your results.





LOAD ON FLOATING SPECIMEN TUBE (g)	HEIGHT OF THE TUBE ABOVE THE WATER (mm)	CHANGE IN HEIGHT (mm)
WATER		
No masses		
10		
20		
30		
20		
10		
OIL		
No masses		
10		
20		
30		
20		
10		

4 Use your results to graph the height versus load for water and oil.

ANALYSIS OF RESULTS

- 1 If the water represented the mantle, what did the specimen tube represent?
- 2 Describe the trend in the change in height as the specimen tube was loaded and then unloaded.
- 3 Oil has a lower density than water. How did the density change affect the buoyancy of the specimen tube?
- 4 In our model, would the oil represent warm or cold asthenosphere? Why do you think so?
- 5 Oil is more viscous than water. Was the speed of adjustment different in the water and oil?
- 6 If the asthenosphere is very viscous, would the isostatic adjustment be fast or slow? Why do you think so?
- 7 Was there anything you needed to change in the experiment to improve its reliability?
- 8 Is the hypothesis supported by your results?

CONCLUSION

Write a conclusion that relates the aim of the investigation to your results.

How thermal energy drives plate motion

Some forces acting on a plate promote the movement of the plate and other forces oppose movement. Because most plates on Earth move with fairly constant velocities, it appears that the forces resisting motion balance the forces that promote motion.

Forces acting on plates

The forces that move plates can be placed in two groups: edge forces that act on plate boundaries, and frictional drag forces acting on the base of the plate caused by convection. Edge forces result from buoyancy, either upward or downward, which is translated into the horizontal movement of the plates over the plastic asthenosphere. Some of the forces that act on a plate are represented in Figure 8.18.

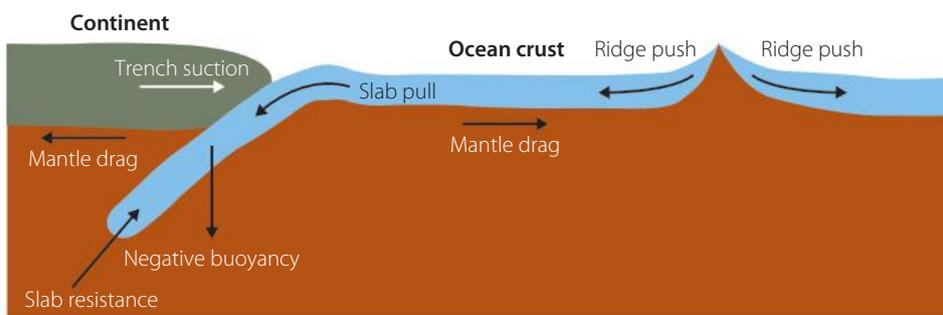


FIGURE 8.18
Some of the forces acting on plates. Arrows represent the direction of the force.

Edge forces as a mechanism

Mid-ocean ridges are found where upwelling mantle provides the buoyancy force to elevate the ridge. Mantle material providing outwards pressure on the ridge and gravitational forces act to make the lithosphere slide to a lower level. Together, these forces are called **ridge push**. Relatively small resistance forces in the upper crust resist plate motion and produce earthquakes along the mid-ocean ridge.

Oceanic lithosphere thickens and sinks as it ages and moves away from the mid-ocean ridge. Thickening occurs as the plate cools and additional mantle material is added to the base of the plate. This underplating process may also contribute to the ridge push force because the subsiding of the thick dense plate exerts a pull on the plate closer to the ridge.

The cooling and thickening of an oceanic plate eventually results in the formation of a subduction zone. The subducting plate creates a strong **slab pull** force that draws the lithospheric plate on the surface towards the trench. The motion of the sinking plate is opposed by slab resistance forces. The mantle resists as the subducting plate pushes into the mantle, and friction along the sides of the plate, and particularly its leading edge, slows the rate at which the plate subducts.

Mantle drag as a mechanism

Mantle convection is the mechanism used to explain plate movement. Two models have been proposed and studied. The mantle drag model sees the convection in the asthenosphere as creating a horizontal flow of cool viscous mantle material beneath the plates. This flow creates drag on the base of the plate, moving it in the direction of the convective flow.

An alternative way of considering convection as a driving force comes from recognising the lithosphere itself as the upper cool boundary layer of a convection cell, with forces moving the plates acting at their margins.

INVESTIGATION 8.3

Plate motion, convection and slab pull

INTRODUCTION

Several forces have been proposed to explain the movement of plates. In this investigation we will use data on the dimensions, edges and speed of Earth's major plates to test whether there are correlations between the speed of a plate and other plate features. This analysis is best done using a spreadsheet. You will have to order, copy and create data. You will also create a number of graphs to assess any relationships that may exist.



Numeracy



Information and communication technology capability



» AIM

To identify correlations between plate speed and other plate characteristics to assess the importance of mantle convection and edge forces as drivers of plate motion

TABLE 8.1 Plate characteristics

PLATE NAME	TOTAL PLATE AREA (MILLIONS OF km ²)	TOTAL CONTINENTAL AREA (MILLIONS OF km ²)	% OF TOTAL	TOTAL OCEANIC AREA (MILLIONS OF km ²)	% OF TOTAL	AVERAGE SPEED (cm year ⁻¹)	CIRCUM-FERENCE (HUNDREDS OF km)	BOUNDARY TYPE – EFFECTIVE LENGTH (HUNDREDS OF km)				
								RIDGE	TRANS-FORM	TRENCH	% TRENCH	% RIDGE
Cocos	2.9	0	0	2.9	100	8.6	88	29	25	25		
Caribbean	3.8	0	0	3.8	100	2.4	88	0	44	0		
Arabian	4.9	4	82	0.9	18	4.2	98	27	0	0		
Philippine	5.4	0	0	5.4	100	6.4	103	0	30	30		
Nazca	15	0	0	15	100	7.6	187	54	52	52		
South American	41	20	49	21	51	1.3	305	71	3	3		
Antarctic	59	15	25	44	75	1.7	356	17	0	0		
North American	60	36	60	24	40	1.1	388	86	10	10		
Australian–Indian	60	15	25	45	75	6.1	420	108	83	83		
Eurasian	69	51	74	18	26	0.7	421	35	0	0		
African	79	31	39	48	61	2.1	418	58	9	9		
Pacific	108	0	0	108	100	8	499	119	113	113		

METHOD

- 1 Create a copy of the data in Table 8.1 in your spreadsheet.
- 2 Complete the empty cells for the Cocos Plate. The percentage will be 100 times the boundary divided by the sum of all three boundaries. Use the example below to help you.

A	B	C	D	E	F
1	Ridge	Transform	Trench	% Trench	% Ridge
2	29	25	25	=100*D2/(B2+C2+ D2)	=100*B2/(B2+C2+ D2)
3	0	44	0		

- 3 Copy the formula for % Trench down the column for the other plates. To do this, highlight the cell with the formula and copy it down the column. The spreadsheet will calculate the percentages for all the other rows.
- 4 Copy the formula for % Ridge down the column for the other plates.
- 5 Create the following three scatter plots using data for the plates with a plate area greater than 10 million km². In each, plot the speed on the vertical (y) axis and the other factor on the horizontal (x) axis. The scatter plots are the following.
 - a Average speed versus Total plate area.
 - b Average speed versus % Trench.
 - c Average speed versus Total continental area.

RESULTS

Format your plots with titles and labelled axes.



» ANALYSIS OF RESULTS

For each plot, describe the nature of any trends or groupings. Identify any plates that seem to plot differently from the trends or group you identify.

DISCUSSION

- 1 Convection currents flowing under a plate might create drag on the plate. Does plot A support this?
- 2 What do the three fastest plates in plot A have in common?
- 3 What trend is shown in plot C?
- 4 Slab pull is thought to be a major force in moving plates. Does plot B support this hypothesis?
- 5 Suggest why only the larger plates were used in this investigation.
- 6 Does a correlation prove that the speed is related to the other factor in the correlation?

CONCLUSION

Which hypotheses for this investigation are supported by your results?

EXTENSION

Use the weblink to investigate if there is a relationship between the average age of an oceanic plate and the speed at which it moves. Use the following plates: Pacific, Philippine, Nazca, Cocos and Scotia. The Scotia Plate has a speed of 2.5 cm year^{-1} .



KEY CONCEPTS

- Planets and moons in the solar system exhibit tectonic structures caused by impacts, volcanism and rifting.
- Only Earth exhibits horizontal motion of plates that assists in heat loss from the planet.
- Loss of heat from other planets is mainly through volcanic activity and resurfacing.
- Heat energy within Earth makes possible the thin, flexible lithosphere and asthenosphere necessary for plate motion and isostatic adjustment.
- The lithosphere can be thought of as the upper boundary layer of a convecting mantle.
- Sinking of dense cold ocean lithosphere helps to move plates.

- 1 Explain the role of gravity in slab pull.
- 2 Describe the forces thought to make plates move.
- 3 Identify three tectonic features found on planets and moons that are not caused by plate tectonics.
- 4 How does the cooling of a planet affect the nature of the lithosphere?
- 5 What three features would you expect to find on a planet that has plate tectonics shaping its lithosphere?

CHECK YOUR UNDERSTANDING

8.5

8 CHAPTER SUMMARY

- ▶ Light from the Sun provides energy for living organisms through the process of photosynthesis.
- ▶ A limited amount of light from the Sun is captured in photosynthesis.
- ▶ Energy stored in plants provides energy for other living things in ecosystems.
- ▶ Energy is lost along food chains, mainly through respiration.
- ▶ Earth is unusual in having water exist in solid, liquid and gas phases.
- ▶ The gain, loss, and transformation of energy in water creates the water cycle.
- ▶ Changes to the amount of heat energy in the atmosphere can alter the rate of water cycle processes.
- ▶ Planets and moons in the solar system exhibit tectonic structures caused by impacts, volcanism and rifting.
- ▶ Only Earth exhibits horizontal motion of plates that assist in heat loss from the planet.
- ▶ Loss of heat from other planets is mainly through volcanic activity and resurfacing.
- ▶ Heat energy within Earth makes possible the thin, flexible lithosphere and asthenosphere necessary for plate motion and isostatic adjustment.
- ▶ The lithosphere can be thought of as the cool upper boundary layer of a convecting mantle.
- ▶ Sinking of dense cold ocean lithosphere helps to move plates.

8 CHAPTER REVIEW QUESTIONS



Review quiz

- 1 Outline the sources of heat energy that generate processes:
 - a within Earth
 - b in the atmosphere, hydrosphere and biosphere.
- 2 Outline, using a labelled diagram, all the processes involved in a cup of hot liquid cooling on a table.
- 3 Explain how heat and gravity contribute to convection.
- 4 Why is convection an efficient method of energy transfer in the ocean and atmosphere?
- 5 Explain why the internal heat in Earth today is less than it was three billion years ago.
- 6 Photosynthesis makes light energy available to living things.
 - a Outline the process of photosynthesis.
 - b Identify the role of chlorophyll pigments in photosynthesis.
- 7 Account for the relatively small amount of energy from the Sun that is incorporated into plants through photosynthesis.
- 8 Explain why marine plants are restricted to shallow depths in the ocean.
- 9 Identify the change of state in the following water cycle processes.
 - a evaporation
 - b condensation
 - c transpiration
 - d ice formation
- 10 Compare the processes of advection and convection.
- 11 How does evaporation of water from a leaf keep cells in the leaf from overheating in strong sunlight?
- 12 Mars has conditions in which water exists as a gas or a solid. Which processes of Earth's water cycle would you expect to find on Mars?
- 13 A plume of hot mantle can cause the lithosphere to dome. Make a flow chart to illustrate how isostasy works in the formation of the dome.
- 14 Use the concepts of isostasy and cooling to explain why the sea floor becomes deeper further away from a mid-ocean ridge.
- 15 Distinguish between the tectonic features common to planets and moons in the solar system and the tectonic features arising from plate tectonics.
- 16 Where do the highest heat flows from the mantle occur on Earth?
- 17 Explain why a body such as the Moon is unlikely today to have an actively convecting interior.
- 18 On Earth, convection in the mantle leads to the horizontal motion of plates. On Venus, strong convection creates uplift and volcanism. Outline three reasons for the difference.
- 19 Assess whether slab pull is a result of mantle convection.
- 20 Compare and account for differences in convection in the mantle and convection in the atmosphere.

9 Geological change

OUTCOMES

In this chapter you will learn about:

- the origin and release of energy in earthquakes [CCT](#)
- the origin and nature of magmas, effusive mafic eruptions, and subduction-related explosive eruptions [CCT ICT](#)
- the interactions of magma and water
- the energy transformations and processes involved in mountain building. [CCT ICT L](#)





A range of energy transfers and transformations occur in the lithosphere. Heat flows through the lithosphere and convection transfers kinetic energy to the plates (Figure 9.1). Each year, volcanic eruptions and earthquakes release a million times more energy than that represented by the motion of Earth's plates. The formation of mountains also involves the transformation of energy when rock bodies are folded and changed. These energy transfers and transformations are the subject of this chapter.



Energy transformation of Earth

View the animation of eruptions, earthquakes and emissions since 1960.



Shutterstock.com/NigelSpiers

FIGURE 9.1 The energy released by an earthquake can destroy roads.

9.1

Earthquakes and energy



Earthquakes happening now

Check out where earthquakes are occurring right now.

1 petajoule (1PJ) = 10^{15} joules

An earthquake occurs when elastic energy stored in rocks is suddenly released. This release happens when the rock fractures or sudden movement occurs along a structure called a **fault**. The energy is rapidly carried away as seismic waves and is referred to as seismic energy. The energy released in earthquakes is enormous (Table 9.1), but seismic energy accounts for less than 10% of the total energy released. A great deal of heat energy is generated by friction along the fault core and in the deformation of rocks. Changes in the elevation of lithosphere also change the gravitational potential energy of the crust. Each year, there are more than two million earthquakes worldwide (Figure 9.2). Most are small and cannot be felt, although they can be detected by sensitive seismometers. In Australia, approximately 100 earthquakes occur in a year.

TABLE 9.1 Some sources of energy in the lithosphere

SOURCE OF ENERGY	ENERGY RELEASED PER YEAR (PJ)
Kinetic movement of the plates	0.001
Volcanic eruptions	10 000
Earthquakes	1000–10 000
Heat flow	1 000 000

The energy released by an earthquake is described by its **magnitude**. The original Richter magnitude scale was developed by Charles Richter and Beno Gutenberg in 1935 and later revised to form the local magnitude scale (M_L). Richter and Gutenberg used the amplitude of waves recorded on a seismograph and the distance from the earthquake to calculate the magnitude. The amplitude of the earthquake waves decreases as they move away from their origin, so it is important to know the distance. Because earthquakes vary so much in terms of the energy they release, the magnitude scale is logarithmic. This means that for every increase of 1 in the scale, the ground displacement increases 10 times and the energy released increases 31.6 times. A doubling of the energy released is represented by a magnitude change of only 0.2 (Figure 9.3).

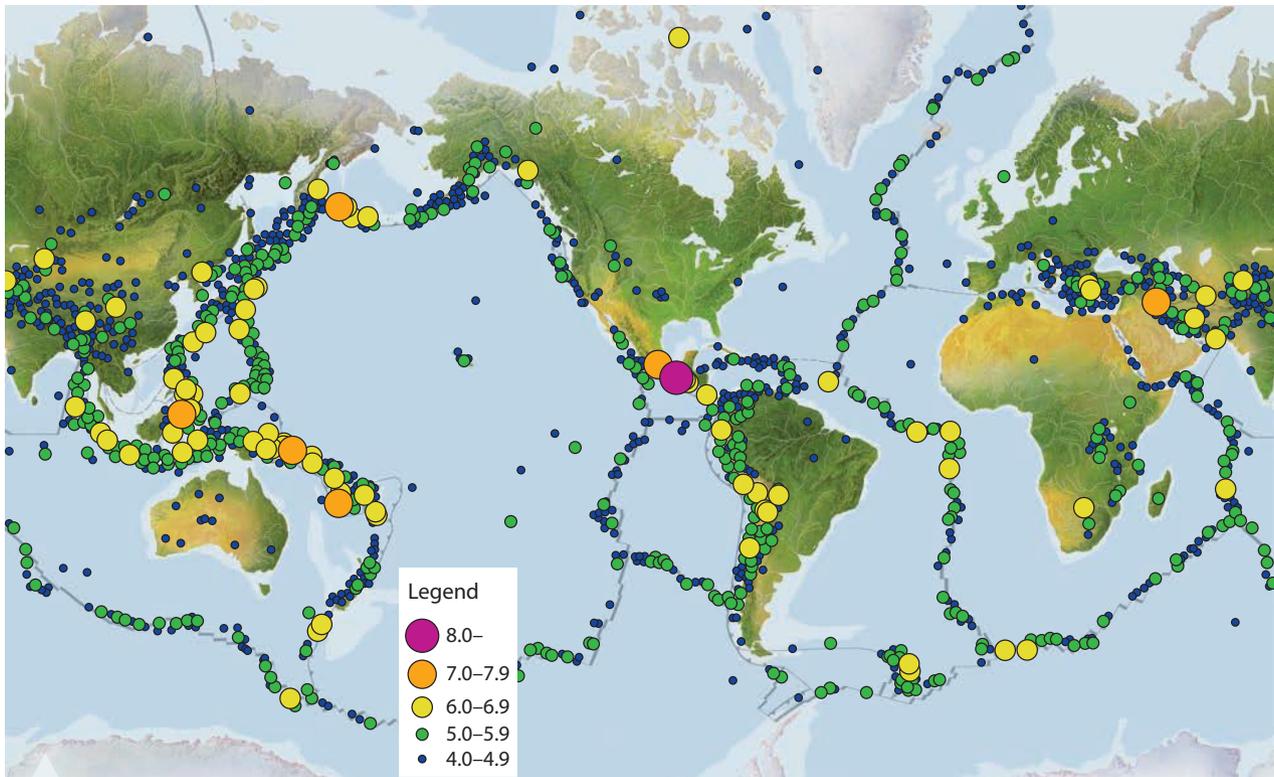


FIGURE 9.2 Earthquakes greater than magnitude 4 during 2017

The local magnitude scale is not accurate for large earthquakes, so for non-scientists today the energy of an earthquake is described using the moment magnitude scale (M_w). Geologists combine information about the properties of the rock involved, the area of the fault involved and the actual movement of the fault to calculate the energy released, producing what is called the seismic moment scale (M_0). The result is converted into a magnitude on the moment magnitude scale, which provides magnitudes of a similar scale to the traditional Richter scale.

Science Photo Library/Gary Hincks

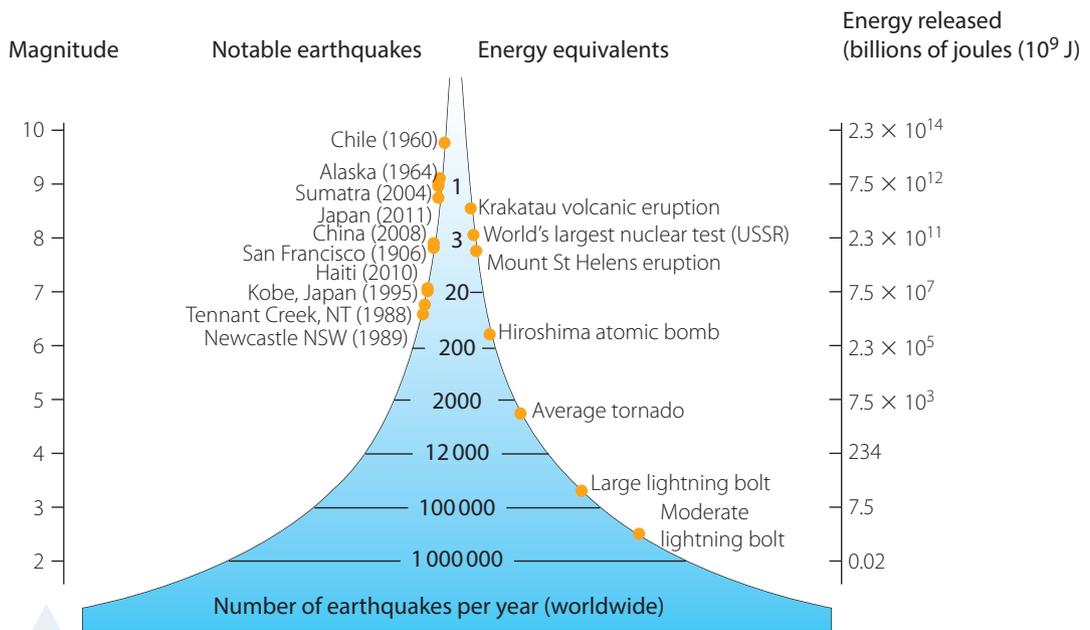


FIGURE 9.3 The magnitude of earthquakes and the energy they release

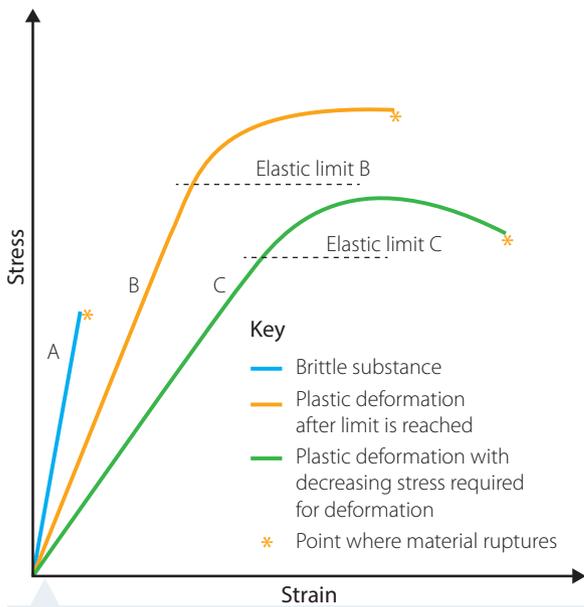


FIGURE 9.4 How materials deform or break when stressed

Elastic rebound theory

To understand how a rock can store and release energy, it is necessary to know something about how rocks behave when forces are applied to them. **Stress** is the force per unit area applied to the surface of an object. **Strain** describes the change in volume or shape of a body caused by the stress on it. Figure 9.4 shows how different materials behave when stress is applied to them. Materials that are strained may return to their original shape when the stress is removed. This is referred to as elastic behaviour and is shown in the linear parts of the curves. A **brittle** material will deform and suddenly break when it reaches its elastic limit (curve A). The breaking is called **rupture**. A more common type of deformation is shown in curves B and C where, after reaching the elastic limit, the materials will deform and will not return to their original shape when the stress is removed. This is called **plastic deformation**, and materials showing this behaviour are referred to as **ductile**. Even ductile materials will rupture if the stress applied is great enough and applied for a long time.

The energy released in an earthquake is transformed from elastic potential energy stored in rocks under stress. The process is illustrated in Figure 9.5. Pressure on the core of the fault causes the sides of the fault to lock together. Stress tries to move the rock in opposite directions on either side of the fault and this causes the rock to strain and store elastic potential energy. Eventually, when the rock in the core ruptures or the friction in the fault core is overcome, the sides of the fault move suddenly. The effect of the rock springing back into its original shape is the release and transformation of the energy stored in the strained rock. This model of earthquake formation is referred to as the **elastic rebound theory**. It was first proposed by Harry Fielding Reid, who used his studies of the massive 1906 San Francisco earthquake to develop the theory.

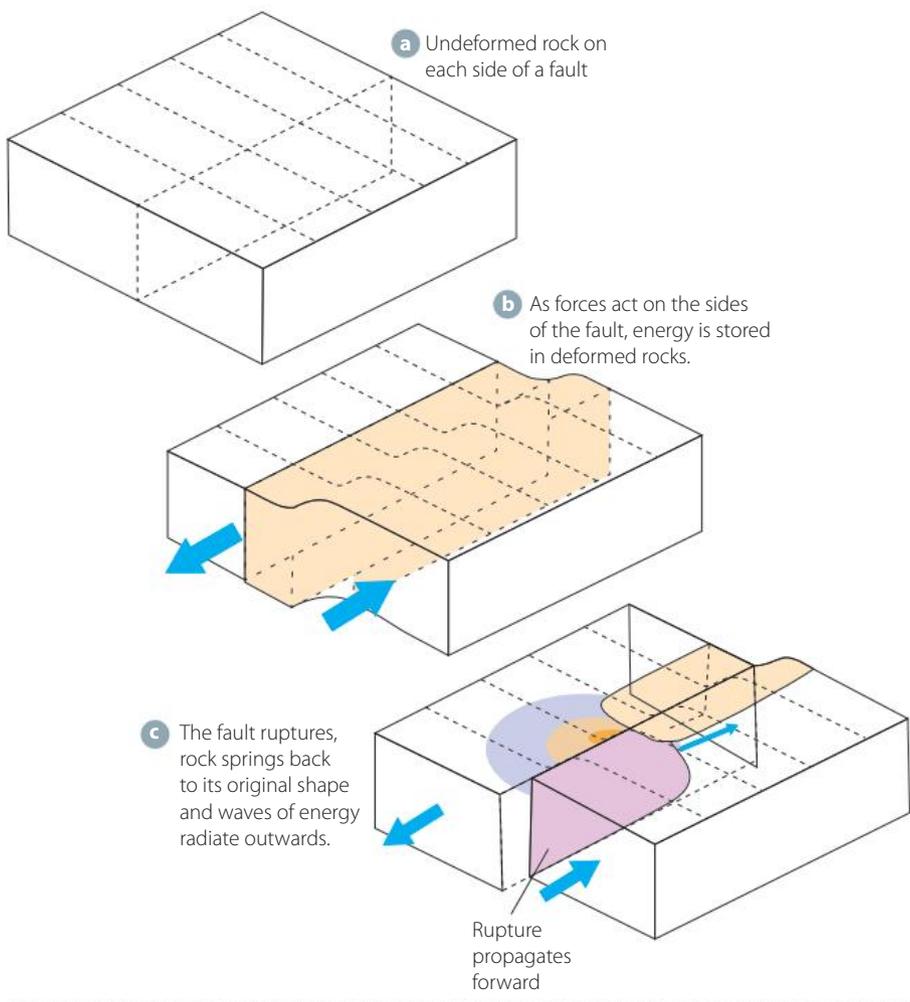


FIGURE 9.5
How elastic rebound occurs

The size of the rupture causing an earthquake affects the duration of the earthquake and the energy released. The elastic rebound of the rocks along the rupture surface is the source of the energy released. Because large magnitude earthquakes involve rupture over large areas, they last longer than smaller earthquakes. Ruptures can occur over distances of several metres to more than a hundred kilometres along the fault. A magnitude 4 (M4) earthquake, for example, will have a rupture length of about a kilometre, but the rupture from an M5 earthquake will be 10 times as large. The rupture starts at one place and propagates at about 3 km s^{-1} . An M8 earthquake with a rupture length of 100 km takes over 30s to occur.

Earthquakes occur when movement occurs at faults. A fault is a structure found in a body of rock where there is evidence of one side of the fault having moved relative to the other side (Figure 9.6). The surface along which movement has occurred is called the fault plane, and is often represented in diagrams as being smooth. In reality, a fault usually has a central fault core surrounded by a damage zone (Figure 9.7). The fault core is a zone of broken and pulverised rock formed when the rocks on either side of the fault move under high pressure. Surrounding the core, where the pressure is less, the damage zone contains deformed rocks that are folded and fractured.

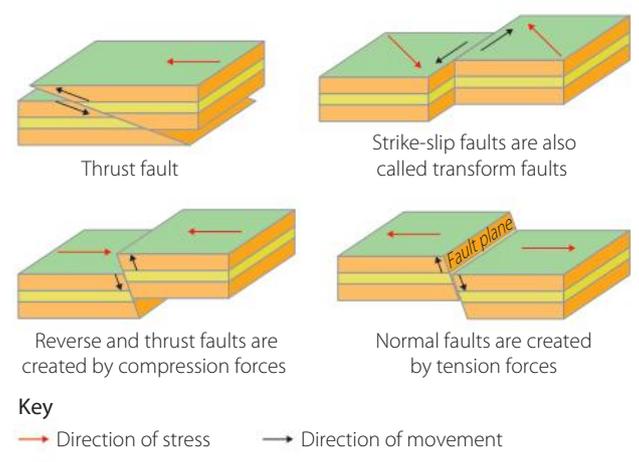


FIGURE 9.6 Types of fault

You also learnt about plate boundaries and faults in Chapter 7.

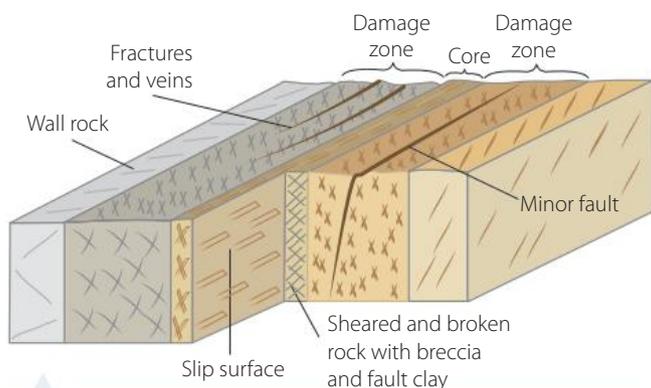


FIGURE 9.7 The structure of a fault – large amount of deformation occurs in and near the core.

Faults are traditionally classified according to the stress that forms them. Faults show a great deal of diversity in their structure but the stress that forms them is usually one of compression, tension or shear. These stress conditions are found at plate boundaries but also exist within plates. Normal faults are usually shallow, found in areas of extensional forces (tension) and usually create earthquakes less than M8. Strike-slip faults are also shallow; they can have magnitudes perhaps a little larger than those created on normal faults. Compression creates reverse and thrust faults. Thrust faults at convergent boundaries generate the largest magnitude earthquakes. Earthquakes at subduction zones occur within the crust and down to a depth of 800km. The mechanism of very deep earthquakes is still to be discovered.

INVESTIGATION 9.1

Investigating elastic and plastic deformation



Critical and creative thinking



Numeracy

INTRODUCTION

In this investigation you will examine elastic and plastic deformation in order to better understand how rocks under strain store energy.

AIM

To assess the relationship between stress, strain and stored elastic potential energy

MATERIALS

- 2 springs of different stiffness
- Retort stand and clamp
- 50 g mass carrier
- 50 g and 25 g masses
- Metre ruler
- 1 m length of nichrome wire
- Cylindrical whiteboard marker

METHOD

Part A: Elastic deformation

- 1 Gently test the springs to determine which is more easily extended (soft spring) and which is harder to extend (stiff spring).
- 2 Hang the softer spring from the clamp on the retort stand.
- 3 Arrange the spring and clamp so the base of the spring is 30 cm above the base of the clamp.
- 4 Copy Table 9.2 into your workbook.
- 5 Add the 50 g mass carrier to the spring and measure the extension or increase in the length of the spring. Record your measurement in Table 9.2.
- 6 Add another mass to the mass carrier. Record the mass added and the extension of the spring relative to the unloaded length.



- » 7 Repeat step 6 twice.
- 8 Remove the masses from the spring and measure and record the length of the spring.
- 9 Repeat the steps above using the stiff spring.
- 10 Complete the table by calculating the force applied. To calculate the force in newton, multiply the number of grams by 0.0098. Convert the extension from millimetres to metres by dividing by 1000.
- 11 Graph the force applied (y -axis) to the spring against the extension (x -axis). Draw a line of best fit for each spring.

See Chapter 1 to revise the line of best fit.

Part B: Non-elastic deformation

- 12 Copy Table 9.3 into your workbook.
- 13 Wind the nichrome wire around the whiteboard marker to form a spring. Make a loop in each end of the spring so you can attach it to the clamp and add masses.
- 14 Hang the spring from the clamp on the retort stand.
- 15 Measure the length of the spring.
- 16 Hang a 25 g mass from the spring. Measure and record the extension.
- 17 Remove the mass and record the unloaded length of the spring.
- 18 Repeat the 3 previous steps, increasing the mass each time.
- 19 Create a graph of extension against mass added. Draw a line of best fit through the points.
- 20 Draw a second graph of unloaded length against mass added. Draw a line of best fit through the points.

RESULTS

TABLE 9.2

			SOFT SPRING		STIFF SPRING	
MASS ADDED (g)	TOTAL MASS APPLIED (g)	FORCE (N)	LENGTH OF SPRING (mm)	EXTENSION (mm)	LENGTH OF SPRING (mm)	EXTENSION (mm)
0	0			0		0
50	50					
50	100					
50	150					

Length of springs after the force is removed:

Spring 1 _____

Spring 2 _____

TABLE 9.3

MASS ADDED (g)	LENGTH (l) (mm)	EXTENSION (x) (mm)	UNLOADED LENGTH (mm)
0		0	
25			
50			
100			

Include the graphs in your results section.

ANALYSIS AND DISCUSSION

- Describe the relationship between force applied and extension for the first spring you tested. What shape is the graph?
- Compare the relationships shown on your graph for the two springs.
- The extension represents the strain created by the applied force. Does the stiffer spring require more or less force to produce a particular amount of strain?
- For each spring, the area under the graph is a measure of the work, or energy change, that has occurred in stretching the spring. Calculate the area under the line of best fit for each spring up to the maximum extension of the stiffer spring. Which spring required more work to deform it?

- 5 The work done in deforming each spring represents the energy stored in the spring as elastic potential energy. Explain which spring would store more energy if they both experienced the same amount of strain.
- 6 Did the springs return to their original length when the mass was removed? If so, how was the energy stored in the springs transformed when the springs returned to their original shape?
- 7 For the nichrome spring, did the graph of extension against mass added produce a similar relationship to the other springs? Describe any differences.
- 8 Interpret the meaning of the graph of unloaded length against mass added. Explain why the spring does not return to its original length.
- 9 Relate the results of this investigation to rocks adjacent to an active fault. As stress causes strain in the rocks, what happens to the amount of elastic potential energy stored in them?
- 10 If the fault moves and the strained rocks can return to their original shape, what happens to the elastic potential energy?
- 11 If the stress on a rock is too great, the rock may deform or fracture. If this happens, how is the elastic potential energy transformed?

CONCLUSION

Describe how a material under stress can store energy and the factors that affect the amount of energy it stores.

KEY CONCEPTS

- In an earthquake, energy is released in the form of seismic waves and heat.
- The energy of an earthquake is measured in terms of magnitude.
- Faults at which earthquakes occur are created by stresses that cause deformation.
- Energy is stored as elastic potential energy when rocks are deformed and released when rocks slip on a fault or fracture.

CHECK YOUR UNDERSTANDING

9.1

- 1 Identify the different forms of energy found in the lithosphere of Earth.
- 2 Outline how the magnitude of an earthquake is determined.
- 3 Explain why a magnitude 2 earthquake is not twice as large as a magnitude 1 earthquake.
- 4 Compare brittle and plastic behaviour.
- 5 Describe how energy is stored in rocks when they are deformed.
- 6 Outline the elastic rebound theory.
- 7 Describe the types of faults found at convergent boundaries that generate large earthquakes.

9.2 Heat, magmas and eruptive styles

Volcanic activity occurs in particular tectonic environments and releases heat from within Earth (Figure 9.8). At divergent boundaries, rifts and within plates, melting occurs in the mantle below the lithosphere. At convergent boundaries, the lithosphere is involved in causing melting as material from the subducting lithosphere rises and causes melting in the mantle above the descending plate.

Magma formation and properties

The nature of volcanic activity and igneous rocks is determined by the nature of the **magma** that forms them. Magma is formed by the melting of pre-existing rock. It is a fluid consisting of liquid rock, dissolved gases and solid minerals and rock fragments. Most magmas on Earth are composed of molten silicate material. Within the molten material there are long chains of linked silica tetrahedra that contribute to the viscosity of the magma. Viscosity plays a key role in determining the nature of volcanic eruptions at the surface of Earth.

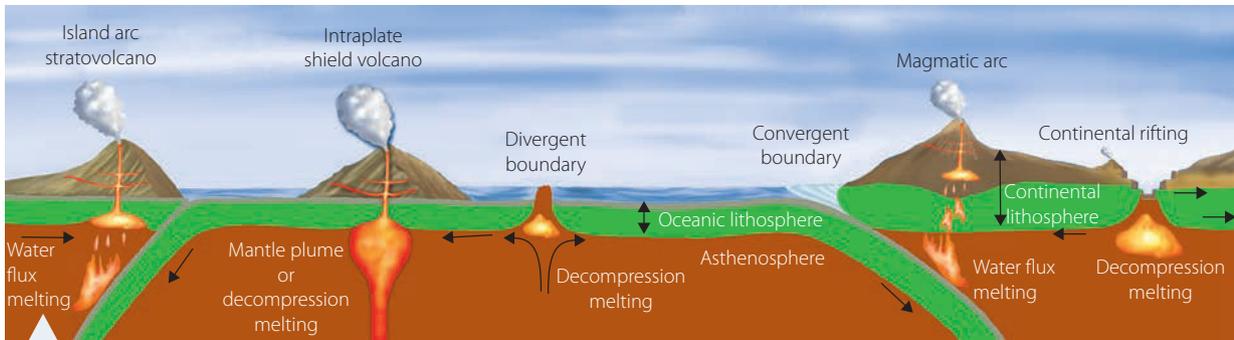


FIGURE 9.8 The tectonic environments in which magmas are created

Magmas can be characterised by their composition and temperature. Basaltic magmas form by the partial melting of mantle peridotite. **Partial melting** occurs when some, but not all, of the minerals in a rock melt. Some minerals are more stable at higher temperatures than others. In the upper mantle, partial melting turns 10–30% of the peridotite into a magma with the chemical composition of a basalt. Basaltic magmas erupt with high temperatures (1000–1200°C) and are relatively low in silica (~50% SiO₂). Melting at convergent boundaries produces magmas that have higher levels of silica (55–65% SiO₂), high levels of dissolved gases and higher viscosity than basaltic magmas. Intermediate composition magmas have a composition similar to andesite and they erupt at lower temperatures (800–1000°C) than the basaltic magmas. Melting of rocks in the crust generates magma that is more silica-rich. At lower temperatures, quartz and potassium-rich feldspar (K-feldspar) melt first, helping to generate magmas with silica concentrations of 65–75%. These magmas formed at convergent boundaries erupt rarely, but when they do erupt, they have relatively low temperatures (650–800°C).

If the temperature rises high enough, a rock will melt. The line describing when melting begins is called the **solidus**. In Figure 9.9, conditions where melting occurs is the area bounded by the temperature in Earth (geotherm) and the solidus.

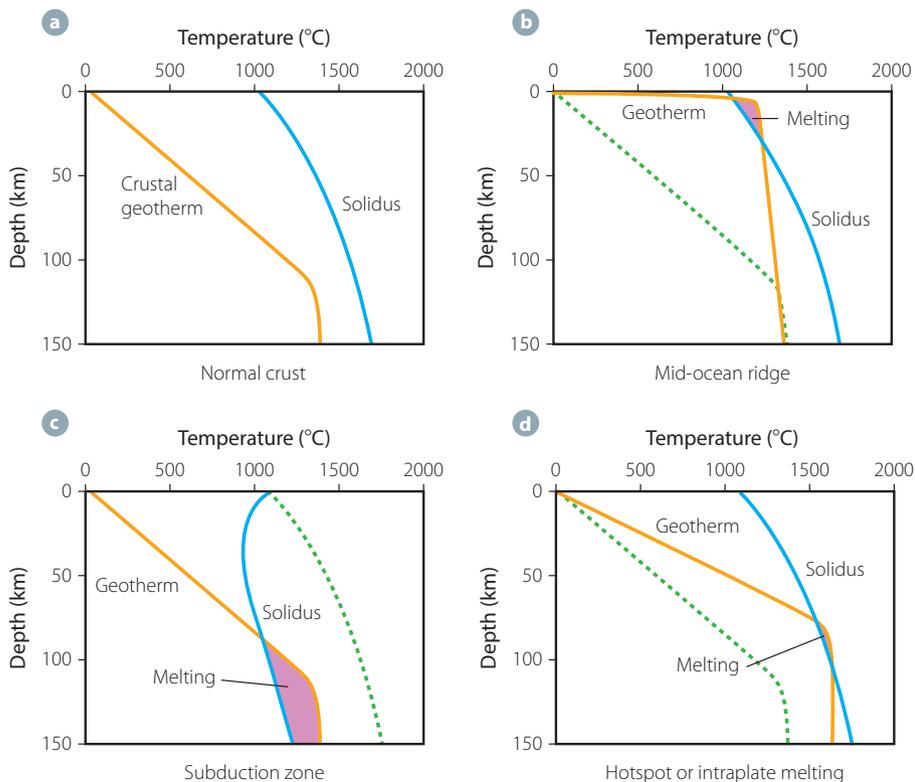


FIGURE 9.9 Conditions in Earth and the creation of magma. **a** Normal crust **b** Mid-ocean ridge **c** Subduction zone **d** Hotspot or intraplate melting

FIGURE 9.10
How water breaks up chains of silica

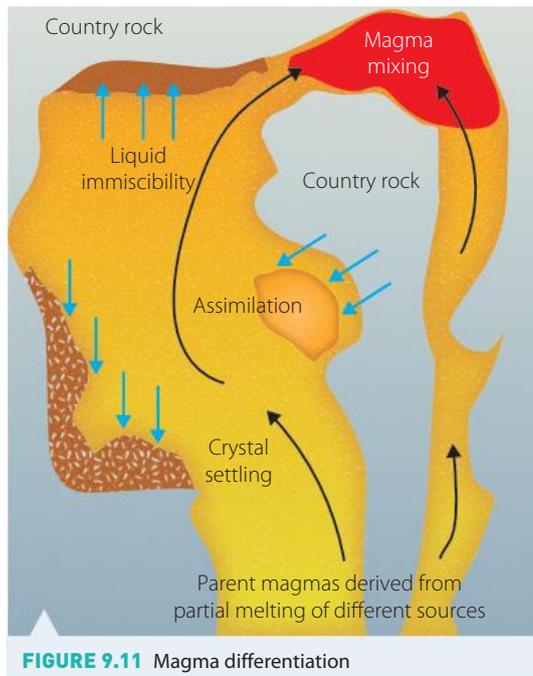
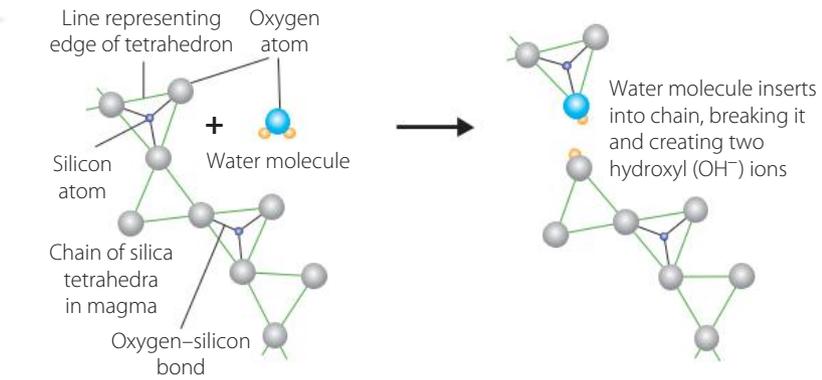


FIGURE 9.11 Magma differentiation

Temperature alone is usually not enough to form magma. Other contributing factors may be a decrease in pressure and the addition of a material such as water that assists melting (Figure 9.8). Within Earth, both temperature and pressure rise as the depth increases. Temperatures that would cause a rock to melt at Earth's surface cannot melt mantle rock because the pressure is too high. At a divergent boundary, however, hot mantle material can rise close to the surface where the pressure is low, and the rock melts to form a basaltic magma (Figure 9.9b). This process is called decompression melting.

Water plays a key role in melting at convergent boundaries. At depths of 50–150 km, water and dissolved material from the sediments on the subducting slab rise into hot mantle. There, the water breaks some of the bonds in the long silicate chains, causing the material to melt (Figure 9.10). This is sometimes referred to as flux melting. A flux is something that reduces the melting point of a

substance. In Figure 9.9c, note how the solidus has been shifted to the right so that partial melting occurs.



Describing the products of differentiation

Magma differentiation

A magma may undergo changes to its composition after it first forms. The magma formed by melting is called a primary magma. Changes to it create what is known as a secondary magma. Change in magma composition that occurs due to material being removed or added is called **magma differentiation**. Heat energy plays an important role in these processes. Figure 9.11 illustrates four common causes of magma differentiation.

One important mechanism that changes a magma is **crystal fractionation**. As a magma loses heat and cools, mineral crystals grow in the liquid. As they do so, the crystals remove some elements from the magma, thereby altering its composition. Bowen's series shows the order in which silicate minerals appear as temperature decreases (Figure 9.12). In a hot, low-viscosity basaltic magma, the minerals that crystallise first, such as pyroxene and plagioclase, stick to the sides of the magma chamber or sink to the bottom. In doing this, the solid crystals remove elements from the **melt**, or liquid part of the magma. The liquid that remains is called the residual melt and it will contain less iron and magnesium but more silica than the original melt.

Temperature of crystallisation (approximate)	Discontinuous series	Continuous series
	Given time, the minerals change from one to the next as the temperature slowly drops.	As temperature drops, calcium decreases as sodium increases.
1800°C ↓ 700°C	↓ Olivine $(\text{Mg,Fe})_2\text{SiO}_2$ ↓ Pyroxenes e.g. augite: $(\text{Ca,Na})(\text{Mg,Fe,Al,Ti})(\text{Si,Al})_2\text{O}_6$ ↓ Amphiboles e.g. hornblende: $(\text{K,Na})_{0-1}(\text{Ca,Na,Fe,Mg})_2(\text{Mg,Fe,Al})_5(\text{Al,Si})_8\text{O}_{22}(\text{OH})_2$ ↓ Biotite mica $\text{K}(\text{Mg,Fe})_3(\text{AlSi}_3\text{O}_{10})(\text{F,OH})_2$ Potassium-rich orthoclase $\text{KAl}_2\text{Si}_3\text{O}_8$ Muscovite mica $\text{KAl}(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ Quartz SiO_2	↓ Calcium-rich plagioclase $\text{CaAl}_2\text{Si}_2\text{O}_8$ Sodium-rich plagioclase $\text{NaAl}_2\text{Si}_3\text{O}_8$ ↓

FIGURE 9.12 Bowen's reaction series. Different minerals form at different temperatures in a magma.

The nature of a magma can also change due to assimilation. **Assimilation** is the process in which the rock surrounding the magma (country rock) dissolves into the magma. Crystallisation releases heat energy, and this assists the melting of the wall rock surrounding the magma body. Because high-silica minerals, such as quartz and orthoclase, have lower melting points, assimilation usually increases the silica content of the magma.

A magma's composition may also change through mixing with other magmas. Some granite is thought to originate in magmas formed by the mixing of silica-rich magma, formed by melting within continental crust, and basaltic magma, sourced from the mantle or lower crust. The resulting magma has a more intermediate composition.

A fourth process causing differentiation of magmas is **liquid immiscibility**. This occurs when two liquids do not mix with each other. An everyday example is oil and water, where the oil floats on top of the water or forms small droplets in the water if the mixture is shaken. In magma, immiscibility depends on temperature. Sometimes when mafic magma is cooling, droplets of liquid sulfide minerals form and separate from the silicate melt. They precipitate but exist as liquid droplets because the temperature is higher than their melting point. A range of important ore deposits, including some nickel sulfide deposits, have formed in this way.

The physical and chemical properties of a magma determine the style of eruption that occurs when the magma reaches Earth's surface. Viscosity and gas content are the key factors. The viscosity of a magma depends on its composition, temperature, volatile (gas) and crystal content. High-silica content means there will be a lot of linking between silica polymers in the melt. This increases the strength of the melt and reduces its flow. High temperatures usually reduce viscosity and more crystals in the magma increases the viscosity. Water plays an important role in magma viscosity. High water content keeps the magma flowing, but if rapidly decreasing pressure allows a loss of water as bubbles, the viscosity of the magma is increased.

The nature of volcanic eruptions

Volcanic eruptions vary a great deal in the energy they release. Eruptions range from very quiet **effusive** eruptions, where **lava** flows out of fissures, to dramatic **explosive** eruptions that violently expel ash and volcanic bombs over considerable distances. The nature of eruptions can be categorised with the Volcanic Explosivity Index (VEI) (Figure 9.13). The key feature of an eruption used by the VEI is the amount of pyroclastic material expelled in the eruption. **Pyroclastic** products are fragments created by explosive eruptions.

Index	Volume of ejected material (m ³)	Frequency	Eruption type	Description	Cloud column height (km)	Injection of material into atmosphere
0	1 × 10 ⁴	Continuous	Hawaiian	Gentle	Less than 0.1	Very little
1	1 × 10 ⁶	Daily	Strombolian	Effusive	0.1–1	Minor
2	1 × 10 ⁷	Once a fortnight	Vulcanian	Explosive	1–5	Moderate
3	1 × 10 ⁸	3 months	Plinian	Colossal	3–15	Significant amounts into troposphere
4	1 × 10 ⁹	18 months			10–5	
5	1 × 10 ¹⁰	12 years			More than 25	Significant amounts into stratosphere
6	1 × 10 ¹¹	50–100 years			More than 25	
7	1 × 10 ¹¹	500–1000 years			More than 25	
8	1 × 10 ¹²	Greater than 50000 years			More than 25	

FIGURE 9.13 Features of the Volcanic Explosivity Index (VEI)

These include material ranging in size from microscopic ash particles through to blocks and bombs the size of a house. A volcanic bomb is ejected from the volcano as molten rock and a volcanic block is solid rock ejected during the eruption. Most of the eruptions described in the VEI produce ash. Large-volume basaltic eruptions are almost always effusive. High-viscosity rhyolite domes generally create explosive eruptions.

Effusive eruptions and thermal plumes

Basaltic magmas generate effusive eruptions that form fissure eruptions, shield volcanoes and flood basalts. A **shield volcano** is formed when lava flows erupt from an eruptive centre, or crater, and flows outwards. The accumulation of rock decreases gradually away from the crater and shield volcanoes have shallow sloping sides. Such volcanoes can be large. Mauna Loa on Hawaii is about 120km wide and rises over 9000m from the ocean floor to its summit. The largest volcano in the solar system, Olympus Mons, is a shield volcano (Chapter 8).

Lava erupts effusively when the magma either lacks volatiles or the magma's low viscosity allows the gas to escape easily. Low viscosity is caused by a low silica content and a higher temperature in most basaltic magmas. On Hawaii, lava reaching the surface allows gas to escape easily and so the gas pressure is low. The escaping gas can create a lava fountain (Figure 9.14).

Fissure eruptions are the most common type of eruption on Earth. Many of the eruptions on Hawaii are fissure eruptions.

A **fissure** is a linear channel that may only be a couple of metres wide, but it may be kilometres long. Magma rises through the conduit and flows out across the surface. This is the way that lava reaches the surface at mid-ocean ridges, where it forms pillow lavas when the ocean rapidly cools the surface of the magma.

Large igneous provinces (LIPs) erupt more quietly and over longer periods. Basaltic lavas may flow for a million years and cover hundreds of square kilometres. The Ontong Java Plateau, north-east of New Guinea, is the largest on Earth. It originally covered approximately 2 million km² and contained over 44 million km³ of basaltic rocks formed from melting within the mantle. On land, the largest LIP is the Siberian Traps in Russia. Over a period of two million years, 4 million km³ of basaltic lavas were erupted. This event is regarded as the most likely cause of the end-Permian mass extinction.

The origin of the magma for most effusive eruptions is mantle **plumes**. The plume hypothesis was originally developed to explain the apparent chains of volcanic islands showing age trends along the chain. The hypothesis describes volcanic activity within plates as the result of plumes of hot mantle material that rise by convection from near the core–mantle boundary and create 'hotspots' below the lithosphere. The hot plume spreads and flattens as it reaches the base of the lithosphere and causes partial melting that generates the magma for volcanoes and LIPs.

Some scientists argue instead that volcanism within plates is more a by-product of plate tectonics. This plate model attributes the formation of magma within plates to tensional stresses in a plate that allow magma to rise towards the surface. The source of the magma is melting in the mantle of a material called eclogite, which melts at the temperatures found in the asthenosphere. The origin of mantle compositional variation is thought to be due to processes occurring at subduction zones and divergent boundaries.



FIGURE 9.14 An effusive eruption on Hawaii

Shutterstock.com/Yvonne Baur



Plume and plate models

Summarise the arguments for and against the plume and plate models.

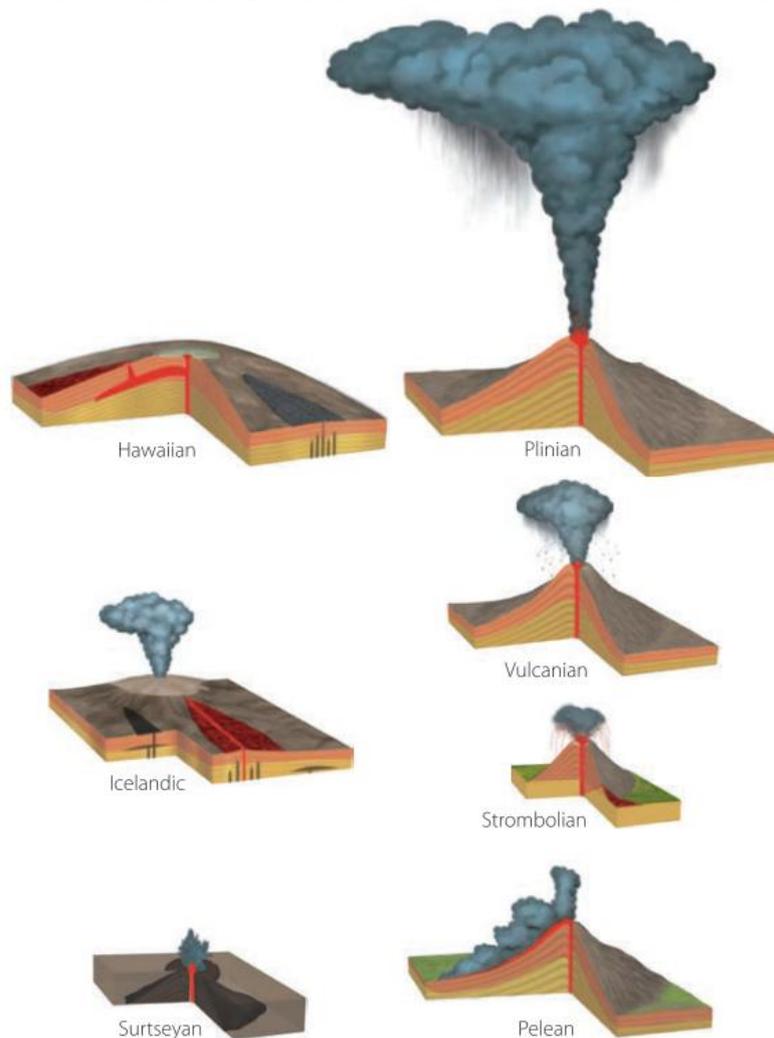
Some seismic evidence supports the plume model for Hawaii and for Yellowstone in the western United States, but the range of effusive deposits and a lack of evidence for features predicted by the plume hypothesis suggests that it does not explain all intraplate activity.

Subduction and explosive eruptions

The characteristic volcanoes formed at subduction zones are stratovolcanoes and rhyolite domes. The intermediate and silica-rich magmas that build these structures have high viscosities and also high volatile contents attributable to their origin in the subduction zone. The magmas at subduction zones are generally cooler than basaltic magmas. This increases the viscosity of the magma and contributes to the generation of ash and other pyroclastic matter.

Volcanic ash is produced when dissolved gases, referred to as **volatiles**, form bubbles within the conduit of the volcano. The **conduit** is the space through which the magma rises from the magma chamber to the surface (Figure 9.15). As the magma rises in the conduit, it reaches a level where the pressure allows bubbles of water vapour to form. As the magma continues to rise, the bubbles increase in size and join together. The magma viscosity increases because water is lost from the magma and incorporated into the bubbles. Suddenly, the bubbly flow changes into a rapidly moving flow of gas and fragmented magma, which erupts as ash. This erupting material is called the eruption column.

FIGURE 9.15
Types of eruptive
styles and volcanoes



In an explosive eruption, heat energy is transformed into the kinetic energy of particles in the eruption column. Heat energy is transferred into the atmosphere and lithosphere as volcanic products cool. Another energy change results from the changes in pressure in the magma chambers beneath the volcano. Stress from the pressure causes strain in the rocks and the stored energy is released as seismic energy when the rocks fracture. By plotting the origin of such earthquakes, scientists can map the magma behaviour within a volcano.

A stratovolcano, or composite volcano, is shaped like a steep-sided cone with a summit crater (Figure 9.16). It is composed of ash layers formed from falling erupted material and lava flows. Andesite and basalt magmas have a viscosity that allows volatiles to escape and lava flows away from the vents rather than generating ash. Stratovolcanoes contain igneous intrusions such as dykes and **sills**. Magma working its way through the sides of the volcano can also cause eruptions on the flanks of the volcano. These volcanoes may experience frequent changes in their shape over time due to explosive eruptions and the action of gravity on poorly compacted material within them.

Due to magmatic differentiation, magmas with high viscosity produce lavas at the surface that do not flow easily. These lavas, which form rhyolite, trachyte and sometimes andesite, form structures called lava domes (Figure 9.17). If the magma is rich in volatiles it may erupt as ash or pumice flows when the volatiles fragment the magma. Very viscous lava does not flow at all. It may form a plug that protrudes from the conduit as pressure from below forces it upwards. Eventually its weight causes the plug to collapse, creating a pile of shattered rock around the top of the conduit.

Stratovolcanoes create columns of ash that may rise high into the atmosphere. Very explosive eruptions, called Plinian eruptions, may inject material into the stratosphere. Such eruptions achieve their height partly through the thrust of the gas and ash mixture expelled from the volcano and partly through convection as the hot air loses some of the material falling out of it. Sometimes, eruptions from lava domes create clouds of ash and heated gases that flow down the sides of the volcano. These eruptions are termed **pyroclastic flows** (Figure 9.18).

Magma and water interactions

Ash clouds can be created when magma or lava comes into contact with water in the environment. Water and magma interactions are of two types. If water seeping into an area near a body of magma is heated to steam, an explosive eruption can result. Such eruptions are termed **phreatic**. The other type of interaction is when magma comes into direct contact with water, causing fragmentation



FIGURE 9.16 Mt Agung in Indonesia is a stratovolcano.

Shutterstock.com/Nina Janesikova



FIGURE 9.17 The glowing summit of Rerombola lava dome on Paluweh, Indonesia

Shutterstock.com/Photovolcanica.com



FIGURE 9.18 A pyroclastic flow descending the side of Soufriere Hills volcano, Montserrat

Alamy Stock Photo/Stocktrek Images, Inc.



Mt Pelee eruption

Read the article and describe the characteristics of the Mt Pelee 1902 eruption.



FIGURE 9.19 The volcano Eyjafjallajökull erupting in Iceland on 12 May 2010

of the magma and an explosive eruption with a great deal of ash. This type of eruption is called **phreatomagmatic**. The eruption of the Eyjafjallajökull volcano (pronounced AYA-feeyapla-yurkul) on Iceland in 2010 began as a phreatomagmatic eruption.

Eyjafjallajökull is a stratovolcano that lies under a glacier. The composition of the magma creating eruptions is basaltic to andesitic, and eruptions are usually small in terms of their energy. In 2010, water that had been melted from the **glacier** by heat energy in the volcano flowed into the volcano's crater. This caused an eruption that pushed ash several kilometres into the air (Figure 9.19). The eruption became notable because the ash disrupted air travel to and from Europe. Another famous phreatomagmatic eruption occurred near Iceland on the island of Surtsey. The island

grew as a series of underwater eruptions and built an island with a central volcanic crater. In 1963, as the island rose above the ocean, wave action allowed seawater to reach the exposed magma conduit and produced explosive eruptions with a large amount of fine ash.

Volcanic structures created by phreatic eruptions are common in Australia. The structures are called **diatremes**. Structures that form in a similar way and fill with water are referred to as maars. Diatremes form when rising magma, possibly moving along joint fractures, encounters groundwater. The groundwater rapidly becomes steam and as it travels it fractures the rock, throwing it out of the vent at the surface and forming a crater. Such eruptions are relatively small and most of the ejected material falls back into the crater. Some material falls around the crater, forming what is called a maar ring. Around Sydney there are the remains of about 25 diatremes. Diatremes are also common in Victoria. In Western Australia, the kimberlite pipes from which diamonds are mined are also diatremes.

A structure common to both stratovolcanoes and shield volcanoes is the **caldera**. This is a circular crater formed when the area at the top of the conduit is exploded outwards or the area collapses. Sometimes magma empties from the magma chamber so quickly that there is nothing to hold up the summit of the volcano. It collapses down, creating the caldera.



Global Volcanism Program

Research the features of three volcanoes.

INVESTIGATION 9.2

Thinking critically about magma differentiation

INTRODUCTION

In this secondary-source investigation you will examine the chemistry and minerals found in a layered intrusion. The intrusion is a sill and is 100m thick. The magma was intruded into the surrounding rocks and slowly cooled without disturbance. The sill shows layering and samples were collected and analysed from each rock type within the intrusion.

AIM

To determine whether the distribution of material in a cooled igneous body is consistent with crystal fractionation



Critical and creative thinking

Information and communication technology capability



TABLE 9.4 A simplified analysis of rocks found in a basaltic sill

HEIGHT ABOVE BASE OF SILL (m)	1	4	32	74	93	97	99
ROCK TYPE	chilled margin	peridotite	gabbro	diorite	grey fine-grained granite	pale fine-grained granite	chilled margin
ANALYSIS							
SiO ₂	49.2	42.3	50.1	47.5	61.2	71.6	49.2
TiO ₂	1.8	0.6	1.1	2.3	0.7	0.4	1.8
Al ₂ O ₃	15.7	4.2	15.5	12.4	14.8	14	15.6
Fe ₂ O ₃ + FeO	10.9	10.2	10.6	21.3	7.3	2.9	10.9
MgO	6.7	34.2	7.7	2.7	1	0.71	6.6
CaO	9.5	5.1	9.6	6.2	2.3	1.8	9.6
Na ₂ O	2.9	0.4	2.4	3.2	5.6	3.7	2.9
K ₂ O	1.1	0.3	0.9	1.1	4.9	4.7	1.1
OTHER	2.2	2.7	2.1	3.3	2.2	0.19	2.3
TOTAL	100	100	100	100	100	100	100
MINERALS PRESENT		olivine minor: pyroxene plagioclase magnetite	pyroxene minor: olivine plagioclase	plagioclase pyroxene magnetite ilmenite	plagioclase hornblende magnetite pyroxenes		plagioclase pyroxenes minor: olivine magnetite

MATERIALS

- A computer with a spreadsheet application
- or
- Graph paper
- Coloured pencils
- Ruler
- Calculator

METHOD

- 1 Examine the information in Table 9.4.
- 2 Construct a graph to show the variation in silica (SiO₂) throughout the sill. Label the vertical axis 'Height above the base of the sill' and the horizontal axis 'Percentage silica'. Ensure your scale for the horizontal axis covers the range of values in the table.
- 3 Construct a second graph with the same axes as the first but ensure the horizontal axis will accommodate values from 0 to 35%.
- 4 In the second graph, plot the analyses for each of the following oxides: MgO, Fe₂O₃ + FeO, CaO, Na₂O, K₂O. Do not plot the values for the chilled margin rocks. Use symbols or colours to separate the data for different oxides.
- 5 Use your graphs and the Bowen's series shown in Figure 9.12 to answer the analysis questions.

ANALYSIS OF RESULTS

- 1 The chilled margin rocks represent the average composition of the intrusion. They formed when the magma cooled rapidly in contact with the cooler rocks surrounding it. Which rock type in the intrusion has a composition closest to the rocks of the chilled margin?
- 2 What is the general trend in the silica content from the base to the top of the sill?
- 3 Describe the trend for each of the other oxides.



- » 4 According to Bowen's series, the first mineral to crystallise would have been olivine. As olivine crystals sank to the bottom of the intrusion, which elements would they have removed from the magma?
- 5 What evidence is there in the data for the possible crystal settling of olivine?
- 6 Plagioclase first crystallises with a high calcium (Ca) content, but this decreases as cooling occurs and sodium (Na) becomes more common in the plagioclase. Comment whether the calcium and sodium oxide trends support this statement.

DISCUSSION

- 1 Why does the percentage of silica rise higher than the average silica content for the intrusion?
- 2 If crystal settling occurred in the intrusion, the last rocks to form would be expected to be near the top of the intrusion. According to Bowen's series, quartz and sodium- or potassium-rich feldspar would be expected to be the last minerals to form. Comment on whether the composition of the pale fine-grained granite rock supports this prediction.
- 3 Does the composition of the rocks towards the base of the intrusion support the order of mineral appearance described in Bowen's series?

CONCLUSION

Does the distribution of elements in the intrusion support the idea that crystal fractionation might have occurred in the cooling intrusion?

KEY CONCEPTS

- Volcanic activity releases heat energy from within Earth at plate margins and within plates.
- Magma is formed by the melting of pre-existing rock due to changes in temperature, pressure or the presence of water.
- Magma compositions change through magma differentiation.
- Causes of magma differentiation include crystal fractionation, assimilation, separation of immiscible liquids and magma mixing.
- The properties of a magma, particularly viscosity and volatile content, determine the types of eruption that are produced.
- Melting of the mantle by mantle plumes due to pressure reduction leads to effusive eruptions of basaltic lava.
- Effusive eruptions form flood basalts, shield volcanoes and spatter cones.
- Melting of mantle above subducting lithosphere leads to intermediate to felsic magmas.
- Subduction volcanism is explosive, with the generation of stratovolcanoes, lava domes and calderas.
- When volcanic eruptions involve the interaction of magma and water, ash clouds can be formed.

CHECK YOUR UNDERSTANDING

9.2

- 1 Under what conditions does rock melt to form magma?
- 2 Describe the environments in which magma is formed in the mantle or lithosphere.
- 3 Outline the most important processes of magma differentiation.
- 4 How does the silica content change in a magma as crystals remove material from the melt?
- 5 Create a table to summarise the magma characteristics, eruption style and structures formed at rifts, subduction zones and hotspots.
- 6 Describe the process in which volcanic eruptions under glaciers can form ash clouds.

9.3

Energy and the formation of mountains

Mountains are defined as features that rise steeply above neighbouring terrain. They generally have a restricted summit area and are considered to rise more than 610m above their surroundings. Mountains vary in terms of their form and origin. Figure 9.20 shows the elevation of Earth's surface. Note the elevated mountain belts on the western edges of North and South America, the mountainous areas of Central Asia and the mountain ranges extending from Asia to the European Alps. Within the oceans, the mid-ocean ridges rise more than 2km above the abyssal plains. Isolated volcanoes such as Kilauea and other volcanoes on Hawaii also meet the definition of mountains.

Mountains are also built by the transformation of heat energy and gravitational potential. While mountains vary in their structure and origin, they display a range of similar energy transformations. Heat energy within Earth can cause melting or density changes that lead to mountain building. As mountains rise, their gravitational potential energy increases. Subsidence due to isostatic adjustment also transforms gravitational potential energy. The energy of convection-driven plate motion is transformed into a range of processes that shape mountains, including igneous activity, rock deformation and metamorphism. Mountains have two direct sources of energy: heat in the mantle and the kinetic energy of moving plates. Chapter 8 discusses how both of these sources originate in heat transfer processes within Earth.

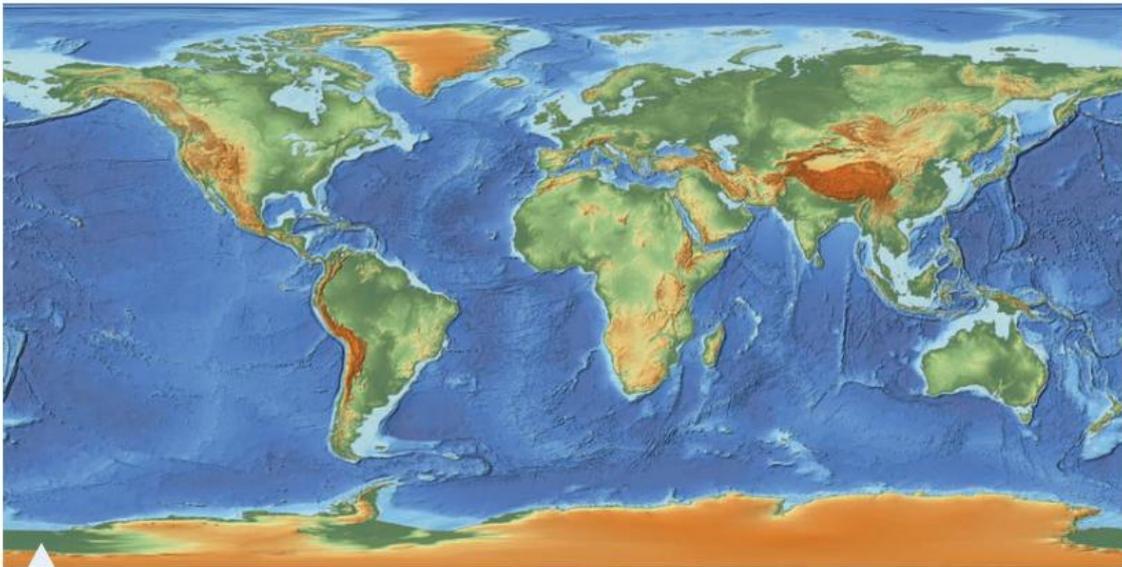


FIGURE 9.20 A relief map of Earth's surface

Energy in the mantle, uplift and expansion

Mantle plumes and hot areas within the mantle can generate mountains. In Chapter 7, the nature of mid-ocean ridges was described. Mid-ocean ridges gain their elevation due to hot buoyant mantle creating an upwards force on the hot new ocean crust. As the oceanic lithosphere cools, it contracts and loses buoyancy within the asthenosphere. As a result, the sea floor becomes deeper away from the ridge. In terms of their height and length, mid-ocean ridges are the longest mountain ranges on Earth if their height is measured relative to the sea floor adjacent to them.

Hot material in the mantle can cause thermal expansion, uplift and volcanism. In describing the origin of hotspot volcanism, we saw that mantle plumes or unusually hot areas in the asthenosphere

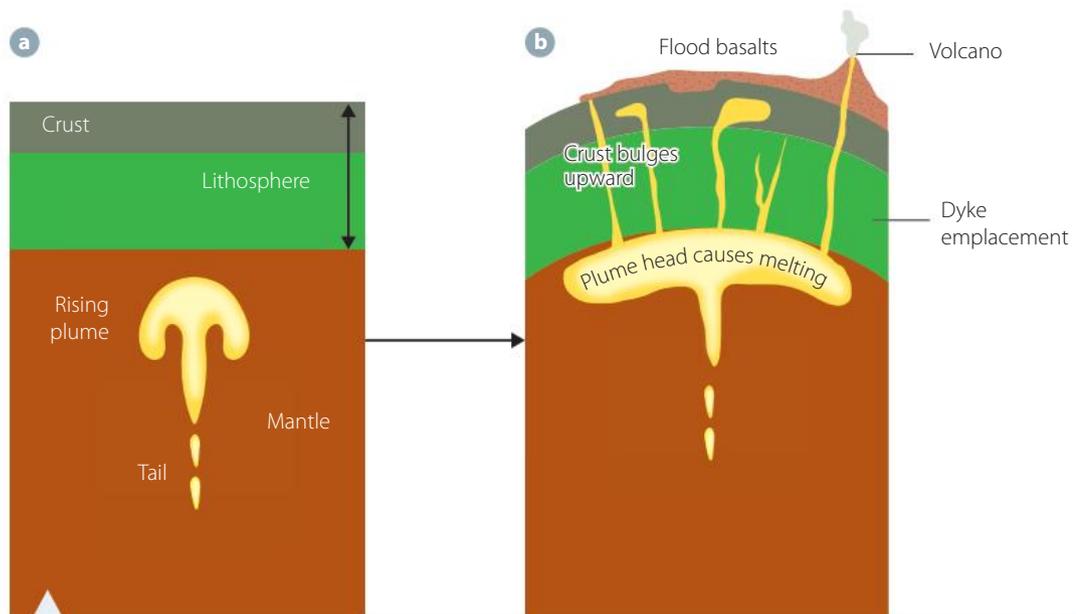


FIGURE 9.21 A model of mantle plume uplift **a** Plume rises below undeformed lithosphere **b** Plume spreads and pushes up, causing volcanic activity.



Zealandia

If Zealandia was part of a continent, why is it covered by ocean?



Australian Alps

More detail on the formation of the Australian Alps can be found here.

Horst-and-graben structures were discussed in Chapter 7.

generate basaltic volcanism at the surface. The heat transfer to Earth's surface by this process generates mountains such as those on Hawaii. Large mantle plumes, such as the one that lies beneath the Ethiopian Highlands in Africa, also cause uplift (Figure 9.21). As the plume rises, it heats the lithosphere. The heat causes thermal expansion and thickens the lithosphere. By reducing the density of the lithosphere, the plume causes the lithosphere to rise. The convection of the plume sideways under the lithosphere also creates tension and extension within the lithosphere. This leads to the creation of rifts and may lead to a new ocean forming between the rifted parts of the continent. The elevated edges of the rift often form mountains. In Africa, volcanic activity on the edges of the rift contributes volcanic mountains, such as Kilimanjaro, to the Eastern Rift Mountains.

The Australian Alps, containing Australia's highest mountains, are the result of rifting. The separation of Australia and the drowned continent Zealandia began with the uplift of a plateau, rifting and basaltic volcanism along what is now the east coast of Australia. As the Tasman Ocean formed, the elevated edge of the plateau remained as the Australian Alps.

In North America, the Basin and Range province contains mountains formed by **crustal extension**. Crustal extension occurs when the lithosphere is heated and placed under tension. Thinning of the lithosphere due to the tension forces created many tilted blocks bounded by normal faults. This creates horst-and-graben structures. The elevated blocks, horsts, rise up to several kilometres above the valley floors of the grabens.

Tectonics, deformation and mountains

At convergent boundaries, the stress generated by the colliding plates gives rise to a range of energy transformations. Stored elastic potential energy is transformed into seismic energy when faults rupture. Fault movement can also lead to stacking of rock strata and substantial thickening of the crust, with changes to the gravitational potential energy of the material uplifted. Sometimes, compressional forces within continents can create fault block mountains such as those in the Tien Shan of Central Asia (Figure 9.22). Such mountains form when compression fractures large areas of rock strata into large blocks – **fault blocks**. These blocks can be tilted, uplifted or depressed to form mountains.

When continents collide at a convergent boundary, energy transformation creates intense folding and faulting. When India collided with Asia, intense deformation created the Himalayas. The continental crust was too buoyant to subduct and the compressional forces caused the rocks to fracture, forming low-angle thrust faults. The rock between the thrusts, termed **thrust sheets**, may be 20km thick, and as they slide over each other, they substantially thicken the crust and help to form the mountains (Figure 9.23). Intense folding and faulting also occurs within the thrust sheets. The highest parts of the Himalayas are composed of folded rocks that were once marine sediments off the coast of the northern edge of the Indian continent.

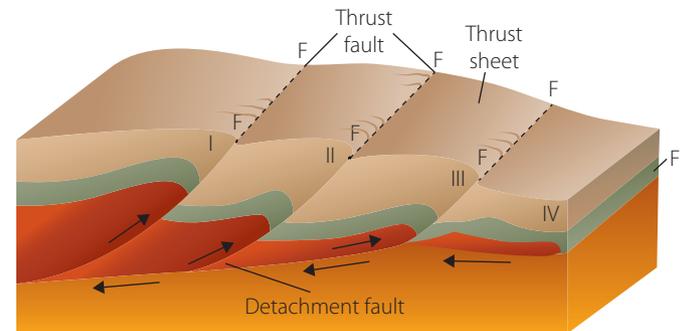
When rocks deform in a plastic way they do not store the energy involved in their deformation. Some of it is transformed into heat. A common type of structure caused by plastic deformation is folding (Figure 9.24). Folding also causes thickening and mountain formation. Because folding happens in rocks that are hot, regional metamorphic rocks are formed. Extreme heat and pressure at depth in mountains forms regional metamorphic rocks such as schist and gneiss. These rocks are exposed when the mountains erode.

Where oceanic crust converges with continental crust, a long belt of fold mountains is formed parallel to the coast in the continent (Figure 9.25). Examples of such environments include the Andes, the European Alps and the Rocky Mountains in North America. Horizontal compression and the intrusion of granitic **plutons** thickens the crust under the volcanoes created by the subduction. This area is called a **magmatic arc** and its elevation is increased by the effect of isostasy on the thicker crust. Inland of the magmatic arc, the strong horizontal pressure from the convergent boundary causes upper layers in the crust to form a **fold and thrust belt**. A **fold** is a structure formed when compression causes rock layers to buckle and bend. **Thrust faults** are low-angle faults formed by compression, and rock units can move tens of kilometres along such faults. Some spectacular folding is present in mountains such as those in the European Alps, where intense folding forms isoclinal, recumbent and overturned folds (Figure 9.24). **Regional metamorphism** is also present in such environments.

Building mountains is the sum of folding, faulting, igneous intrusion and metamorphism. The mountain-building process is termed **orogeny**. Ocean–ocean convergence also creates mountains in the form of volcanoes in the volcanic arc. When such island arcs are subducted up against a continent they become welded to the continent because they do not subduct easily. It was the convergence of volcanic arcs and their compression and intrusion that helped to form much of eastern Australia.



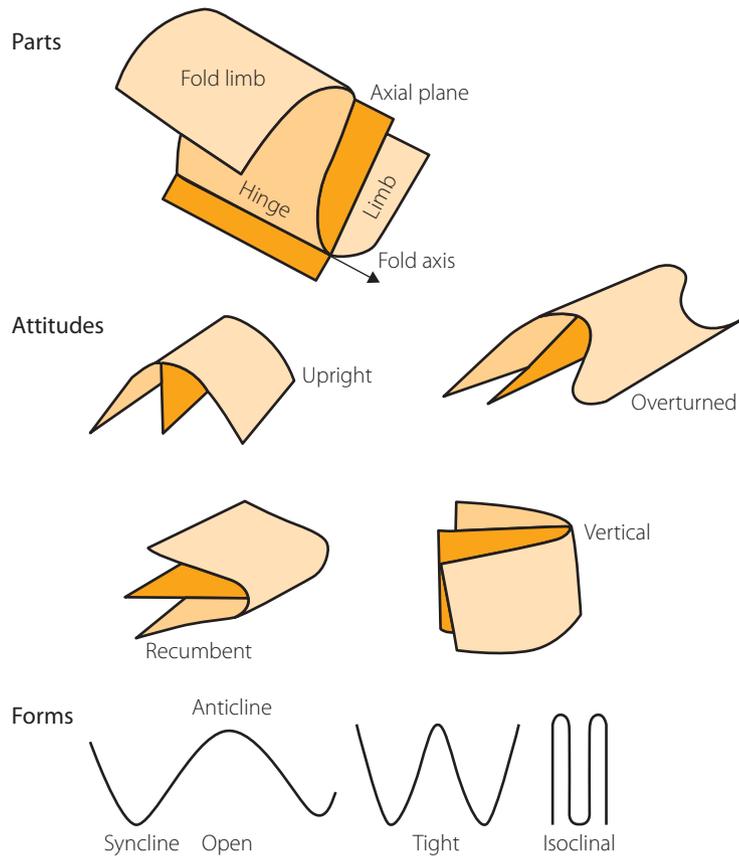
FIGURE 9.22 Mountains in Central Tien Shan



F–F fault
I–IV thrust sheets

FIGURE 9.23 Thrust sheets are a way that the crust accommodates compression and increases in thickness.

FIGURE 9.24
Features of folds –
plastic deformation



Hubble, Huxley, Imray-Gillespie, Earth and Environmental Science: The HSC Course Cambridge University Press.
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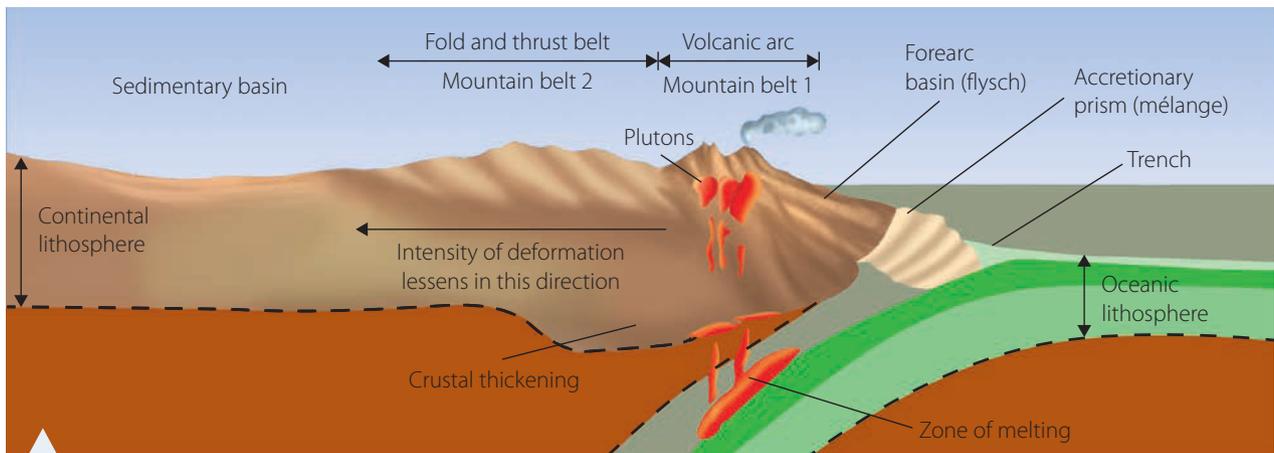


FIGURE 9.25 A cross-section of the Andes Mountains

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INVESTIGATION 9.3

Modelling deformation

AIM

To create a presentation that effectively communicates the processes involved in the formation of mountain structures

PROCEDURE

- 1 Select one of the subjects below.
 - Nappe
 - Decollement
 - Fault-block mountains
 - Plume-generated uplift
- 2 Using the Internet and/or library resources, gather information about the processes involved in forming your chosen subject. Include source information, examples of the subject, and the forces and energy transformations involved.
- 3 Review the criteria for the task below and ensure you have gathered all the information needed to complete your presentation.
- 4 Decide the form that your presentation will take. It may be a computer-based presentation, a poster, an annotated model, or another form of presentation that fulfils the requirements for the task.
- 5 Construct your presentation and then, with another student, review it using the rubric.
- 6 Make changes on the basis of your review and submit your presentation.

RUBRIC FOR THE PRESENTATION

A complete presentation will contain:

- a description of the structure
- an outline of the tectonic environment in which it is found
- a sequence of images or models showing stages in the formation of the structure
- an analysis of the forces and energy transformations involved in the structure's formation
- an assessment of the structure's role in mountain building.

A sound presentation will:

- have a logical sequence
- use clear and well-labelled graphics
- use language appropriate for an audience of other Year 11 students
- contain references to the sources of information used.



Critical and creative thinking



Information and communication technology capability



Literacy



Crossword summary

KEY CONCEPTS

- Mountains are features that rise steeply above surrounding terrain. They vary in terms of their form and origin.
- As rocks are elevated in mountain building, they increase in gravitational potential energy.
- Heat energy transfers cause melting, thermal expansion and isostatic changes that create mountains.
- Mantle plumes and hot areas in the mantle form mid-ocean ridges and hotspot volcanoes.
- Convection and plate motion can create tension, leading to mountains formed by faulting and isostatic adjustment.
- Volcanic activity at convergent boundaries forms mountains.
- Fault movement at convergent boundaries can form mountains by crustal thickening.
- Heat energy transfer contributes to the formation of metamorphic rocks and plastic deformation in mountains.
- Fold mountains are formed by deformation and volcanic activity at convergent boundaries.
- In fold mountain belts, folding, faulting, metamorphism and igneous intrusion contribute to the building of mountains.

CHECK YOUR UNDERSTANDING

9.3

- 1 Outline three ways in which the energy of mantle convection is transformed into processes that form mountains.
- 2 Identify mountains around the world that are the result of:
 - a thermal expansion or uplift by material in the mantle
 - b volcanic activity
 - c tension and normal faulting
 - d fold mountain formation.
- 3 Describe how a mantle plume or hot material in the mantle can generate mountains.
- 4 Make a series of diagrams to show how rock layers transform energy by forming faults and folds.
- 5 Explain how crustal thickening can lead to the formation of mountains.
- 6 Summarise the processes that form fold mountains and identify the energy transformations involved in each one.

9 CHAPTER SUMMARY

- ▶ In an earthquake, energy is released in the form of seismic waves and heat.
- ▶ The energy of an earthquake is measured in terms of magnitude.
- ▶ Faults where earthquakes occur are created by stresses that cause deformation.
- ▶ Energy is stored as elastic potential energy when rocks are deformed and is released when rocks slip on a fault or fracture.
- ▶ Volcanic activity releases heat from within Earth. It occurs at plate margins and within plates.
- ▶ Magma is created by melting of pre-existing rock due to changes in temperature, pressure, or the presence of water.
- ▶ Magma compositions change through magma differentiation.
- ▶ Causes of magma differentiation include crystal fractionation, assimilation, separation of immiscible liquids and magma mixing.
- ▶ The properties of a magma, particularly viscosity and volatile content, determine the types of eruption that are produced.
- ▶ Melting of the mantle by mantle plumes or pressure reduction leads to effusive eruptions of basaltic lava.
- ▶ Effusive eruptions form flood basalts, shield volcanoes and spatter cones.
- ▶ Melting of mantle above subducting lithosphere leads to intermediate to felsic magmas.
- ▶ Subduction volcanism is explosive with the generation of stratovolcanoes, lava domes and calderas.
- ▶ When volcanic eruptions involve the interaction of magma and water, ash clouds can be formed.
- ▶ Mountains are features that rise steeply above surrounding terrain and vary in terms of their form and origin.
- ▶ As rocks are elevated in mountain building, they increase in gravitational potential energy.
- ▶ Heat energy transfers cause melting, thermal expansion and isostatic changes that form mountains.
- ▶ Mantle plumes and hot areas in the mantle form mid-ocean ridges and hotspot volcanoes.
- ▶ Convection and plate motion can create tension, leading to mountains formed by faulting and isostatic adjustment.
- ▶ Volcanic activity at convergent boundaries forms mountains.
- ▶ Fault movement at convergent boundaries can form mountains by crustal thickening.
- ▶ Heat energy transfer contributes to the formation of metamorphic rocks and plastic deformation in mountains.
- ▶ Fold mountains are formed by deformation and volcanic activity at convergent boundaries.
- ▶ In fold mountain belts, folding, faulting, metamorphism and igneous intrusion contribute to the building of mountains.

9 CHAPTER REVIEW QUESTIONS



Review quiz

- 1 Describe the types of energy released by an earthquake.
- 2 Explain why large earthquakes, such as those of magnitude 7 or 8, do not always create a lot of damage a long way from their origin.
- 3 Explain the relationship between stress and strain.
- 4 Describe the elastic rebound theory as a mechanism for transforming and releasing energy.
- 5 Summarise the locations in and at the edges of plates where volcanoes are formed.
- 6 Outline the reasons why a mantle rock might melt.
- 7 Explain how crystallisation in a magma changes the composition of the remaining liquid rock.
- 8 Where in a magma chamber would you expect to find the results of crystal fractionation, assimilation and liquid immiscibility? Give reasons for your predictions.
- 9 Describe the key properties of a magma that determine the type of eruption the magma can produce.
- 10 Explain why a high volatile content in a magma can lead to the production of volcanic ash.
- 11 Contrast the products of effusive and explosive eruptions.

- 12** Contrast the nature of a Hawaiian eruption with a Plinian eruption.
- 13** When magma erupts under the sea, it forms pillow lavas. When water enters a volcanic conduit, an explosive eruption with lots of ash results. Explain the difference in these eruptive styles.
- 14** In a series of drawings, explain how a mantle plume rising below the lithosphere can result in mountain building.
- 15** Draw a fault block mountain and label the drawing to show how it gained its height.
- 16** Summarise the processes that help build mountains at convergent boundaries.
- 17** How does energy in Earth lead to metamorphism? Create a flow chart to show the energy changes that occur from heat in the mantle to the deformation and development of metamorphic rocks.
- 18** Draw three of the structures you would expect to find in a fold mountain range.
- 19** Assess the origin of the energy that is transformed during the formation of folds and faults.
- 20** Explain how crustal thickening or the intrusion of granites can cause the formation of mountains.
- 21** Create a concept diagram to show the energy transformations, key structures and processes involved in earthquakes, volcanic activity and mountain building. Link the parts of your diagram to show the relationships between the structures, processes and energy transformations.

10

Heat, the atmosphere and hydrosphere

OUTCOMES

In this chapter you will learn about:

- the unique properties of water that make it a key component of Earth systems [CCT ICT](#)
- the factors that generate currents in the ocean
- the role of heat transfer in creating atmospheric processes [CCT ICT](#)
- changes in the cryosphere. [ICT L](#)





Why does Australia experience floods in some years and drought in others? The short answer is the interaction of the atmosphere and ocean. Ocean currents influence the weather along the Australian coast. Air masses near the equator and those moving north from Antarctica also influence the weather we experience.

Predicting how the atmosphere and oceans create our weather is difficult because the ocean-atmosphere system is extremely complex. What we do understand, however, are some of the processes that affect how the system works.

Differences in the amount of solar energy absorbed by different parts of Earth's surface set the atmosphere and ocean in motion. The processes that move air create our climate and weather (Figure 10.1). In this chapter, we examine the critical role of water and heat energy in changing the atmosphere, the oceans and the frozen waters of Earth: the cryosphere.



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FIGURE 10.1 Ocean, Sun and atmosphere create our weather.

10.1 The properties of water

Water plays important roles in so many aspects of Earth. It is part of the non-living (**abiotic**) and living (**biotic**) parts of our environment. In Chapter 9 we saw how water facilitates mantle melting and determines the nature of volcanic eruptions. In Chapter 8 you learnt that Earth is unique in having water exist as a solid, liquid and gas. We encounter water so often that we tend to forget how special it is.

The nature of water

The hydrogen and oxygen that make up water are the first and third most abundant elements in the solar system. Analysis of light from stars suggests the elements have similar ranks in the abundance of elements in our galaxy. On Earth, however, hydrogen ranks as the eighth most abundant element as a result of the loss of hydrogen and other volatiles during the long evolution of Earth's atmosphere.

Most of the properties of water are due to the structure, size and charged nature of the water molecule. The two tiny hydrogen atoms make a V-shape with the much larger oxygen atom. The hydrogens are bound strongly to the oxygen by the sharing of electrons. Because the charge on the oxygen nucleus is larger than that on the hydrogen atoms, it attracts the electrons more strongly. As a result, the area around the hydrogen atoms has a slight positive electric charge. Slight negative charges form at the oxygen vertex of the molecule due to the electron arrangement. As a result of the molecular shape, water molecules have both positively and negatively charged parts and these can form bonds with other water molecules (Figure 10.2).

The attraction of the positively charged hydrogens to the negative oxygen of adjacent molecules is called **hydrogen bonding**. A single water molecule can be attracted to as many as four other molecules (Figure 10.3). It can also attract other charged atoms, called **ions**. The breakdown of the mineral olivine by water, for example, involves the removal of magnesium or iron ions that bind silica units in the crystal together. The negative charges of the water molecules first draw the positively charged metal ions away from the olivine crystal. Surrounded by the charged oxygen of the water molecules, the ions are kept dissolved in the water and the crystal structure of the olivine breaks down.

Surface properties

Surface tension is the resistance of a fluid to change in its surface area. It occurs because the forces acting on water molecules at a surface are not the same as the forces acting on molecules within the liquid. A molecule at the surface experiences attraction from the molecules around and below it but not from above. This creates a net force on the molecule, trying to move it inward. On a large scale, this behaviour leads to the surface acting like an elastic surface that pushes back on small objects resting on the water surface (Figure 10.4). The water resists the increase of the surface area.

Surface tension is measured as the energy required to increase the surface by a unit amount. It depends on the strength of the bonds between particles in a liquid. Water has one of the highest surface tensions of any liquid (Figure 10.5).

Surface tension in water results in the formation of droplets, bubbles, surface waves and capillary action. **Capillary action**, or capillarity, refers to the rising of water through a narrow space against the force of gravity. Capillarity is due to both the attractive forces that draw the molecules inward (**cohesion**) and the attraction between the water molecules and the surface the water is in contact with (**adhesion**). The water creeps up the edges of a narrow space and surface tension also causes the level of the water to rise. It is capillarity that draws water up a piece of paper or paint into a brush and enables water to move within plants and through the soil.

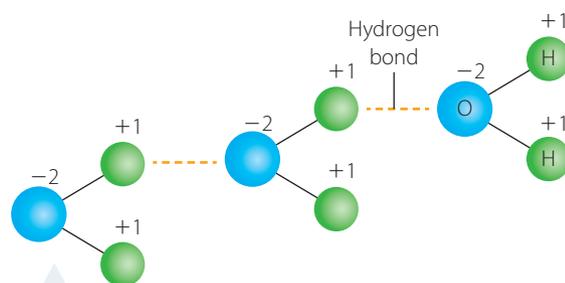


FIGURE 10.2 Charges on water molecules form bonds between molecules.

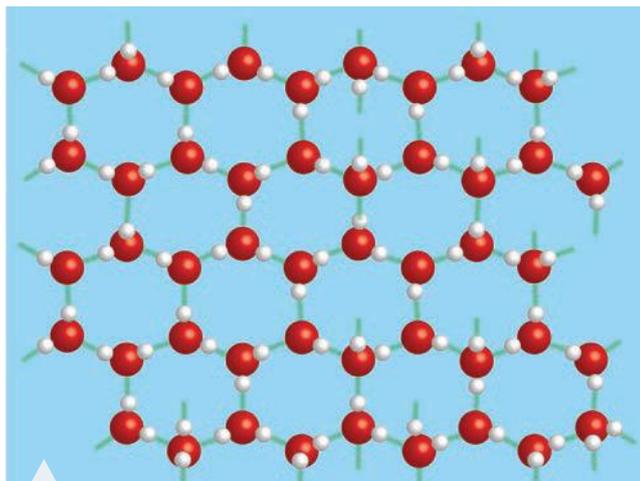


FIGURE 10.3 The arrangement of water in ice, showing bonding between molecules



FIGURE 10.4 A paperclip floating on water. The water contains a dye and shadows have been cast on the surface to show how the paperclip distorts the surface.

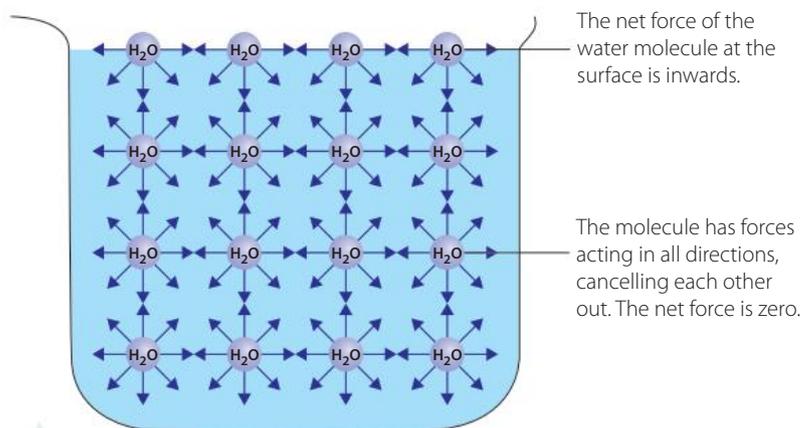


FIGURE 10.5 Forces on water molecules within and at the surface of a water drop

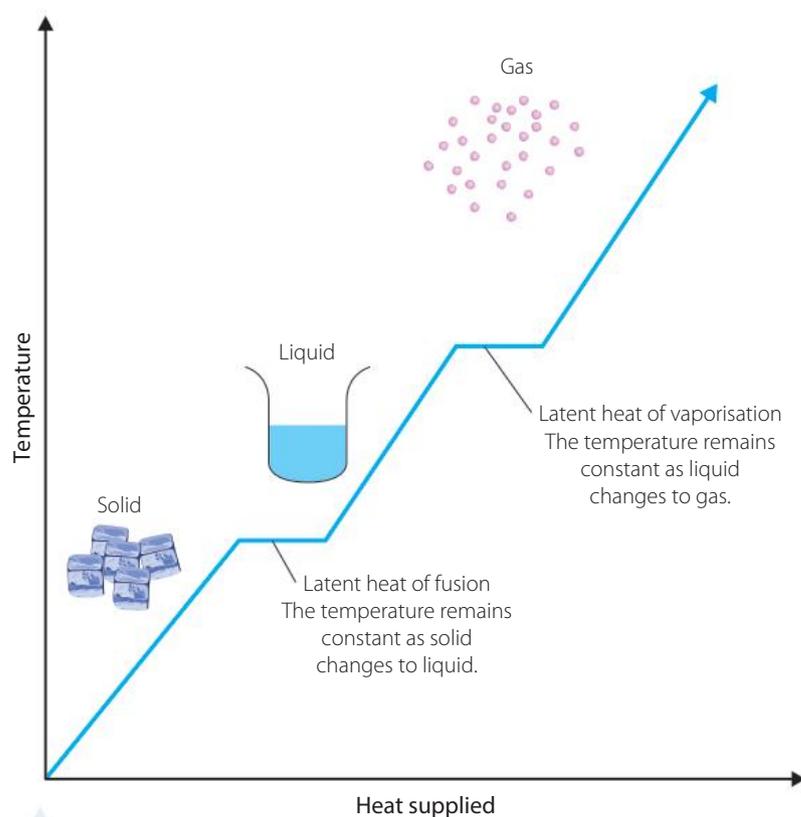


FIGURE 10.6 Latent heat of fusion is the heat required to change a solid to a liquid, and the latent heat of vaporisation is the heat required to change a liquid to a gas.

Thermal properties

The way water interacts with heat energy has profound effects on climate and life. Most compounds that are not charged like water molecules have much lower melting and boiling points. If molecular size alone affected the amount of heat needed to melt or boil a substance, the boiling point of water would be 200° lower. Water would then exist on Earth only as a gas.

Three important thermal properties of water are specific heat capacity and the heats of fusion and vaporisation. The high specific heat capacity of water means that water bodies change temperature slowly when heat is added. The **specific heat** of a substance is the amount of heat needed to raise the temperature of 1 gram of the substance by 1°C . Liquid water has a very high specific heat capacity of $4.184\text{Jg}^{-1}\text{C}^{-1}$. Ice and water vapour have heat capacities approximately half that of liquid water. Compare the specific heat capacity of water with sand ($0.853\text{Jg}^{-1}\text{C}^{-1}$) and glass ($0.5\text{--}0.75\text{Jg}^{-1}\text{C}^{-1}$). Raising the temperature of liquid water by the same amount as these materials requires approximately 5 to 8 times the amount of energy. Because of water's high heat capacity, sunlight absorbed by water creates only a small change in temperature. As a result, water bodies provide stable temperature environments for aquatic and marine organisms.

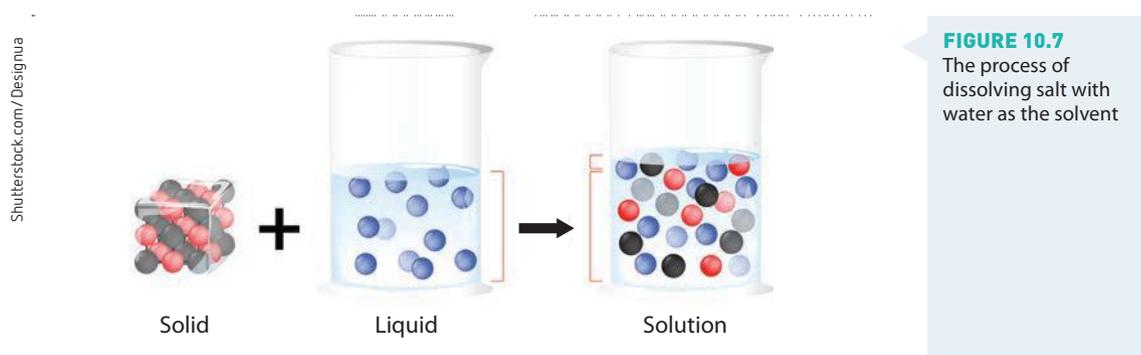
The **heat of fusion** and **heat of vaporisation** refer to the heat required to transform the state of a substance (Figure 10.6). The gain or loss of heat in a change of state is called **latent heat**. When liquid water is heated, its temperature remains at the boiling point until all the liquid water has changed into water vapour. The energy being added is used to change the state

of the water from liquid to gas but the temperature does not change. The energy required to change the state of the water is called the heat of vaporisation. When the state reverses during condensation, the latent heat is released. When a body of water is heated by sunlight, the evaporation of a small amount of water removes enough heat to keep the temperature of the water fairly constant. In a similar way, energy must be absorbed for ice to turn into water. This is called the heat of fusion. For ice, the heat of fusion means that ice is slow to melt and ice sheets and glaciers are partly resistant to the heating effects of the atmosphere and sunlight.

Solvent properties

A **solvent** is a substance that can dissolve other substances. Water is able to dissolve a wide range of substances, including a variety of acids, salts and gases. It is the charged nature of water molecules and their small size that allows this. Many of the substances that water dissolves are polar in nature. This means that atoms or groups of atoms are electrically charged. When salt dissolves in water, the water molecules surround the metal and non-metal ions. The negatively charged oxygen atoms in the water are attracted to the positively charged metal ions from the salt, and the positively charged hydrogen atoms in the water are attracted to the negatively charged non-metal ions. By surrounding the ions from the salt, the water molecules prevent them from reattaching to other ions from the salt crystal (Figure 10.7).

Gases such as oxygen and carbon dioxide dissolve in water because they have or develop slight charges. Oxygen atoms in water have the ability to induce charges on oxygen molecules. The negative charge of the oxygen in the water molecule repels some of the electrons around the oxygen atoms in the oxygen molecule, creating a charge distribution that allows the oxygen to be surrounded by water molecules. As the temperature of a solution increases, both oxygen and carbon dioxide can escape from the liquid.



Carbon dioxide interacts with water to create a bicarbonate ion and a hydrogen ion. This enables the carbon dioxide to dissolve and also creates a slightly acidic solution. Bicarbonate is the major form of dissolved carbon in the ocean and it is this ion that organisms such as molluscs and corals use to create their shells and other hard parts.

Because of its solvent properties, water plays a critical role in cells and in a wide range of environmental processes. A living cell contains a large variety of molecules dissolved in water; the chemical reactions that support life processes occur in these solutions. The movement of gases and materials in our blood is another example of the importance of water's solvent ability. Finally, the composition of the ocean, the way life utilises dissolved substances, and the way that materials precipitate from solution are determined by water's solvent behaviour. Unlike gases such as carbon dioxide, salts usually increase their solubility in water as the temperature increases.

Density and viscosity

Water is also unusual in the way its density changes as it cools. The density of water is approximately 1 g cm^{-3} . As water cools, its density increases, reaching its greatest density at 4°C . The density then begins to fall because the forces between the molecules are able to move the molecules further apart. When ice forms, the density decreases by approximately 9%. In cooling water bodies at high latitudes, the fact that water becomes most dense at 4°C , and at 0°C in saline water, has important consequences for life. As the water becomes dense, it sinks and will flow along the floor of the water body. This means that the water at the bottom of the water body does not freeze. Therefore, ponds and the ocean do not freeze

You will learn more about density and how it moves ocean water when you study the thermohaline circulation later in this chapter.

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FIGURE 10.8 In the open ocean, wind on the water surface creates waves.

from the bottom up and kill the life in the water. The sinking cold water also can mean that nutrients in deeper waters are moved upward as the descending water displaces deeper nutrient-rich waters.

Water has a low viscosity, and this is important in water's solvent behaviour and the creation of water movements such as waves. Because water flows easily, forces across its surface can create movement and generate waves (Figure 10.8). Water's viscosity, like that of lava, changes with temperature. As temperature increases, water's viscosity decreases.

INVESTIGATION 10.1

Latent heat of fusion of ice



Critical and creative thinking



Information and communication technology capability



Numeracy

INTRODUCTION

In this investigation, you will calculate the latent heat of fusion for ice. You will do this by measuring the changes in the heat contained in a closed system containing ice and water. As the ice melts, heat from the water is transferred to the water from the ice. By measuring this change, you will determine how much energy is required to cause the change of state.

AIM

To measure the amount of heat required to melt 1 g of ice

MATERIALS

- Cutting board
- Styrofoam cup or thermos flask
- Styrofoam or cardboard lid
- Digital thermometer or data logger with temperature probe
- Glass rod
- 250 mL measuring cylinder
- 250 mL beaker
- Roll of absorbent paper
- Crushed ice or 3–4 ice cubes
- Tongs
- Warm (20°C–30°C) water



WHAT RISKS ARE THERE IN DOING THIS INVESTIGATION?

Ice can cause skin damage if prolonged skin contact occurs.

HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

Handle the ice with tongs or pour it from a beaker rather than handling it with your fingers.

What other risks are associated with your investigation, and how can you manage them?

METHOD

- 1 Place the styrofoam cup on an insulated surface such as a cutting board.
- 2 Use the beaker and measuring cylinder to measure 200 mL of warm water. Record the exact amount and add the water to the cup.



- 3 Prepare three ice cubes or an equivalent amount of crushed ice by blotting the ice dry on some absorbent paper.
- 4 Measure the temperature of the water in the cup and record it in a copy of the table below.
- 5 Add the ice carefully to the water in the cup and gently stir it with the glass rod until the ice melts.
- 6 Measure the water temperature and record it in the table.
- 7 Use the measuring cylinder to measure the volume of water in the styrofoam cup.
- 8 Repeat the investigation twice more, using different amounts of water and ice.

RESULTS

	MEASUREMENT 1	MEASUREMENT 2	MEASUREMENT 3
WATER VOLUME (mL)			
WATER + ICE VOLUME (mL)			
ICE VOLUME (mL)			
STARTING TEMPERATURE (°C)			
FINAL TEMPERATURE (°C)			
TEMPERATURE CHANGE (°C)			

ANALYSIS OF RESULTS

The energy removed from the water by the ice is given by:

$$E = m \times C \times \Delta t \quad \text{(equation 1)}$$

where E = energy change in joules

m = mass of water in grams (Assume 1 mL of water has a mass of 1.0g.)

C = specific heat of water ($4.19 \text{ Jg}^{-1} \text{ } ^\circ\text{C}^{-1}$)

Δt = change in temperature in $^\circ\text{C}$

The energy absorbed by the ice is given by:

$$E = m_{\text{ice}} \times L_{\text{ice}} + m_{\text{ice}} \times C_{\text{ice}} \times (T_{\text{final}} - 0^\circ\text{C}) \quad \text{(equation 2)}$$

Here, E = energy gained by the ice in joules = energy removed from the water (equation 1)

m_{ice} = mass of ice in grams

L_{ice} = latent heat of ice ($\text{Jg}^{-1} \text{ } ^\circ\text{C}^{-1}$)

C_{ice} = specific heat of ice ($2.11 \text{ Jg}^{-1} \text{ } ^\circ\text{C}^{-1}$)

T_{final} = final temperature in $^\circ\text{C}$

The latent heat of the ice, L_{ice} , is unknown and is the quantity you will determine. If the water and ice do not lose heat to their surroundings, the heat lost by the water is equal to the heat gained by the ice. Use equation 1 and equation 2 to calculate the latent heat, in Jg^{-1} , for each of your sets of measurements.

DISCUSSION

- 1 What was the average latent heat of fusion you measured?
- 2 How does your value compare with the standard value of 333.55 Jg^{-1} ?
- 3 What assumptions were made in the calculation of the latent heat of fusion?
- 4 Outline the possible sources of error in the experiment.
- 5 How could some of the sources of error be minimised?
- 6 How reliable was the method? What are some improvements you could make to the method to improve reliability?

CONCLUSION

State the latent heat of fusion for water as determined in your experiment.

State the level of confidence you have in your result.

- Water is a substance with unique properties.
- Many of the properties of water are due to the shape and charged nature of the water molecule.
- Surface tension allows water to form droplets, bubbles and waves and display capillary action.
- The high heat capacity of water means that water changes temperature slowly, providing a stable environment for life.
- Water is a powerful solvent, dissolving a wide range of compounds, salts and gases.
- Water's solvent properties are important for the processes in cells and in the composition of the ocean.
- Water is most dense at 4°C, but density decreases below that temperature.

CHECK YOUR UNDERSTANDING

10.1

- 1 Define boiling point, solvent, density, viscosity, surface tension, latent heat, specific heat.
- 2 Distinguish between heat of fusion and heat of vaporisation.
- 3 Draw a labelled diagram to represent the water molecule. On your drawing, show the charges on the molecule.
- 4 Outline how the forces between water molecules lead to surface tension.
- 5 Why are bubbles and water droplets round?
- 6 Contrast the meanings of specific heat and latent heat.
- 7 How does the high specific heat of water create a stable environment for life?
- 8 Outline the types of substances that dissolve in water to form a solution.
- 9 How does the density behaviour of water prevent bottom-up freezing in water bodies? How does this support life?

10.2

The ocean–atmosphere system and heat distribution

The ocean surrounding Australia interacts with the atmosphere to generate our climate and weather. Both the ocean and the atmosphere are layered. These layers can be distinguished in terms of temperature and thermal boundaries. Four of the layers move heat: the troposphere of the atmosphere (Figure 10.9) and the surface, thermocline and deep layers of the ocean (Figure 10.10).

The troposphere and global air circulation

The outer limit of the atmosphere lies 30000–40000 km above sea level but most of the gas occurs in the layers closest to the planet – the troposphere and stratosphere. These layers extend to a height of 50 km above sea level. The higher layers do not contain much gas but play important roles in absorbing and reflecting some solar radiation, preventing it from reaching Earth's surface. The **troposphere** is the layer closest to Earth's surface and this is where weather and climate processes occur.

The troposphere's lower boundary is the 2 km of atmosphere closest to the planet's surface. This layer responds rapidly to surface heating and shows rapid changes in properties as air movement mixes the layer. Air flow in this layer generates the winds we are all familiar with. Water vapour, which plays a key role in heat transfer, is restricted to the troposphere. Temperature falls with altitude until the upper boundary, the **tropopause**, is reached. At the tropopause, the temperature stops falling and instead it rises throughout the stratosphere.

Within the troposphere, the transfer of heat energy from the equator towards the poles generates atmospheric convection. The heating at the equator causes moist air to rise, creating an area of low pressure. Cold air descends at the poles, creating areas of high pressure. The difference in pressure causes air to flow from the poles, where pressure is high, to the equator, where pressure is low.

Global air movement is complex because air movement is affected by Earth's rotation. As an air mass flows, Earth's rotation generates a force on the air mass called the **Coriolis force**. As a result, rather than moving in a straight line, the air travels in a curved path. In the southern hemisphere, the direction of the Coriolis force is towards the left of the direction the air is moving. Air ascending spirals clockwise if viewed from above. Where air descends in a high-pressure area, the air spirals anticlockwise. The rotation is reversed in the northern hemisphere (Figure 10.11). The Coriolis force has a similar effect on moving water bodies in the ocean.

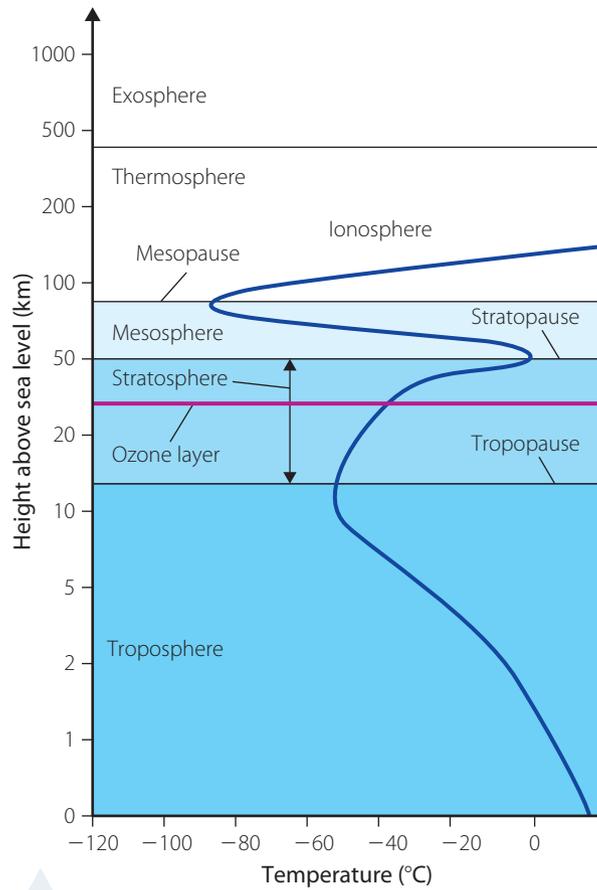


FIGURE 10.9 Layered structure of the atmosphere

The Coriolis force
Use the information to write an explanation of why air or water currents bend to the left.

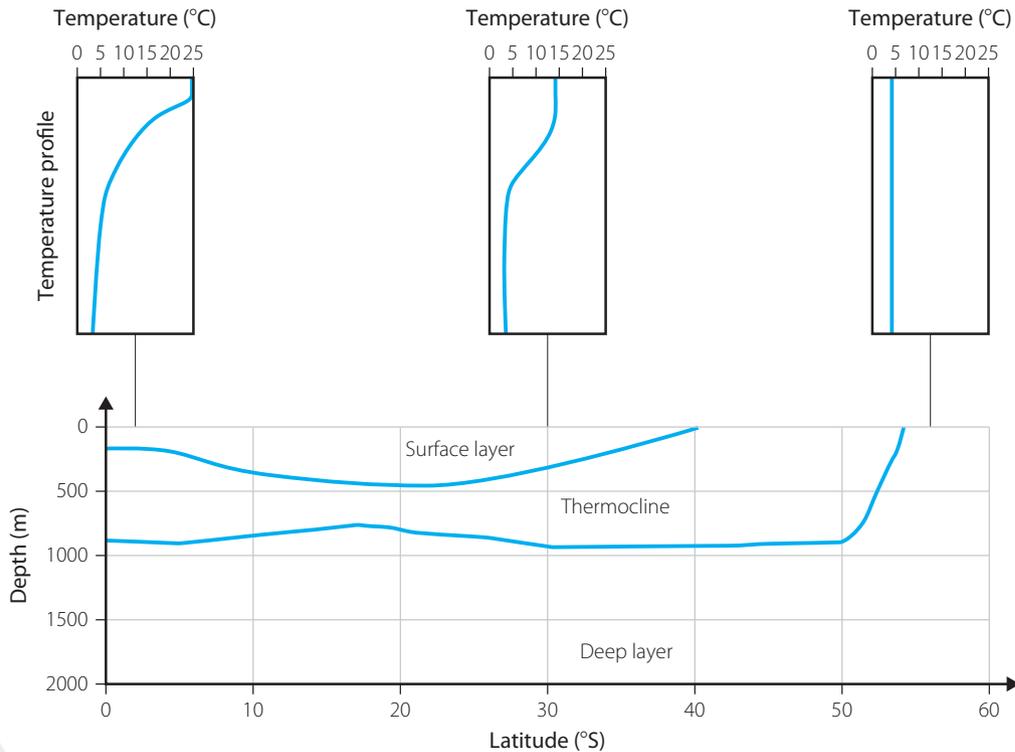


FIGURE 10.10 The layers of the ocean in the southern hemisphere. A similar pattern occurs in the northern hemisphere.

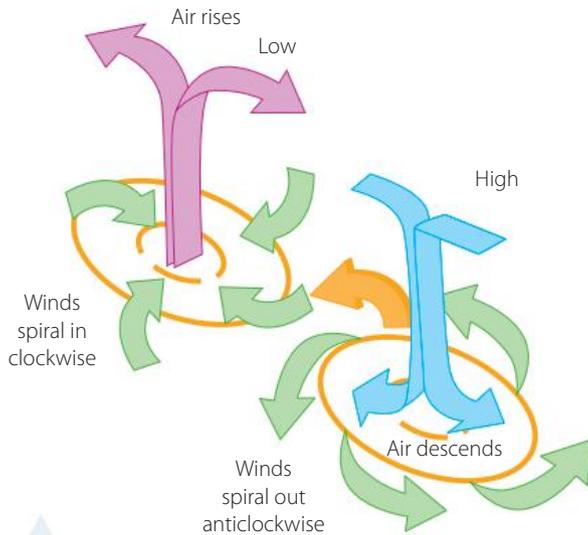


FIGURE 10.11 Air flow around and between high- and low-pressure areas

The uneven distribution of land masses and Earth's spin generate three separate convection cells in each hemisphere (Figure 10.12). At the equator, strong surface heating causes moist air to rise, creating a region of low pressure. As the air cools on rising, the moisture it contains condenses and returns to the surface as rain, and the air loses latent heat to its surroundings. The resulting cold dry air rises to the tropopause. It cannot ascend any higher than this and diverges to the north and south. The air flows outwards, its direction curving due to the Coriolis force, then it descends to the surface approximately 30° north and south of the equator. This cold dry air creates a belt of high pressure around Earth, termed the **subtropical high**.

It is in this region that most of Earth's dry and desert areas occur. The air then flows back towards the equator, curving towards the west. The two large convection cells created by this process are called **Hadley cells**, and the winds flowing in a westward arc towards the equator are called the **trade winds**. Where the trade winds meet at the equator, they flow strongly towards the west. This area of low pressure is referred to as the **intertropical convergence zone (ITCZ)**.

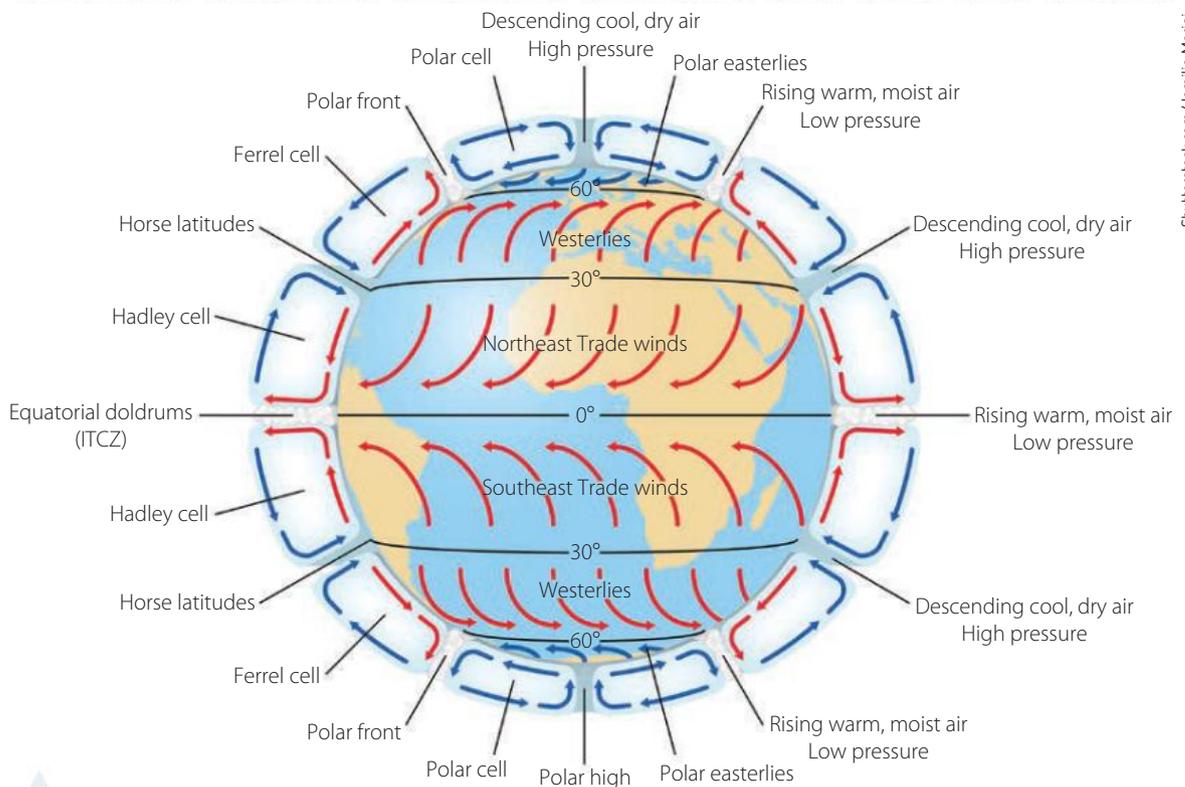


FIGURE 10.12 Global atmospheric circulation

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Between latitudes 30° and 60°, other circulation cells called the mid-latitude or Ferrel cells occur. At the base of these cells, air flows as surface winds towards the poles and the flows curve towards the east. North and south of about 60°, the polar cells create a high pressure area over the poles. Air flows outwards away from the poles until it reaches the boundary with the Ferrel cells. It then convects upwards and back towards the poles.

Structure of the ocean

The ocean can be divided into three layers as shown in Figure 10.10. The ocean increases in density and decreases in temperature with depth. The **surface layer** is approximately 200m thick and comprises approximately 5% of the oceans' volume. This layer interacts strongly with the atmosphere. The surface layer is also referred to as the **mixed layer** because surface winds and currents ensure the water is fairly uniform in composition and properties. The Coriolis force also affects surface currents in the surface layer. One way the surface layer does vary is in the concentration of salt. Along the equator, rainfall keeps salinity relatively low, but at latitudes 20°–30° north and south, the surface salinity increases because evaporation is higher than precipitation. The surface layer's temperature also varies with the seasons, although it remains fairly constant at the equator and the poles.

Below the surface zone lies the **thermocline**. Here, temperature changes with depth until it reaches the deep-water layer. The thermocline extends from the base of the surface layer down to approximately 1000m, but the layer thins with increasing latitude. Salinity and density show strong gradients of change. As a result, this layer is also known as the halocline, referring to salinity, or the pycnocline, referring to density. Temperature falls steadily, but salinity and density increase. The density at the base of the thermocline prevents water moving easily between the surface and deep parts of the ocean.

The **deep layer**, or deep zone, contains 80% of the ocean water. This layer extends from approximately 1 km below the surface to the sea floor. Water in this layer is only 4°C but water in contact with the sea floor in the Antarctic cools to –0.4°C. The pressure can be more than 100 times that at the base of the atmosphere. In high latitudes, the deep-water layer extends to the surface.

KEY CONCEPTS

- Convection in the troposphere redistributes heat from the equator to higher latitudes.
- When warm air rises, a low pressure area is formed. When dense air descends, a high pressure area forms.
- The movement of air and water masses is influenced by the Coriolis force – a force caused by Earth's rotation.
- Global atmospheric circulation involves three convection cells in each hemisphere: the Hadley, mid-latitude or Ferrel and polar cells. The Hadley cell transfers heat away from the equator.
- The ocean has three layers, with the surface layer being well mixed and carrying more heat than deeper layers.
- The thermocline is the middle layer of the ocean where physical properties change with depth.
- The deep-water layer of the ocean makes up the largest part of the ocean waters and is much colder than upper layers.

- 1 Outline three characteristics of the troposphere.
- 2 Describe changes in air as it is moved in a Hadley cell.
- 3 Compare the movement of air near the ocean surface on the edges of a Hadley cell and a polar cell.
- 4 In what ways does the energy stored in air rising by convection change as it gains altitude?
- 5 How does the rotation of Earth affect the movement of air masses in the atmosphere?
- 6 How is heat distributed in the layers of the ocean?
- 7 Contrast the features of the surface and deep-water layers of the ocean.

CHECK YOUR UNDERSTANDING

10.2

10.3 Origin of ocean currents

Australian ocean currents

Use the information to summarise the characteristics of the four important currents found around Australia.

The interaction of the atmosphere and the surface of the ocean creates surface currents.

Surface currents

As wind drags on the ocean surface, it causes the water to move in the direction of the wind. The Coriolis force causes the current to move along curved paths. The size of the Coriolis force is smallest at the equator and highest near the poles. A simplified map of the air pressure and winds is shown in Figure 10.13.

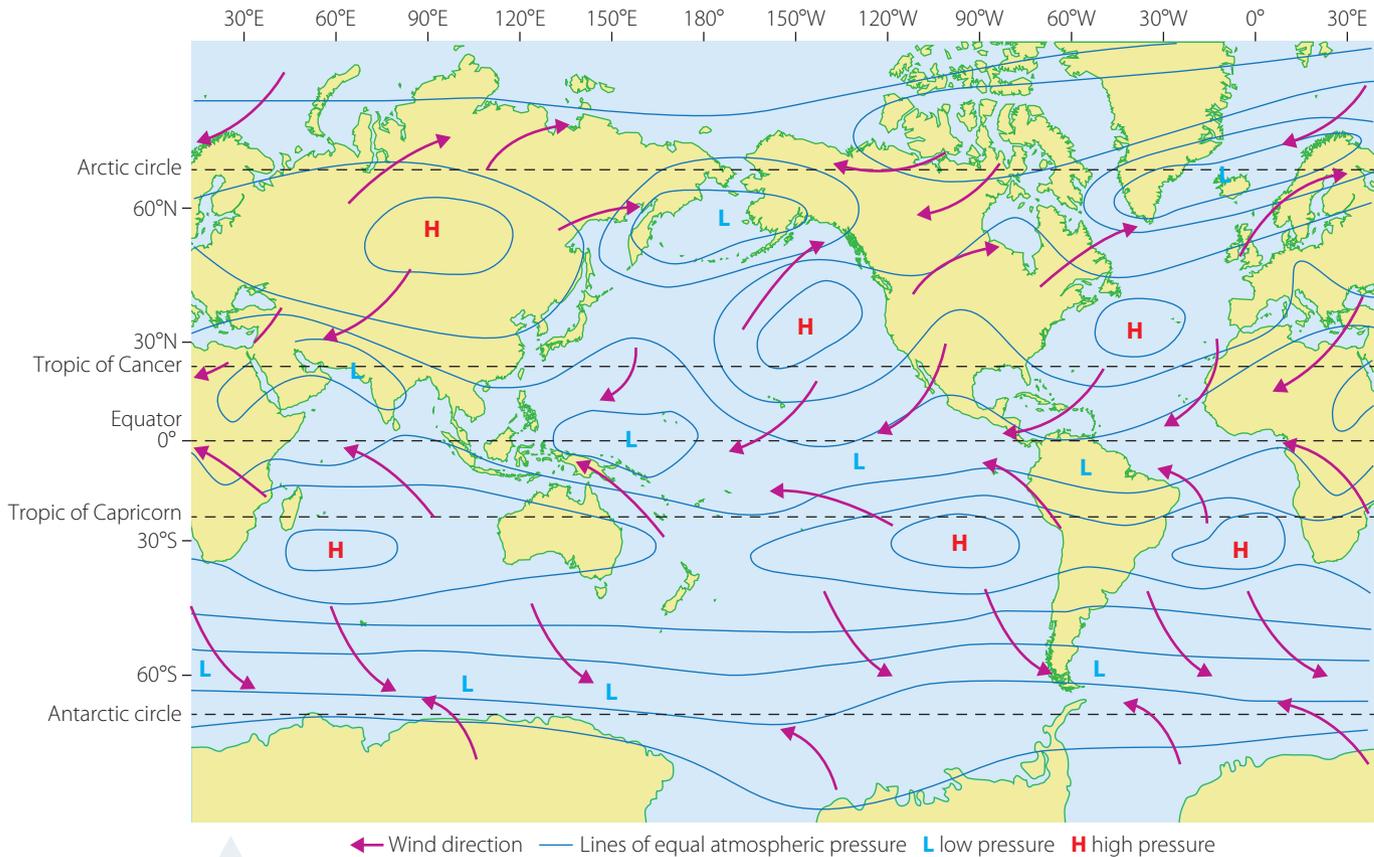
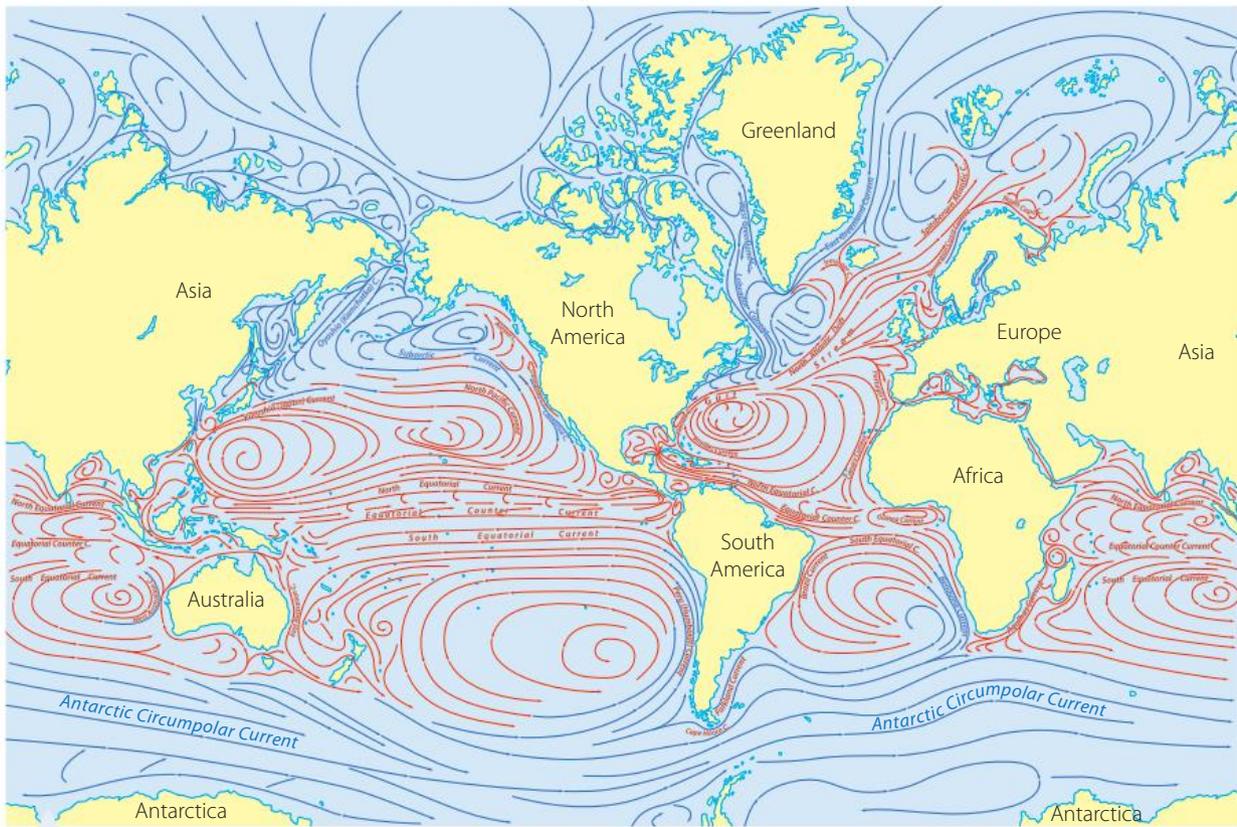


FIGURE 10.13 Air flow and pressure cells at the ocean surface

Areas of high and low pressure resulting from atmospheric convection generate the winds that produce the currents. At 30°S, high pressure areas occur in the Indian, Pacific and Atlantic oceans. The air flows outwards from these areas in an anticlockwise direction and the air friction and Coriolis force generate ocean-wide circulating flows of water called **gyres**. The gyre between Australia and South America is called the South Pacific gyre.

Generally, the surface currents of the ocean reflect the wind patterns that form them (Figure 10.14). Note that the land masses in the northern hemisphere generate slightly more complex current patterns at high latitudes. The gyres in the southern hemisphere flow anticlockwise, but the northern hemisphere gyres in the Pacific and Atlantic flow clockwise. The gyres move cool water from high latitudes towards the equator and warm water from the equator towards the poles.

Equatorial countercurrents are an exception to ocean currents mirroring winds. As the trade winds push water westward, water accumulates. The ocean surface in the west Pacific can rise 15cm higher than in the east Pacific, and the surface mass of water can force the thermocline layer 100m deeper



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FIGURE 10.14 Ocean currents

than normal. Because the Coriolis force is weak near the equator, water flows back towards the east. As it flows, the countercurrent moves heat energy and salinity across the equator. The countercurrent is located 5° – 7° north and south of the equator where the surface winds are weak, but its location changes slightly with the seasons. In the Pacific, the countercurrent flows all year.

Upwelling and downwelling

A combination of wind direction, the Coriolis force and shorelines can cause vertical movement of water. When winds blow southward along the New South Wales coast, the upper 30m of the ocean is moved east, away from the coast. This is called the **Ekman flow** and is caused by the Coriolis force. To replace the moving water, deeper cold water flows upwards. This process is called **upwelling** (Figure 10.15). In situations where the wind direction creates an Ekman flow towards the coastline, surface waters are forced downwards and this is called **downwelling**.

Upwelling and downwelling also occur in the open ocean. At the equator, the wind flow north and south of the equator causes water to move away from the equator and upwelling occurs. The upwelling brings both cooler water and dissolved nutrients to the surface. This can support very large plankton populations, which in turn support large fish populations. These are exploited by important fisheries around the world. Where downwelling occurs, the warm nutrient-poor water forced downwards can restrict biological activity.

The 'Ekman transport' effect
Summarise how cold water upwelling currents occur along the Australian coast.

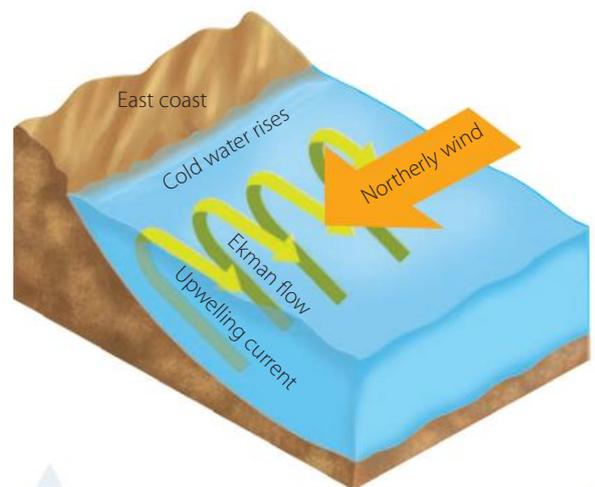


FIGURE 10.15 Upwelling in the southern hemisphere

Thermohaline circulation

Density drives the currents in the deep ocean. The term **thermohaline** refers to the temperature (thermo-) and salinity (-haline) factors that affect water density. In the polar oceans, the formation of ice and the low temperatures increase seawater density. Ice excludes salt as it forms and so the water becomes more saline and dense. As a result, the water sinks and flows slowly across the floor of the ocean basin. This flow is called a **density current**. Density currents flow very slowly. It may take a thousand years before the sinking cold water reaches the surface again.

As the cold, dense water flows along the sea floor, it absorbs some heat from the environment. This causes it to rise gradually, and when it reaches the surface, currents move the water across the ocean. Figure 10.16 shows a generalised model of the circulation. We refer to the overall process as the **thermohaline circulation**.

The thermohaline circulation moves heat from the equator and cold water from the poles. In this way heat is redistributed around Earth. The thermohaline circulation also provides oxygen to the deep ocean, locks carbon dioxide into the deep and moves nutrients from the deep to the surface.

Generalized Walker Circulation (December–February) during ENSO-neutral conditions. Convection associated with rising branches of the Walker Circulation is found over the Maritime continent, northern South America, and eastern Africa. NOAA Climate.gov drawing by Fiona Martin.

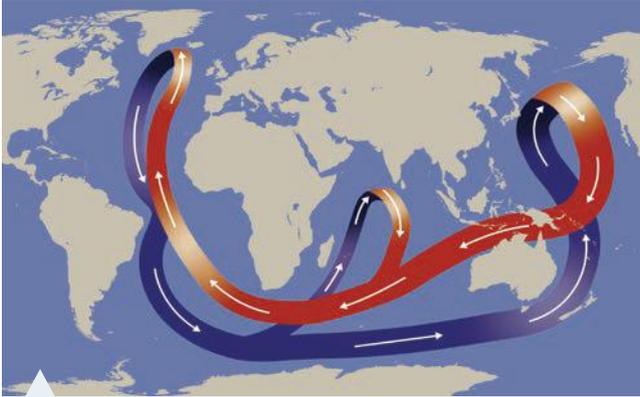


FIGURE 10.16 A global conveyor belt – thermohaline circulation

KEY CONCEPTS

- Surface currents in the ocean are created by surface winds and the Coriolis force.
- Surface currents create gyres within ocean basins that distribute cold and warm water to the edges of continents.
- Along coasts, wind-created currents and the Coriolis effect create Ekman transport, leading to upwelling or downwelling.
- Near the poles, the creation of cold saline and dense water masses generates deep ocean currents.
- Deep ocean currents are part of the global thermohaline circulation that redistributes heat in the oceans around Earth.

CHECK YOUR UNDERSTANDING

10.3

- 1 Describe how a surface current is formed.
- 2 Define gyre.
- 3 How does the Coriolis force affect surface currents in the southern hemisphere?
- 4 What are the consequences of ocean upwelling?
- 5 Using a flow chart, describe how processes in the Antarctic create density currents of cold, dense water.
- 6 Explain how global thermohaline circulation redistributes heat in the ocean.

10.4 Effect of atmospheric processes on weather

Complex interactions between the ocean and atmosphere create a range of processes that affect Australia's weather. Some processes, such as the El Niño–Southern Oscillation, occur over years. Others, such as the Madden–Julian Oscillation, occur over periods measured in days or weeks. The complexity of the processes and their interactions make long-term weather prediction very difficult.

How the atmosphere redistributes heat energy

The ocean and atmosphere together play a key role in the redistribution of heat energy around Earth. In the ocean, heat energy is transferred from the ocean when sunlight causes evaporation. The evaporation removes heat energy from the ocean, rather than sunlight increasing the temperature of the water.

The circulation of heat energy in both the atmosphere and the ocean works towards distributing heat evenly around the planet. While the system strives to create an equilibrium, the higher level of heating at the equator means that equilibrium is never achieved and the processes that create our climate and weather continue to operate.

El Niño–Southern Oscillation (ENSO) cycle

While the Hadley, mid-latitude (Ferrel) and polar cells transfer heat between the equator and the poles, heat also moves along the equator. The system is known as the **Walker circulation** and the convective cells that make it up are called Walker cells (Figure 10.17). Walker cells are named after Gilbert Walker, who established a link between changing pressures between the Indian and Pacific oceans and patterns of rainfall and temperature in the tropics.



Sequencing ENSO

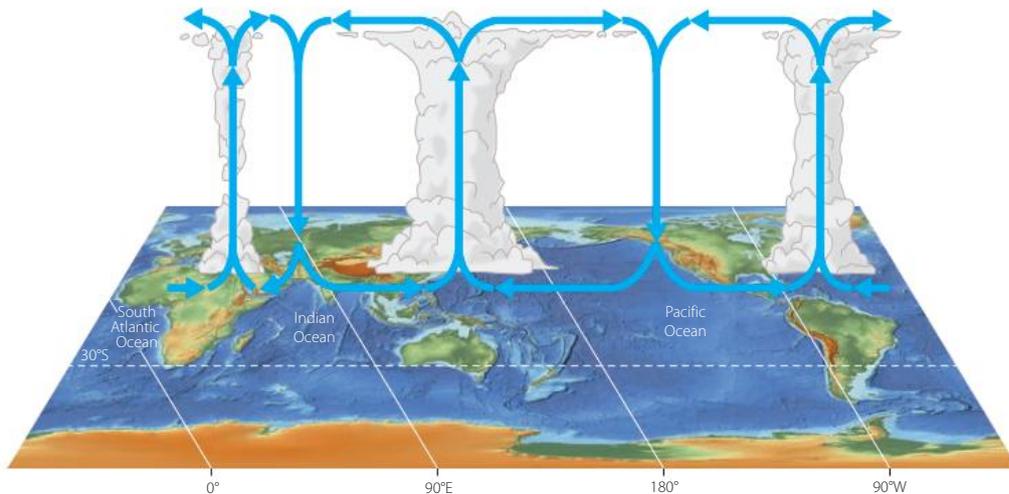


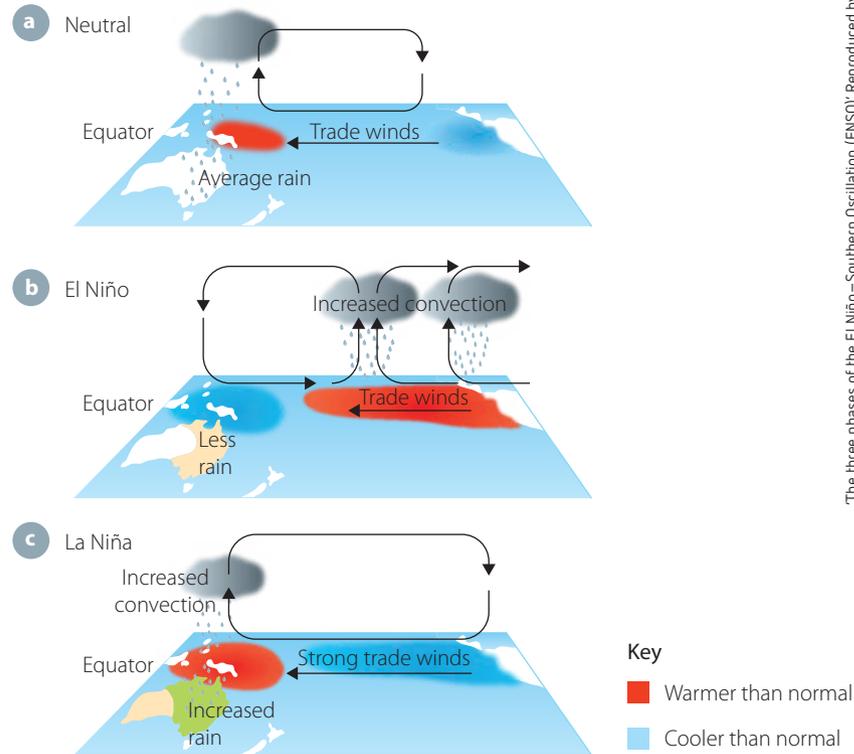
FIGURE 10.17
The Walker circulation

When the Walker circulation is in a neutral phase, winds blowing from east to west along the equator move warm water towards the area north of Australia (Figure 10.18a). As the water moves, it warms by about 8° . When it reaches the western side of the Pacific, a low pressure region forms over the warm water and generates clouds and rain. As the air continues to rise, it moves back east across the Pacific. It sinks over the eastern Pacific, creating an area of cool, dry air and reduced rainfall.

The movement of the water also creates upwelling and downwelling. The upwelling of water to replace the water moving west brings nutrients to the surface in the eastern Pacific. In the west, the water arriving there causes the water to rise up to 0.6m higher than the eastern Pacific. This causes downwelling and causes water to flow back towards the east.

El Niño conditions form when the trade winds weaken (Figure 10.18b). The reason for this is not well understood, making the prediction of El Niño conditions difficult. When the trade winds weaken, warm water is not moved into the western Pacific. As a result, surface waters in the central and eastern Pacific become warmer and the Walker cells adjust their position. This leads to the low-pressure areas, and the rain they create, moving over the central or eastern Pacific.

FIGURE 10.18
El Niño and the
Southern Oscillation:
a Neutral
b El Niño
c La Niña



The three phases of the El Niño–Southern Oscillation (ENSO). Reproduced by permission of Bureau of Meteorology, © 2018 Commonwealth of Australia

The consequences for Australia and Indonesia of an El Niño event include reduced rainfall, higher temperatures and increased risk of bushfires. On the other side of the Pacific in Ecuador, increased rainfall can result in flooding, mudslides, increased disease levels and crop losses. Strong El Niño events also weaken monsoon rainfall in South-east Asia and can have effects far from the equator. Famines in Africa, Asia and South America from 1876 to 1878 killed 50 million people and were caused, in part, by an intense El Niño event.

When trade winds are stronger than usual, conditions referred to as **La Niña** occur (Figure 10.18c). During a La Niña, rainfall in Australia is higher than average, maximum temperatures are lower than normal and the frequency of cyclones increases. As with El Niño, a La Niña event has effects far beyond the Pacific.

Together, El Niño and La Niña phases are referred to as the **El Niño–Southern Oscillation** (ENSO) cycle. Historically, El Niño and La Niña events occur with a frequency of 2–7 years and have a duration of between 9 months and a year. El Niño events are more common than La Niña events. ENSO is monitored using a calculation called the Southern Oscillation Index (SOI). The SOI is calculated using the difference in atmospheric pressure between Tahiti and Darwin. During El Niño events, the SOI remains below -7 for a long period. SOI values that remain above $+7$ indicate La Niña conditions.

Indian Ocean Dipole

ENSO is not the only weather phenomenon to affect Australia. The **Indian Ocean Dipole** is an irregular change in the sea-surface temperatures between the western and eastern sides of the Indian Ocean. When water in the east, near Indonesia, is warmer than in the western Indian Ocean, moist air rises and westerly winds develop, generating rain in northern and southern Australia.

If the sea surface temperatures increase in the west, easterly winds become stronger across the ocean, rain increases in the west and less moisture is carried to Australia. These changes also affect downwelling and upwelling in the ocean, which in turn affect the amount of moisture available to generate rain.

Madden–Julian Oscillation (MJO)

The **Madden–Julian Oscillation** (MJO) influences rainfall patterns in equatorial areas, including northern Australia. While ENSO remains relatively stationary, the MJO slowly moves eastward across the Indian and Pacific oceans at a speed of 6 m s^{-1} and recurs every 1–2 months. As it travels, the MJO creates strong vertical convection and rain that diminishes as the system moves across the Pacific. Because the MJO interacts with the surface of the ocean and the upper areas of the troposphere, it may play a role in how ENSO develops. It influences the timing of the northern monsoon in Australia.

INVESTIGATION 10.2

Atmospheric phenomena and the global transfer of heat

INTRODUCTION

Several climate phenomena affect weather patterns in Australia. The interaction of ocean surface temperature and the movement of air masses can increase or decrease rain in Australia. In this secondary-sourced investigation, you will examine how some of these phenomena affect rainfall in Australia.

AIM

To create a concept diagram showing how the interaction of atmospheric phenomena determines rainfall in Australia

MATERIALS

- Access to the Internet
- 1–3 sheets of A3 paper
- Colour felt-tip pens or pencils for highlighting

METHOD

- 1 Use the BOM Australian Climate Influences and the Climate Kelpie weblinks to review the nature of the Indian Ocean Dipole (IOD). What are the changes in the Indian Ocean that lead to changes in rainfall in Australia? Record your research as a set of dot points for use later.
- 2 Use the same weblinks and this text to summarise the nature of ENSO. Again, record your research as dot points. Try to identify how ENSO and the IOD are similar and related to each other.
- 3 Another atmospheric circulation pattern that affects Australia is the Southern Annular Mode or Antarctic Oscillation. Using the same weblinks, repeat your analysis for the Southern Annular Mode.
- 4 Review your notes and highlight the concepts that are important in each atmospheric process.
- 5 Follow the advice in the weblink to create a concept map addressing rainfall and the factors that affect rainfall in Australia.
- 6 Visit the weblink detailing 118 years of Australian rainfall. Use your concept map to predict the likely cause of the rainfall shown for the years 1959, 1974, 1992 and 2015.

RESULTS

Draw your final concept map on one or more of the A3 sheets. Be sure to make as many links between concepts as you can.

DISCUSSION

- 1 How important to understanding Australian weather is information about the surface temperature of the ocean?
- 2 How do weather systems interact to create dry or wet seasons?



BOM Australian climate influences



Climate Kelpie



How to build a concept map

Use the weblink to review, or learn, how to create a concept map.



118 years of Australian rainfall





- 3 Can the concept map be used to predict conditions affecting rainfall in northern and southern Australia?
- 4 How might your concept map be adapted to create a model of Australia's climate?
- 5 Supercomputers are used by the Bureau of Meteorology to create computer models of Australia's climate. Why is such computer power needed?

CONCLUSION

Why is it correct to describe the processes that create weather as a complex system?
What are the key phenomena that affect rainfall in southern Australia?

KEY CONCEPTS

- The circulation of heat in the atmosphere and the ocean works towards distributing heat evenly around the planet.
- A range of phenomena created by the atmosphere and ocean affect Australia's weather.
- Changes in equatorial convection, called the Walker circulation, result in the El Niño–Southern Oscillation (ENSO).
- El Niño conditions occur when the low-pressure systems that generate rain for Australia are displaced to the central Pacific.
- El Niño conditions lead to reduced rainfall, higher temperatures and increased risk of bushfires in Australia.
- La Niña conditions occur when the low-pressure systems that generate rain for Australia are displaced to the western Pacific.
- La Niña conditions lead to higher rainfall, lower temperatures and more frequent cyclones in Australia.
- The Indian Ocean Dipole is another weather process caused by changing ocean temperatures that affects rainfall in Australia.

CHECK YOUR UNDERSTANDING

10.4

- 1 Use a table to compare a Hadley cell and a Walker cell.
- 2 Outline how El Niño conditions are created.
- 3 What weather effects does El Niño create in Australia and in Ecuador?
- 4 Describe the Indian Ocean Dipole conditions that generate above-average rainfall for southern Australia.
- 5 How does the Madden–Julian Oscillation (MJO) affect weather in northern Australia?
- 6 Explain how air pressure and ocean surface temperatures contribute to weather in Australia.

10.5 The changing cryosphere

The **cryosphere** is the part of Earth where water exists in solid form. Almost 75% of Earth's fresh water on land exists as ice or snow in glaciers and ice sheets. The cryosphere occurs at all latitudes of Earth. In Antarctica, the Arctic and Greenland, ice and snow form ice sheets, **ice shelves** and sea ice. At high altitudes and in high-latitude areas, glaciers, snow, river and lake ice and frozen ground occur. About 11% of the land surface is covered by glaciers.

Cryosphere components

The four major components of the cryosphere are ice sheets, ice shelves, glaciers and ground ice. **Ice sheets** are large areas of ice covering more than 50000km². They are thick and exist for a long time. Because they flow over time, ice sheets are also referred to as continental glaciers. They comprise the

greatest mass of the cryosphere and cover the largest area. Antarctica contains a little more than 90% of the cryosphere's mass and the Greenland ice sheet accounts for almost 8%. Near the poles, ice sheets exist in stable environments.

Glaciers are slow-moving masses of ice created by the accumulation and compaction of snow. Glaciers are found all over the world but contain only 0.3% of the world's ice mass and cover 3.4% of the surface. They form in mountains when snow falls and accumulates in high areas then compresses into ice. Under the influence of gravity, the ice flows along valleys towards lower elevations, shaping the land surface as it goes. Such glaciers are referred to as valley glaciers. Eventually, the glacier encounters conditions where it melts. In many parts of the world this meltwater provides important water resources for natural and human communities.

Ice shelves are created where glaciers flow into the sea. **Ice shelves** are floating masses of ice attached to a land mass. The Larsen B and Ross ice shelves in Antarctica are good examples of such structures. Ice, being less dense than seawater, floats on the surface and the ice in polar areas can extend a long way from the source glaciers into the ocean. Ice shelves can cover 7% of the global ocean and average 2.5m in thickness. They thin in the direction of open water and expand and shrink as the seasons change.

Ground ice exists in cold areas where the ground freezes. In areas where it snows, snowfall acts as an insulating surface so the ground does not lose heat and does not freeze. In cold arid areas, the pore water in the soil does freeze. As much as a quarter of Earth's land surface is permanently or seasonally frozen. In polar or alpine areas where the ground remains frozen continually for two or more years, the ground is referred to as **permafrost**.

The cryosphere is important to many human societies. More than a sixth of the world's population relies on water from glacier-fed rivers for drinking and irrigation. The damming of this water also contributes to the generation of hydroelectric power. In Australia, the snowfields of eastern Australia provide recreation for many people. The seasonal melting of the snow and ice, termed **snowmelt**, also contributes water to rivers, which sustain natural ecosystems and agriculture.



FIGURE 10.19 The Franz Josef glacier on New Zealand's South Island

Shutterstock.com/Dan Breckwoldt

How the cryosphere changes

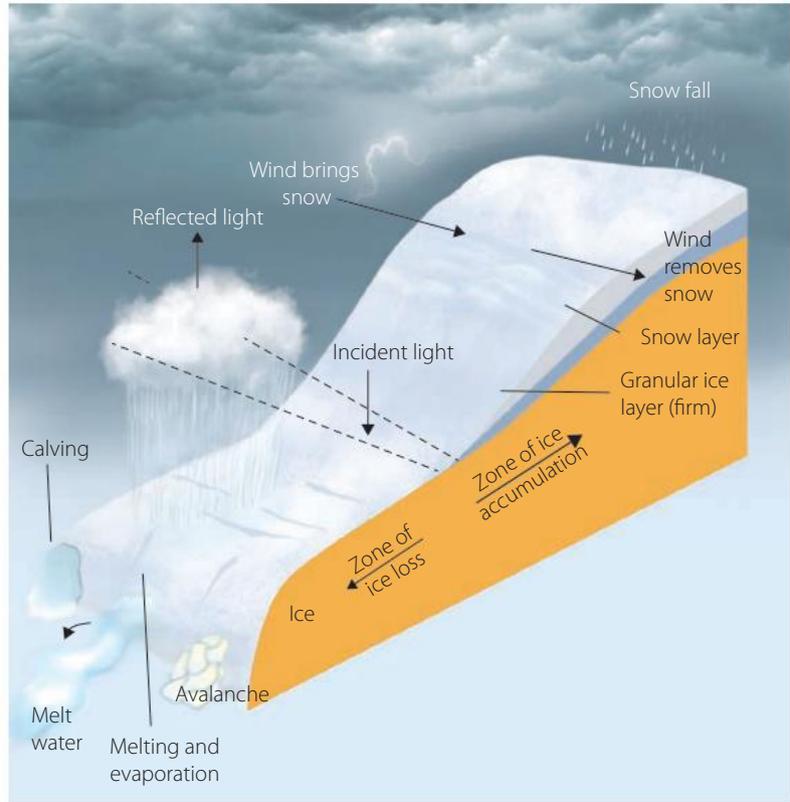
As the global climate warms, all the different parts of the cryosphere are showing signs of change. The area covered by snow and ice has changed throughout geological time. Antarctica became covered in ice only 14 million years ago. Greenland and the Arctic ice sheets are even younger. The glaciers there date from about 3.2 million years ago. The temperature change that triggered these changes is thought to have resulted from the formation of the Himalayas. The increased weathering caused by mountain building absorbed carbon dioxide from the atmosphere, causing the atmosphere to cool.

Today, an increasingly warm atmosphere is causing changes in how ice forms and how quickly it melts. How much ice exists depends on two processes. **Accumulation** refers to the addition of ice, usually in the form of snowfall. **Ablation** is the removal of ice or snow by melting and evaporation. When accumulation and ablation are of the same magnitude, a glacier or ice sheet has a constant mass, but if one process is greater than the other, material will be added to or lost from the ice. Some of the factors affecting glaciers are shown in in Figure 10.20.

The history of ice on Earth

Summarise the changing distribution of ice and factors creating ice ages.

FIGURE 10.20
Factors affecting the growth and decline of glaciers



Satellite observations of the Arctic
Use the link to summarise some of the changes occurring in the Arctic.

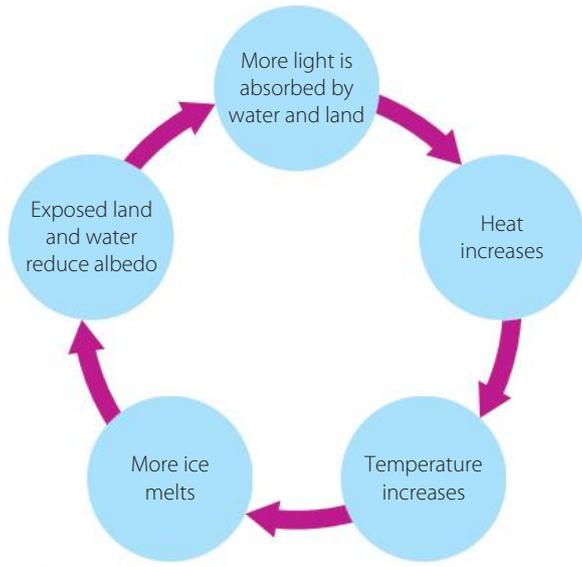


FIGURE 10.21 A feedback loop between albedo change and sea ice melting

Scientists who study glaciers and how they change use a concept called mass balance. **Mass balance** is the difference between annual accumulation and annual ablation. A positive mass balance means that a glacier grows, and a negative mass balance means the glacier is retreating. At present, the world's glaciers are in retreat.

The cryosphere is very sensitive to atmospheric change and is influenced by several feedback loops. **Feedback loops** occur in systems of interconnected processes where a change in one part of the system either causes changes that reinforce the original change (positive feedback) or make the change smaller (negative feedback). An example of a feedback loop is the change of albedo and the extent of sea ice (Figure 10.21). As heat increases in the ocean, its temperature increases and sea ice melts.

Because there is less ice to reflect light, more light is absorbed by the water and the heat in the ocean increases. As a result, the rate of melting increases.

INVESTIGATION 10.3

Glacier decline

INTRODUCTION

In this investigation you will use data from reliable sources to investigate changes in ice sheets and glaciers.

AIM

To identify and analyse trends in changes to parts of the cryosphere

METHOD

Part A: Changes in glaciers

In this part of the investigation, you will examine changes in some glaciers from around the world. You will use data from the World Glacier Monitoring Service (WGMS) to identify trends in the length of glaciers over time.

- 1 Draw a table similar to that shown in the results section below. Allow space for 4–5 lines for each glacier.
- 2 Access the WGMS Fluctuations of Glaciers Browser using the weblink on this page.
- 3 Type 'Franz Josef' into the search box at the bottom left of the browser. A list of possible glaciers should appear. Click on the name in the list.
- 4 A window will open on the right of the browser showing how the front of the glacier has changed over time. Click on the window to enlarge it.
- 5 Record the latitude of the glacier using the information in the bottom right of the browser. For Franz Josef, this should be approximately -50° (50°S).
- 6 Record the trend shown in the graph into your table. Note when the slope of the trend changes and any sudden troughs or spikes. Record the approximate year for these changes.
- 7 Calculate the average change for the last 20 years using the graph. Do this using the following formula:

$$\text{Average change (m year}^{-1}\text{)} = \frac{\text{front distance now} - \text{front distance 20 years ago}}{20 \text{ years}}$$

- 8 Repeat steps 3–7 for the other glaciers in the table.
- 9 Complete the Discussion questions (Part A) before you move to Part B.

Part B: Change in polar ice sheets

In this second part of the investigation, you will examine changes in sea ice in the Arctic and Antarctic. You will use data from the National Snow and Ice Data Center (NSIDC) to compare trends in sea ice coverage over time.

- 10 Begin by opening the Sea Ice Index page using the weblink.
- 11 Examine the page. Note how you can change the hemisphere and type of map as well as the months to compare.
- 12 In the first column, set the Hemisphere to 'Northern' and Map to 'Extent trends'.
- 13 In the second column, set the Hemisphere to 'Southern' and Map to 'Extent trends'.
- 14 Next, set the Month of the first row to 'Jan' (for January) and the Month of the second row to Jul (for July). Remember that in the southern hemisphere, January is summer and July is winter. It is the opposite in the northern hemisphere.
- 15 In the Control Panel, set the scale to 100% and press the refresh button. The anomalies in the graphs are the variation from the averages recorded on each graph.
- 16 Examine the four graphs carefully. How are they similar? How are they different?
- 17 Design a table to summarise the information in the graphs.
- 18 Create your table and then consider the discussion questions (Part B).



**WGMS
Fluctuations of
Glaciers Browser**

Use this link for Part A
of the investigation.



Sea Ice Index

Use this link for
Investigation 10.3
Part B





RESULTS

Part A

GLACIER NAME, COUNTRY	LATITUDE	TREND IN POSITION OF GLACIER FRONT	AVERAGE CHANGE IN LENGTH OVER THE LAST 20 YEARS (m)
Franz Josef, New Zealand			
Meren, West Papua			
Lewis, Kenya			
Sorapiss Occidentale, Italy			
Oberer Grindelwald, Switzerland			
Upsala, Argentina			

Part B

Plan and create a table to summarise the information provided.

DISCUSSION

Part A

- 1 In what ways are the trends for the glaciers similar?
- 2 Is there any relationship between latitude and the rate of glacial retreat?
- 3 Use Figure 10.20 to identify all the possible reasons that could account for the trends you have described.
- 4 Would there possibly be a correlation between rate of glacier loss and altitude? If so, how could this be studied?

Part B

- 5 Contrast the winter trends in the northern and southern hemispheres.
- 6 How do the summer trends differ between the two hemispheres?
- 7 Can you identify possible reasons for the variability in the summer trend for Antarctica?
- 8 Higher ocean temperatures lead to more precipitation and possibly a weaker shelf ice in Antarctica. Is there any evidence in the anomaly graph to support these changes?

CONCLUSION

What conclusion have you reached about the changes to ice sheets and glaciers during the last 30 years?

What are the possible implications of these changes?

How might your confidence in the conclusions you have reached be strengthened?

KEY CONCEPTS

- The cryosphere is the part of Earth where water exists as ice. It includes ice sheets, glaciers, ice shelves and frozen ground.
- The extent of the cryosphere changes over time. At present the cryosphere is becoming smaller.
- Processes associated with accumulation and ablation affect how much ice exists from year to year.
- The cryosphere is sensitive to climate change, and global warming is creating feedback loops that are altering the accumulation of ice around the world.

CHECK YOUR UNDERSTANDING

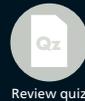
10.5

- 1 Describe the nature and components of the cryosphere.
- 2 Where are the largest parts of the cryosphere found?
- 3 Outline the processes that build and remove material from a glacier.
- 4 Describe how a loss of albedo due to ice shelf melting can accelerate the loss of ice.
- 5 What is the worldwide trend in the length of glaciers?
- 6 Describe two potential effects of the loss of glaciers on society and the environment.

10 CHAPTER SUMMARY

- ▶ Water is a substance with unique properties.
- ▶ Many of the properties of water are due to the shape and charged nature of the water molecule.
- ▶ Surface tension allows water to form droplets, bubbles and waves and to display capillary action.
- ▶ The high heat capacity of water means that water changes temperature slowly, providing a stable environment for life.
- ▶ Water is a powerful solvent, dissolving a wide range of compounds, salts and gases.
- ▶ Water's solvent properties are important for the processes in cells and the composition of the ocean.
- ▶ The density of water changes with temperature and can create movement of water in the ocean.
- ▶ Convection in the troposphere redistributes heat from the equator to higher latitudes of Earth.
- ▶ When warm air rises, an area of low pressure is formed. When dense air descends, an area of high pressure forms.
- ▶ The movement of air and water masses is influenced by the Coriolis force – a force due to Earth's rotation.
- ▶ The pattern of global air circulation involves three convection cells in each hemisphere: the Hadley, mid-latitude (Ferrel) and polar cells.
- ▶ The ocean has a three-layered structure with the surface layer being well mixed and carrying more heat than deeper layers.
- ▶ The thermocline is a layer of the ocean in which the temperature falls with depth.
- ▶ The deep-water layer of the ocean makes up the largest part of the ocean waters and is much colder than the upper layers.
- ▶ Surface currents in the ocean are created by surface winds and the Coriolis force.
- ▶ Surface currents create gyres within ocean basins that distribute cold and warm water to the edges of continents.
- ▶ Along coasts, wind and the Coriolis force create Ekman transport, leading to upwelling or downwelling.
- ▶ Near the poles, the creation of cold saline and dense water masses generates deep-ocean currents.
- ▶ Deep-ocean currents are part of the global thermohaline circulation that redistributes heat in the oceans around Earth.
- ▶ The circulation of heat in the atmosphere and the ocean works towards distributing heat evenly around the planet.
- ▶ A range of phenomena created by the atmosphere and ocean affect Australia's weather.
- ▶ Changes in the equatorial convection called the Walker circulation result in the El Niño–Southern Oscillation (ENSO).
- ▶ El Niño conditions occur when the low pressure systems that generate rain for Australia are displaced to the central Pacific Ocean.
- ▶ El Niño conditions lead to reduced rainfall, higher temperatures and increased risk of bushfires in Australia.
- ▶ La Niña conditions occur when the low pressure systems that generate rain for Australia are displaced to the western Pacific Ocean.
- ▶ La Niña conditions lead to higher rainfall, lower temperatures and more frequent cyclones in Australia.
- ▶ The Indian Ocean Dipole is another weather process that affects rainfall in Australia and is also caused by changing ocean temperatures.
- ▶ The cryosphere is the part of Earth where water exists as ice. It includes ice sheets, glaciers, ice shelves and frozen ground.
- ▶ The extent of the cryosphere changes over time. At present the cryosphere is becoming smaller.
- ▶ Processes associated with accumulation and ablation affect how much ice exists from year to year.
- ▶ The cryosphere is sensitive to climate change, and global warming is creating feedback loops that are altering the accumulation of ice around the world.

10 CHAPTER REVIEW QUESTIONS



Review quiz

- 1 Describe the features of a water molecule that create water's unique properties.
- 2 How does the high heat capacity of water influence the rate of temperature change in the ocean?
- 3 Explain why water's solvent properties are important for living things.
- 4 How does surface tension aid in capillary action?
- 5 Explain how evaporation of water removes heat energy from the water.
- 6 Describe how the density of water changes as it cools.
- 7 Outline four features of the troposphere.
- 8 Describe the cause of air circulation in the troposphere.
- 9 Describe the Coriolis force and its effect on water and air movement.
- 10 Outline the changes that occur to air as it moves around the Hadley cell from the equator and back as part of the trade winds.
- 11 Explain how the subtropical high affects climate.
- 12 Describe, using a labelled diagram, the layered structure of the ocean.
- 13 Explain the role of air movement and the Coriolis force in the creation of surface currents.
- 14 Outline how the South Pacific gyre redistributes heat in the South Pacific.
- 15 Evaluate the role of upwelling and downwelling in the redistribution of heat and nutrients in the ocean.
- 16 Explain the origin and nature of thermohaline circulation.
- 17 Outline the difference between El Niño and La Niña conditions in the western and eastern Pacific.
- 18 Explain why El Niño conditions lead to low rainfall in Australia.
- 19 Compare the ENSO and Indian Ocean Dipole systems.
- 20 Describe the major components of the cryosphere.
- 21 Analyse how global warming might influence the factors that determine accumulation and ablation in a glacier.
- 22 Describe how the loss of glaciers and decline in ice shelves will affect society and the environment.

Answer the following questions.

- The water cycle describes how water moves between the atmosphere, lithosphere and ocean.
 - Name the source of energy that drives the water cycle.
 - Draw a labelled diagram to show four processes that operate as part of the water cycle.
 - Account for the length of time water molecules exist in the deep ocean compared with the length of time water molecules stay on the surface of the ocean.
- Discuss the role of heat and gravity in the vertical and horizontal motion of the lithosphere.
- Account for the differences in the types of volcanoes and their distribution on Venus and Earth.
- Assess the factors that determine the amount of energy released and the duration of an earthquake.
- The table shows information about rocks from four different layers in the same volcano.

LAYER	A	B	C	D
SILICA (% SiO ₂)	75	65	60	50
IRON AND MAGNESIUM (% Fe ₂ O ₃ + % MgO)	3.3	11.0	12.6	18.8
POTASSIUM (% K ₂ O)	4.2	2.9	2.0	0.1
AGE (MILLIONS OF YEARS)	3	7	12	18

- Construct a graph to show how silica content changes with time.
- Explain why Layer A is more likely than the other layers to contain ash.
- Evaluate the data as evidence of magmatic differentiation.

- As part of this module, you modelled movement caused by gravity and heat.
 - Construct a labelled drawing to show how your model caused movement.
 - Describe the source of the energy in Earth that enables the process you modelled.
 - Evaluate how accurately your model represented the cause of movement.
- The map in Figure EOM 3.1 shows the location of four volcanic eruption sites, labelled A, B, C and D.

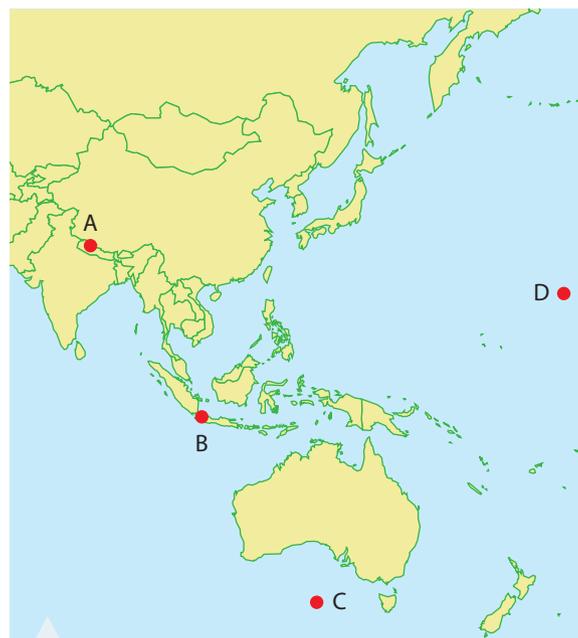


FIGURE EOM 3.1

- Identify the site that is not likely to be currently active.
- Contrast the origin of the magmas found at locations B and D.
- Explain the difference in volcanic eruptions at sites B and D.

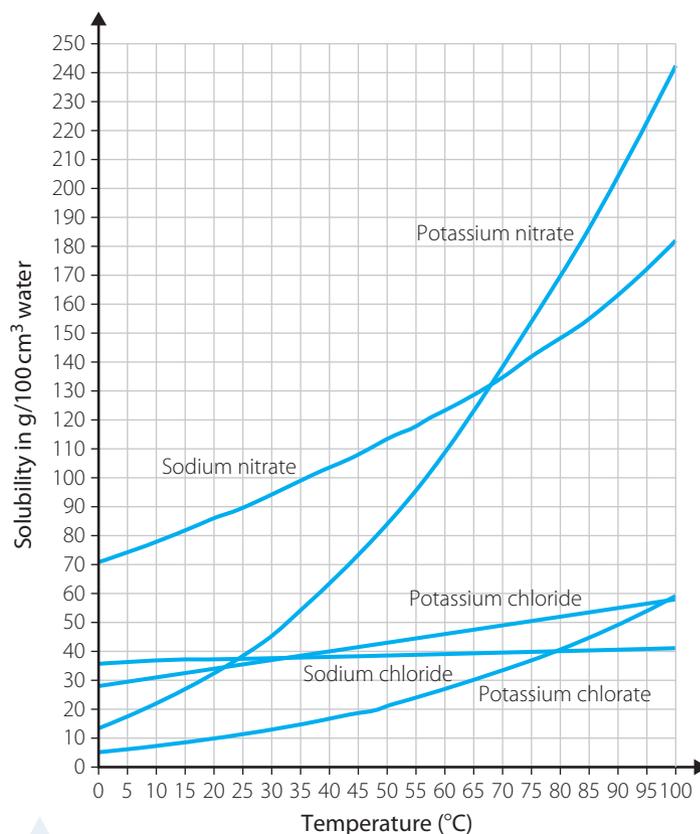


FIGURE EOM 3.2

- 8 The graph in Figure EOM 3.2 shows how the solubility of five salts changes with temperature.
- How much of 130 g of sodium nitrate would dissolve in 100 g of water with a temperature of 40°C?
 - Contrast the solubility of sodium chloride and sodium nitrate.
 - Explain why water's ability to act as a solvent is important in the geosphere and the biosphere.
- 9 A student used water in thin glass tubes to measure how water density changes with temperature. The tubes were sealed at one end and the diameter and length of the water column in the tube was accurately measured during the experiment at a range of temperatures from 20°C to -7°C.
- In addition to volume, what other properties of the water would need to be measured accurately?
 - Predict how the water column length would change as the temperature of the water decreased.
 - Describe how you would ensure that the data collected in this experiment was reliable.
- 10 Ocean currents occur at the surface and along the sea floor of ocean basins.
- Outline the role of the Sun's energy in creating surface currents.
 - Using a flow chart, describe how deep-ocean currents are created in polar regions.
 - Evaluate the role of ocean currents in redistributing heat between the poles and the equator.
- 11 The El Niño–Southern Oscillation (ENSO) is an interaction between the atmosphere and ocean in the tropical Pacific.
- Using a diagram, describe how an area of low pressure and increased rainfall is created by a warm surface layer of the ocean.
 - Explain why changes in the heat distribution of water in the ocean cause changes in rainfall in Australia.

- 12 The graph in Figure EOM 3.3 shows how two New Zealand glaciers have changed in length from the 1890s to 2014.
- Describe the trend in glacial length change for the Franz Joseph Glacier.
 - Assess the similarity of the length changes in the length of the Fox Glacier and the Franz Josef Glacier.
 - Account for the increases and decreases in the glaciers' lengths.

- 13 Assess the importance of convection in the solid Earth, hydrosphere and atmosphere.

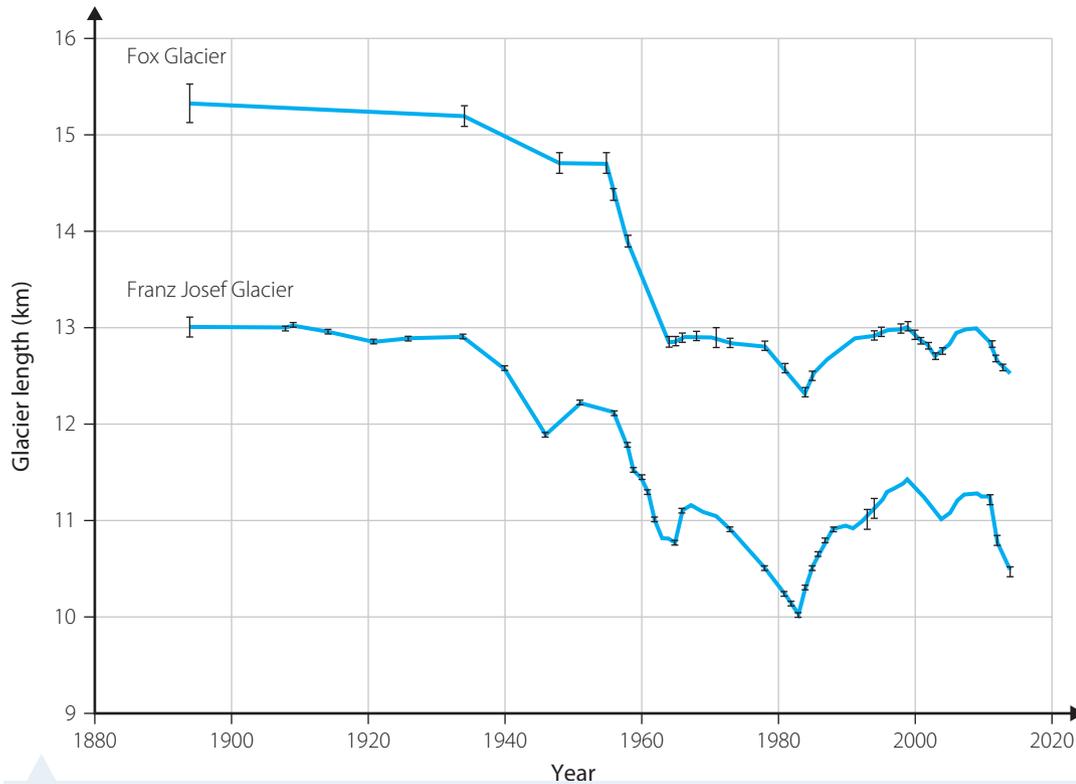


FIGURE EOM 3.3

Reprinted from Global and Planetary Change, Volume 121, Heather Purdie et al. Franz Josef and Fox Glaciers, New Zealand: Historic length records, October 2014, Pages 41–52, Copyright 2014, with permission from Elsevier

DEPTH STUDY SUGGESTIONS

- Investigate differences in convection as the amount of heat at a hot boundary is varied.
- Evaluate how light wavelength or intensity affects the rate of photosynthesis in algae.
- Analyse the relationship between plate subduction angle and subducting plate speed.
- Compare the origin, structures and products of volcanic activity on Earth and three other bodies of the solar system.
- Model the relationship between rupture area and the force needed to create movement on a fault plane.
- Evaluate the Galápagos Islands as volcanic islands created by a mantle plume.

- Investigate the changes in a volcano's volcanic rock composition as the magma chamber ages and cools.

- Investigate how the temperature of a material affects whether it fractures or bends when energy is used to deform the material.

- Evaluate a range of salts in terms of their ability to modify surface tension, thermal capacity or temperature of precipitation in water.

- Explore how a reduction in temperature difference between the equator and poles is predicted to affect wind strength and circulation.

- Does a relationship exist between the elevation of the terminus of a glacier and the frequency of crevasses in the glacier? If so, can you explain the cause of the relationship?

» MODULE FOUR

IMPACTS OF HUMANS

- 11 Water
- 12 Soil
- 13 Introduced species



11

Water

OUTCOMES

In this chapter you will learn about:

- the distribution of Earth's water [CCT, ICT, L, N](#)
- options for water treatment and reuse [S, CCT, ICT, AAEA](#)
- direct and indirect effects of human activity on water. [S, CCT](#)



Earth is often called the blue planet because water covers approximately 71% of its surface. No other body in the solar system has such an abundance of surface water (Figure 11.1). You learnt about the origin of the hydrosphere in Chapter 2. In this chapter, we are going to take a closer look at water and the ways human activity affects it. Access to water has always been a major factor in where and how humans live.

The terrible irony of our blue planet is that most of the water is useless to terrestrial animals and plants. Fresh water scarcity affects every continent. Scarcity can be due to lack of water or inadequate distribution of water. UNESCO estimates that, by 2025, 1.8 billion people will be living with a physical lack of water and two-thirds of the world population will be under conditions of water stress.



Shutterstock.com/MarcelClemens

FIGURE 11.1 Earth, the blue planet



11.1 Distribution of Earth's water

Earth's water cycles through different states (solid, liquid, gas) and reservoirs or locations, such as oceans, rivers, ice, atmosphere and biosphere. Water may be saline, brackish or fresh, depending upon the concentration of salts it contains. Australian guidelines define fresh water as that with less than 500mgL^{-1} salt. Water containing $500\text{--}1000\text{mgL}^{-1}$ salt is marginally fresh but may damage ecosystems. Brackish water has $1000\text{--}2000\text{mgL}^{-1}$ salt and saline water contains more than 2000mgL^{-1} salt. Sea water has a typical concentration of $35\,000\text{mgL}^{-1}$ salt. When water evaporates, salts and other dissolved substances are left behind.

Humans use water in many ways, but the amount that cycles through Earth's spheres is finite.

Saline water

Most of Earth's water is saline. Most of this saline water is found in the oceans. Earth's oceans are home to 50–80% of living things, of which approximately 90% have not been scientifically named and classified. Most ocean waters remain unexplored, although humans use oceanic surface waters for transport, fishing and recreation.

Ships carry more than 80% of world trade on an ever-growing merchant fleet. The oceans provide around 16% of the world's total protein, with 10% of people depending on fishing for their livelihood. In 2016–2017, the value of Australian commercial fishing and aquaculture was \$3.06 billion (ABARES *Australian fisheries and aquaculture statistics report*, 2017).

In addition to the oceans, a significant amount of Earth's saline water is found in saline lakes and groundwater. The best known salt lake in Australia is Kati Thanda–Lake Eyre, covering 9500km^2 and usually dry. Many saline lakes in Australia occur in flood plains and semi-desert areas.

Fresh water

Fresh water represents only 2.6% of the global total. Most of this exists as ice and snow in the cryosphere (Table 11.1). This leaves very little fresh water for humans and other terrestrial organisms.

The water cycle was discussed in Chapter 8.

You will learn more about saline groundwater in Chapter 12.



Groundwater

TABLE 11.1 Global distribution of fresh and saline waters

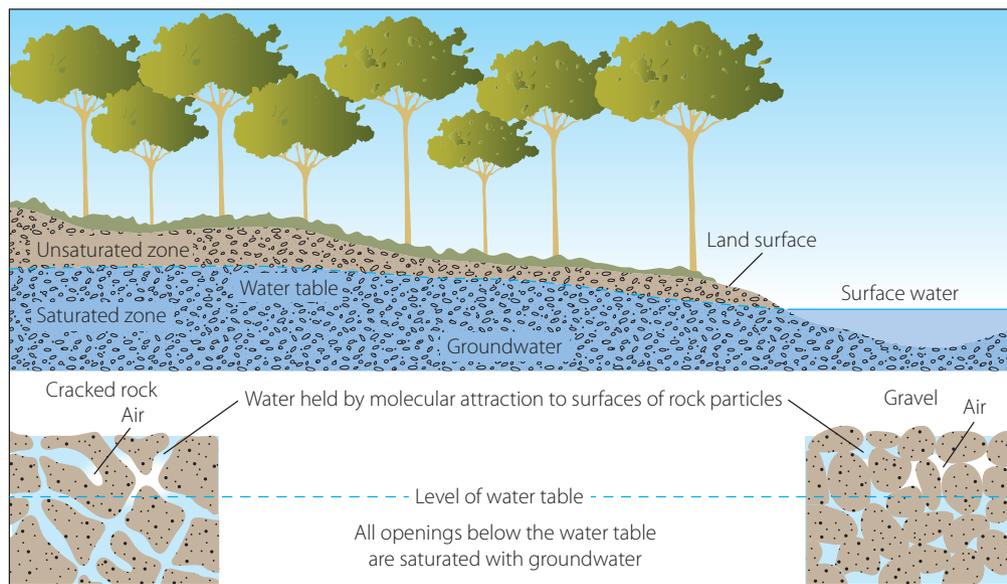
WATER SOURCE	WATER VOLUME (km ³)	PERCENTAGE OF TOTAL WATER
Oceans, seas, bays (saline)	1 338 000 000	96.5
Saline lakes and groundwater	12 955 400	0.9
All fresh water	35 027 990	2.6

U.S. Geological Survey

Of the liquid fresh water, nearly all is groundwater. This water exists within the pore spaces and cracks of soil, sand and rock, as shown in Figure 11.2. An **aquifer** is a geological formation containing water. The saturated layer closest to the surface is known as the **water table**. Groundwater discharges to surface water in springs, swamps, lakes and the ocean. Some groundwater is accessible to plants, but much is stored in deep aquifers that require bores for access.

FIGURE 11.2

An aquifer is water stored in rock, sand and soil. The top of the saturated layer is the water table.



U.S. Geological Survey

Humans alter the distribution of fresh water by damming rivers to create lakes for water storage and hydroelectricity. Table 11.2 shows the distribution of fresh water on our planet.

TABLE 11.2 Global fresh water distribution

WATER SOURCE	WATER VOLUME (km ³)	PERCENTAGE OF TOTAL FRESH WATER
Ice caps, glaciers and permanent snow	24 064 000	68.699
Ground ice and permafrost	300 000	0.856
Fresh groundwater	10 530 000	30.062
Freshwater lakes	91 000	0.260
Soil moisture	16 500	0.047
Atmosphere	12 900	0.037
Swamp water	11 470	0.033
Rivers	2 120	0.006

U.S. Geological Survey

INVESTIGATION 11.1

Global water distribution

INTRODUCTION

The quantity of water in different locations on Earth varies over several orders of magnitude. This makes water distribution difficult to represent and understand. Most of the water (97.4%) is saline. Terrestrial animals and plants need accessible fresh water to live. In this secondary-sourced investigation you will use your skills in graphing and design to create a representation of water distribution that shows why water is a precious resource.

AIM

To create an infographic that accurately depicts global water distribution and the amount available to terrestrial animals and plants

MATERIALS

- Computer with spreadsheet and presentation software

METHOD AND RESULTS

- 1 Set up your spreadsheet and enter the data from Tables 11.1 and 11.2.
- 2 Experiment with different graph types such as pie chart, column and stacked column graphs.
- 3 Decide whether you need to combine some water sources for graphing purposes.
- 4 You will need to create at least two graphs to depict water resources effectively. One should show global saline and fresh water sources; the other should show only fresh water sources.
- 5 Calculate the percentage of fresh water that is available to animals and plants.
- 6 Calculate the percentage of global water that is available to animals and plants.
- 7 When you are satisfied with your graphs, create an explanatory poster using presentation software. Your poster should include the graphs, but also incorporate text and pictures to emphasise the amount of fresh water available to animals and plants.

DISCUSSION

- 1 Outline the water sources you combined to make your graphs.
- 2 Explain which sources you consider available to animals and plants.
- 3 In *The Rime of the Ancient Mariner* by Samuel Taylor Coleridge (1798), a sailor stuck on a calm sea laments 'Water, water, every where, nor any drop to drink.' (often modernised as 'Water, water, everywhere, but not a drop to drink.'). Relate this quote to the results of your investigation.
- 4 The data in Tables 11.1 and 11.2 are based upon information published in 1993. Describe the probable changes to global water distribution due to increasing temperatures.
- 5 Suggest ways your infographic could be used to encourage people to conserve water.

CONCLUSION

Summarise your findings about the global distribution of water.



Critical and creative thinking



Information and communication technology capability



Literacy



Numeracy

KEY CONCEPTS

- Most of Earth's water is in the oceans.
- Humans use the oceans for transport, fishing and recreation.
- A significant amount of saline water is found in groundwater and salt lakes.
- Most fresh water occurs as ice in the cryosphere.
- Most liquid water is groundwater.

CHECK YOUR UNDERSTANDING

11.1

- 1 Distinguish between cryosphere, aquifer and water table.
- 2 Calculate the total amount of water (in km³) on the planet.
- 3 Outline reasons why the oceans are important to humans.
- 4 Identify the largest source of liquid water at Earth's surface.
- 5 Explain the connections between groundwater and surface water.
- 6 Identify three sources of water available to:
 - a plants
 - b animals.

11.2 Options for water treatment and reuse

You learnt about the effects of ocean currents and atmospheric movements on rainfall in Chapter 10.

As you discovered in Investigation 11.1, fresh water is a precious resource. This is particularly true in Australia, where rainfall is highly variable. In 2016–2017 Australia's water use was dominated by agriculture, which accounted for 72% of water use, urban water utilities (19%) and other industries (9%) (Bureau of Meteorology 2019). Because water is a finite resource it makes sense to be able to treat it and make it available for reuse.

Sewage treatment

You will learn more about eutrophication in section 11.3.

Sewage comes from showers, sinks, toilets, washing machines and dishwashers. It is 99% water, but also contains human waste, oils, food, soaps and household chemicals. Human waste can carry disease. Oils, soaps and food scraps are rich in nutrients that can cause **eutrophication**, leading to the death of aquatic ecosystems.

Figure 11.3 shows a sewage treatment plant. The three basic stages of sewage treatment remove different contaminants. Details of each stage vary by treatment plant and not all sewage is fully treated. For example, 80% of Sydney's sewage is treated to primary level and then discharged through deep ocean outfalls. Inland cities must treat water to a tertiary level for discharge into waterways that may be used for recreation and agriculture.

Primary treatment

Primary treatment removes solid material and oils from sewage. The first step involves screening to remove large solids, followed by grit removal, sedimentation and scraping off floating oil.

Many items removed by screening in primary treatment should never have been flushed or washed down drains. Flushable wipes are a major problem. The wipes combine with fats, oils and debris to create 'fatbergs' in sewers. The 500t of wet wipes flushed in Sydney each year are involved in about 75% of sewer blockages and cost Sydney Water \$8 million per year to remove.



FIGURE 11.3 Aerial view of a sewage treatment plant

INVESTIGATION 11.2



Flushable or not?

INTRODUCTION

Water treatment authorities say that only 'the three Ps' should be flushed – pee, poo and paper. Despite this, manufacturers claim a variety of products are flushable. In 2018, the Australian Competition and Consumer Commission (ACCC) prosecuted the manufacturer of White King's 'flushable' toilet and bathroom cleaning wipes. The company was fined \$700000 for falsely claiming that its products would disintegrate in the sewage system 'just like toilet paper'. In this investigation, you will observe the result of simulated flushing on toilet paper and other wipes.

AIM

To determine which tissues and wipes disintegrate when flushed

MATERIALS

- 4 identical screw-top jars with lids, at least 500 mL capacity
- Marking pen
- Toilet paper
- Facial tissue
- Makeup removal wipe
- 'Flushable' wipe

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Wet jars are slippery and can shatter when dropped.	Dry the jar after adding water. Ensure that the lid is secure and hold firmly in two hands when shaking.



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

METHOD

- 1 Label each jar with the name of the paper or wipe and half-fill with water.
- 2 Place each paper product or wipe in the appropriately labelled jar and secure the lid.
- 3 Hold the jar firmly in two hands and shake vigorously for 15 seconds.
- 4 Record your observations.
- 5 Screen or pick out solids from the jars. Pour the waste water down the sink and dispose of the solid waste in a rubbish bin.

RESULTS

Record your observations in a carefully planned table. You may wish to add photos of the jars after shaking as documentation.

ANALYSIS OF RESULTS

- 1 Toilet paper is designed to break up during the turbulence of flushing. Compare the disintegration of toilet paper with that of the other wipes.
- 2 Soaps or solvents on wipes can add chemical waste that must be removed during sewage treatment. Describe any evidence of chemical waste that you found in your investigation.
- 3 Based upon your investigation, what features are needed for a wipe to be truly flushable?
- 4 Analyse the validity and reliability of your investigation. What improvements would you make if this investigation was to be used as evidence in a court case?

CONCLUSION

Summarise your findings about the disintegration of different wipes.

Secondary treatment

Secondary treatment removes carbon and nutrients (nitrogen and phosphorus) from wastewater. A variety of microbes are used for this process. The microbes feed on the carbon and nutrients, converting this to biomass.

The details of secondary treatment vary with each facility, but there are three basic stages. These produce different products.

- 1 **Aeration:** Air is pumped through diffusers into the treatment tank. Aerobic microbes remove phosphorus and break ammonia into nitrates and water. Figure 11.4 shows this stage.
- 2 **Settling:** Oxygen levels drop. Nitrates are converted into nitrogen, which is released into the atmosphere, and the microbes feed on carbon.
- 3 **Decanting:** Clear wastewater is sent to tertiary treatment. Some solids are retained for the next batch of water. The remaining solids are sent to digesters for complete breakdown of organic material before dewatering to produce biosolids.

Remaining phosphorus may be removed using alum (an aluminium salt) or pickle liquor (an iron-containing waste product of the steel industry), which cause flocculation or sedimentation of phosphorus particles. Sediments from this process may be combined with sludge from secondary treatment to produce biosolids. Nutrient-rich biosolids are re-used in agriculture (as fertiliser), landscaping and land rehabilitation.



FIGURE 11.4 Aeration encourages the growth of microbes that feed on organic material, breaking down ammonia and absorbing phosphorus.

Tertiary treatment

In tertiary treatment, wastewater is filtered to trap fine particles and then disinfected. These steps remove the last solids in the water and kill pathogens that might affect humans who come into contact with discharged water. The most common disinfection options are chlorination and dechlorination, ultraviolet light treatment and ozone treatment. Water that has been through tertiary treatment is free of solids, fats, nutrients and pathogens. However, many substances have not been removed, including salts, pharmaceuticals and chemical pollutants.

Australian rivers may contain traces of up to 100 different human drugs and medicines, the effects of which are poorly documented. Global studies have revealed concerning information about some pharmaceuticals. Oestrogen levels in treated wastewater have been shown to affect the sex of fish, leading to more intersex individuals. Anti-anxiety drugs and cocaine in wastewater affect fish behaviour. The painkiller diclofenac, commonly found in treated wastewater and sludge, causes kidney damage in birds. Antibiotics in treated water are accelerating the evolution of antibiotic-resistant bacteria in the environment.

These remaining substances may be removed by more rigorous forms of tertiary treatment, such as **reverse osmosis**, the process used at desalination plants (Figure 11.5). This produces pure water free from the salts, pharmaceuticals and other chemical pollutants that may remain after standard tertiary treatment. Micro-filtration systems are also used to reduce the concentration of pharmaceuticals and pesticides in water.

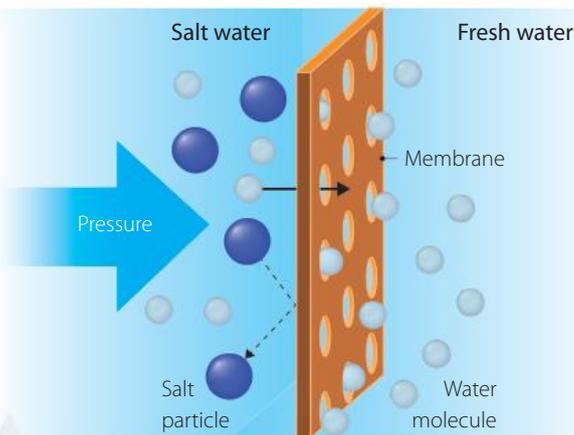


FIGURE 11.5 Reverse osmosis is used in desalination and can also be used for water treatment.

Reuse of treated wastewater

Tertiary-treated wastewater may be released into the environment to provide environmental flows to wetlands and rivers. Chlorine would kill aquatic organisms, so water must be de-chlorinated before release.

Other uses for treated water include firefighting, dust control at industrial and construction sites, irrigation, cooling water for power plants, toilet flushing, garden use and processing water for industry. Treated water is not directly used for drinking in Australia. However, tertiary-treated water from upstream areas flows into some Australian reservoirs and replenishes some aquifers that are used to provide drinking water.

In 2006, residents of Toowoomba rejected a \$68 million proposal that would have returned recycled water to the drinking water supply. Instead, residents chose a \$187 million pipeline from Wivenhoe Dam to Toowoomba. Recycled water is less costly and less damaging to the environment than additional dams or desalination, but public resistance to the idea has so far kept Australia from recycling water for drinking purposes.

INVESTIGATION 11.3

Overcoming the 'yuck factor' for recycled water

INTRODUCTION

Public reluctance to drink recycled water is a key reason desalination plants were built in major Australian cities such as Perth, Melbourne and Sydney. However, as climate change continues and droughts become more common, Australians may need to re-think their objections to drinking recycled water. The people of Singapore have already done so.

Branded NEWater, Singapore's recycled water is sourced from rigorously treated sewage that has been through ultrafiltration, reverse osmosis and UV disinfection. NEWater is used directly for non-drinking purposes and is also added to reservoirs, where it mixes with rainwater before being treated for drinking. Careful branding and public education were used to overcome the 'yuck factor' and gain public acceptance.

AIM

To design a public education campaign to convince residents of your community to drink recycled water

METHOD

- 1 Find out where your local drinking water comes from and how long it could supply the community during a drought.
- 2 Research the techniques used in Singapore to increase acceptance of recycled water.
- 3 View advertisements that you find appealing. Analyse the factors that make them effective.
- 4 Design a public education campaign for your community to convince residents to drink fully treated water recycled from sewage. This should be informed by both fact and effective advertising techniques.

RESULTS

Present your campaign as a video, pamphlet or poster.

ANALYSIS OF RESULTS

- 1 What forms of tertiary treatment would you use for water that will be recycled for drinking? How do these remove pollutants and protect human health?



Recycled water in Singapore

Use the information in this report to summarise steps taken in Singapore to build acceptance of recycled water.





- 2 Explain the rationale for your campaign. Which key facts and persuasive techniques did you choose to convince local residents to drink recycled water?
- 3 Does your campaign appeal more to emotion or to intellect? Justify your choice.

CONCLUSION

Summarise the features that are vital in educating the public about the benefits of drinking recycled water.

Stormwater

You will learn more about erosion in Chapter 12.

Stormwater is rain that falls on sealed surfaces and anything that is carried in them. Pollutants on roofs, roads, driveways and paths may end up in stormwater; these include sediments, rubbish, animal waste, oil, household chemicals and leaves. This water is diverted through stormwater drains directly into local waterways. The sudden influx of water from many sealed surfaces can cause erosion.

Pollutants in rainwater can have devastating effects on aquatic ecosystems, so many local councils require stormwater treatment systems for new developments. They also work to retrofit systems in existing catchments. An open gross pollutant trap is a basic device that allows water to slow and sediments to settle out, with a trash rack to catch rubbish, leaves and sticks (Figure 11.6a). Open devices require a relatively large open space, so compact underground systems are commonly used in densely populated areas (Figure 11.6b). Both types of device require regular cleaning to remove sediments and rubbish.

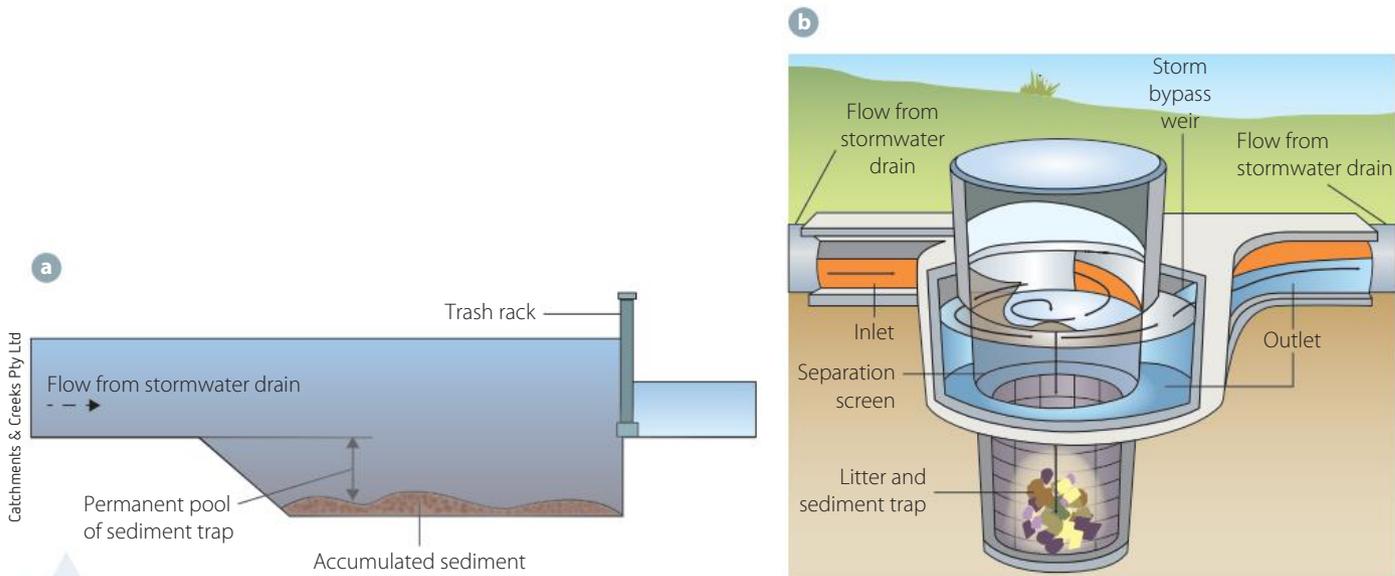


FIGURE 11.6 Gross pollutant traps: **a** an open gross pollutant trap allows sediment to settle out and collects large litter; **b** a compact in-ground system concentrates litter and sediments with a swirling water flow.

Gross pollutant traps remove solid pollutants, but not excess nutrients, pesticides or heavy metals. Gross pollutant traps are analogous to primary sewage treatment. Secondary biological treatment is required to remove dissolved pollutants. This is desirable in any stormwater outfall and crucial in catchment areas where water is collected for drinking water.

Artificial wetlands, as shown in Figure 11.7, remove suspended solids, nutrients and heavy metals. The fine sediments settle out in dispersed water. Nutrients are taken up by vegetation and bacteria. Heavy metals bind to fine clay particles. Wetlands also provide habitat and an attractive landscape feature. Small systems have some benefit, but larger areas yield maximum results. Treated stormwater can be retained and used for watering sports grounds, irrigation or **recharge** of groundwater.

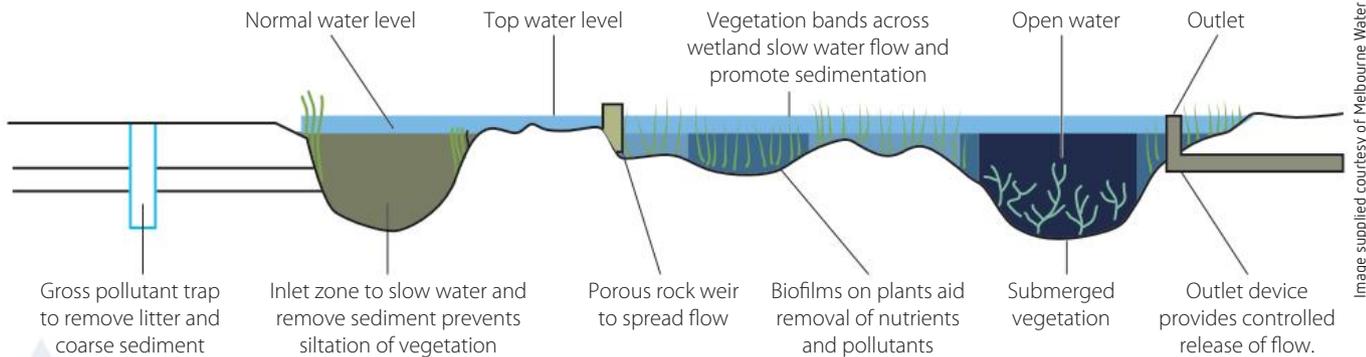


Image supplied courtesy of Melbourne Water

FIGURE 11.7 A large artificial wetland, used in conjunction with a gross pollutant trap, removes fine sediments and nutrients.

Industrial wastewater

The contents of untreated industrial wastewater are as varied as the ways in which industries use water and the substances that can be dissolved in or carried by water.

If water used for cooling and in boilers is released into waterways it may cause thermal pollution, harming heat-sensitive organisms. Heated water also dissolves traces of metal from pipes as well as reducing the amount of dissolved gases.

The pulp and paper industry uses 54m³ of water to produce a tonne of paper or pulp. The large volume of wastewater contains suspended solids, organic material, chlorine and organic compounds. Before wastewater can be released to the environment, most manufacturers are required to treat it onsite to reduce the heavy contaminant load. Primary treatment in settling tanks or clarifiers removes suspended solids from the water. Secondary biological treatment removes organic material. Tertiary treatment by membrane filtration or UV disinfection may be employed if higher quality outflow is required. Treated industrial water may be recycled onsite for further manufacturing, treated further at a municipal sewage treatment plant, or released into local waterways to provide environmental flows.

The solids removed in water treatment at paper mills may be combined with ash from the boilers and furnaces, as well as leftovers from pulping. This organic material can be anaerobically digested and the resulting biogas used to fuel boilers, as in the mill shown in Figure 11.8. The remaining residue is a valuable fertiliser. Waste-to-energy systems are becoming more common as large plants invest in digestors.



Getty Images / iStock / Getty Images Plus

FIGURE 11.8 This paper and pulp mill generates 50% of its own power by combusting waste from the treatment process.

Water from mining

Mining can be very water intensive. For example, 1600L of water is needed to obtain the 19kg of copper in the average mid-size car. Mines use water for dust control (Figure 11.9), **hydraulic fracturing** (commonly known as fracking), ore processing and irrigation of land during rehabilitation. Coal mining uses 58% of mining water in New South Wales, with metal ore making up 39% of the mining use.



FIGURE 11.9 Water is required for dust suppression, as shown at this gold mine.

Mines obtain water from a variety of sources, including recycled wastewater, local waterways, groundwater, and removal of excess runoff and seepage into the mine itself. The content of the wastewater varies according to the initial water quality and mining process. Water from a coal mine may range from highly acidic to near neutral. Heavy metal, silica and phosphate levels will vary.

Best-practice treatment of water from a coal mine would involve primary physical treatment to remove suspended solids by settling. Heavy metals, silica and phosphate can be removed by

chemical precipitation and settling. Filtration or clarification would be used next, followed by pH (acidity) adjustment and reverse osmosis to produce clean water. Treated water from mining is often reused onsite. It may be released into the environment if of a similar quality to environmental water.

Acid mineral drainage

Water that has seeped through mining waste poses a challenge, particularly at derelict mine sites. Sulfur-containing wastes react with water and oxygen in the air to form sulfuric acid. Acidic runoff poses a serious hazard to the surrounding ecosystem and waterways. This hazard is multiplied when the drainage originates from a multi-metal mine. In these cases, the acidic water dissolves elements such as lead, arsenic, copper and magnesium that are present in the mine waste.

The most cost-effective way of treating acidic mine runoff is through passive systems such as anoxic limestone drainage (ALD), as illustrated in Figure 11.10. The system is kept anoxic to limit the amount of acid formed. This is achieved by clay capping over the mine waste and limestone drain. Acidic water runs through underground drains filled with rocks and pebbles of high-grade limestone (90% calcium carbonate), which neutralises the acid. The limestone-containing drain is encased in impermeable plastic and covered with a compacted clay layer to prevent the entry of water from outside. Water leaving the limestone drain flows to a settling pond that allows the metals to oxidise and precipitate before the treated water flows into the environment.

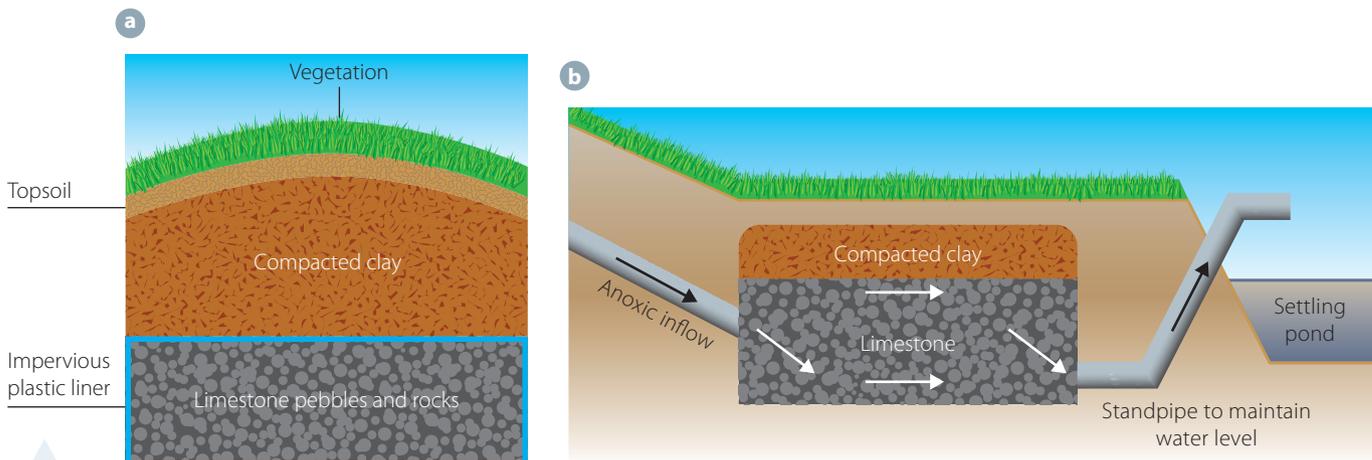


FIGURE 11.10 Anoxic limestone drainage is a cost-effective passive treatment of contaminated acid mineral drainage: **a** cross-section **b** lateral section

You will learn about heavy metal contamination of soil and human health effects in Chapter 12.

INVESTIGATION 11.4

Simulating water treatment



INTRODUCTION

Treatment processes for wastewater can be categorised as physical, chemical and biological. Physical treatment removes solids; chemical treatment is used to precipitate dissolved substances for physical removal, and in biological treatment, organisms are used to absorb pollutants.

In this investigation you will model physical and chemical treatment processes using simulated wastewater.

AIM

To simulate processes used in water treatment

MATERIALS

- Approximately 200 mL simulated wastewater containing soil, leaves, Epsom salt (magnesium sulfate) and table salt (sodium chloride)
- Sieve
- 250 mL beaker
- Filter paper
- Filter funnel
- 250 mL conical flask
- Washing soda (sodium carbonate)
- Silver nitrate solution (0.1 M)
- 2 test tubes
- Safety glasses and disposable gloves

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Soil may contain harmful microbes.	Wear gloves. Wash hands after handling soil residue and wastewater.
Epsom salt: low toxicity	Wear safety glasses.
Washing soda: eye and skin irritant	Wear safety glasses, avoid skin contact and wash hands after use.
Silver nitrate: corrosive to eyes and skin, toxic to aquatic life	Wear gloves. Wear safety glasses, avoid skin contact and wash hands after use. Dispose of the silver nitrate as instructed.



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

METHOD

- 1 Stir your wastewater mixture to ensure that all components are well mixed. Copy Table 11.3 and record your observations of this mixture.

Part A: Screening

- 2 Place the sieve on top of a 250 mL beaker and carefully pour approximately 200 mL of wastewater through the screen. Record the substances that are removed in this step and the appearance of the remaining wastewater.

Part B: Filtration and sedimentation

- 3 Place the filter paper in the funnel and set this on the neck of the conical flask.
- 4 Pour water from step 2 into the funnel to nearly fill it.





- 5 Record your observations of the filtrate and residue. Retain the filtrate for Part C. Place the filter paper and residue in the bin.
- 6 Set the wastewater remaining in the beaker aside overnight for part D.

Part C: Testing for salt

- 7 Pour the filtrate from Part B into a test tube and test for salt by adding two drops of silver nitrate solution. A milky colour indicates that salt is present. Record your observations.
- 8 Empty the test tube with silver nitrate into a labelled waste container. Place all solid waste in the bin and wash other liquid waste down the sink.

Part D: Sedimentation and precipitation

- 9 Record your observations of sedimentation in the wastewater remaining in the beaker.
- 10 Place a pea-sized amount of washing soda into a test tube, adding water to half-fill the tube and dissolve the washing soda.
- 11 Decant water from the sedimentation beaker into the test tube containing the washing soda. Record your observations.
- 12 Leave the test tube with washing soda overnight for sedimentation. Observe the result.

RESULTS

TABLE 11.3 Wastewater treatment results

PROCESS	APPEARANCE OF WATER BEFORE TREATMENT	APPEARANCE OF WATER AFTER TREATMENT	WHAT WAS REMOVED?
Screening			
Filtration			
Sedimentation			
Precipitation			

Observation of result of filtrate testing with silver nitrate solution: _____

ANALYSIS OF RESULTS

- 1 State which types of substances in real wastewater might be removed by each process you modelled.
- 2 Explain the scientific principles used in physical separation.
- 3 Why might you need a chemical process such as precipitation to treat wastewater?
- 4 Is another water treatment process required after precipitation?
- 5 What substances remained in the water after treatment? Explain the evidence you have for these substances.
- 6 Recommend a method to remove the remaining contaminants in the water.

CONCLUSION

Summarise your findings about wastewater treatment.

EXTENSION

Simulate biological treatment by allowing water with a small amount of fertiliser to slowly filter through vegetation. Measure the dissolved phosphorus level of the water input and outlet. Do different flow rates result in different nutrient uptake? Can you determine the optimal flow rate for your system?

KEY CONCEPTS

- Sewage is wastewater that comes from sinks, showers, toilets, dishwashers and washing machines.
- Sewage treatment has three main steps:
 - primary treatment removes solids
 - secondary treatment removes carbon and nutrients
 - tertiary treatment kills remaining pathogens.





- Pharmaceuticals are not removed by sewage treatment and may damage ecosystems.
- Treated wastewater can be used for many purposes, including watering gardens, in industry and for firefighting.
- Stormwater is runoff from sealed surfaces that is directed into local waterways.
- Stormwater may contain sediments, leaves, oils, household chemicals, rubbish and animal waste.
- Gross pollutant traps and artificial wetlands may be used to treat stormwater.
- Industrial water may carry any sort of pollutant.
- Pulp and paper wastewater is treated by clarification and biological treatment.
- Wastewater from coal mining is treated by sedimentation, precipitation and filtration.
- Acid mineral drainage may be treated with limestone neutralisation.

- 1 Identify the main use of fresh water in Australia.
- 2 Create a table identifying four substances that may be in sewage and the stage or step in treatment that removes each substance.
- 3 Explain why disinfection is a vital part of tertiary sewage treatment.
- 4 Identify at least five pollutants that may be in stormwater.
- 5 Explain the environmental benefit of gross pollutant traps.
- 6 Outline the problems with thermal water pollution from industry.
- 7 How is water used for mining?
- 8 Outline the advantages of using passive treatment for acid mineral drainage.

CHECK YOUR
UNDERSTANDING

11.2

11.3

Direct and indirect effects of human activity on water

In the first two sections of this chapter you learnt that fresh water is a precious resource that humans use for a variety of purposes and that it is treated after use. As the human population increases, increased demands are being put on a limited amount of water. This leads directly to problems such as over-extraction and pollution. The direct effects have indirect consequences, such as eutrophication, ecosystem changes and effects on human health.

Groundwater

Groundwater used to be regarded as a resource to be mined, but it is now seen as a renewable resource that must be managed as carefully as surface water. Management challenges are greater because groundwater is unseen and its movements are poorly understood. The use of groundwater is increasing rapidly across Australia, but much is extracted by individual users and is not metered or managed. It is a vital resource for cities such as Perth and Alice Springs, which rely on groundwater for 80% and 100% of their water respectively.

The amount of groundwater increases when it is recharged by rainfall. It decreases when it is extracted through bores or discharges naturally to waterways, wetlands and the ocean. There are many connections between groundwater and surface water. Rivers that flow all year are generally maintained by groundwater discharge. Excessive pumping of groundwater causes rivers to recharge aquifers and so river levels drop, wetlands dry up and ecosystems may be irreparably damaged. Thus, groundwater and surface water need to be managed together.



FIGURE 11.11 River red gum growing along the Murray River

Saline groundwater is an environmental problem that you will explore in Chapter 12.

Over-extraction of groundwater will eventually cause the water table to drop below bore levels so that users can no longer pump out water, directly affecting the water users. The indirect effect of excessive use is the drying up of wetlands, rivers and lakes. Trees such as river red gums along the Murray River, shown in Figure 11.11, normally survive extended drought by accessing deep groundwater. When the groundwater has been overused, these trees will die.

Groundwater may be replenished by treated stormwater, sewage or industrial water. Pumping water back into an aquifer requires careful consideration of the aquifer water quality. Water used for recharge should be of similar or better quality to safeguard the health of the ecosystems and people who may depend on that groundwater system.

Substances that infiltrate with rainwater, are injected into the ground during drilling operations or seep into the ground from septic systems, underground storage tanks or landfill, may all contaminate groundwater. Salts, herbicides and fertilisers that are soluble in water can infiltrate into groundwater via rainfall or irrigation. Hydraulic fracturing for gas extraction may result in gas and/or chemical contamination of groundwater. Septic systems that are not properly maintained can leak bacteria, viruses and household chemicals into groundwater. Storage tanks containing petrol, oil and other chemicals can corrode and develop leaks over time. Leachate from landfill can allow contaminants such as battery acid, household cleaners and bacteria-rich water to seep into groundwater. Any of these pollutants can have serious consequences for human and ecosystem health.

INVESTIGATION 11.5

Modelling human impacts on groundwater



Sustainability



Critical and creative thinking

INTRODUCTION

Australia is increasingly dependent upon groundwater but it is being extracted more quickly than it can be recharged. Sustainable extraction should not exceed 50–70% of recharge. In addition to excessive extraction, groundwater may be polluted from a variety of sources. This investigation allows you to observe the movement of groundwater and the effect of land and surface water pollutants upon it.

AIM

To observe the effect of extraction and pollutants in a groundwater model

MATERIALS

- Rectangular clear plastic container
- Small gravel or aquarium stones
- Soil
- Pump from soft-soap bottle or similar
- Small watering can or spray bottle
- Dropper bottle with red food colouring
- Dropper bottle with blue food colouring



- » ■ Cup or beaker for extracted water
- Sieve
- Digital camera (optional)

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Soil may contain harmful microbes.	Wash hands after handling soil.



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

METHOD

Part A: Effect of extraction

- 1 Place the gravel in the plastic container, heaping the stones so that they are higher at one short end than the other. The low end represents a lake.
- 2 Add a layer of soil on top of the stones. Press it down to minimise erosion.
- 3 Add water to your model using the watering can or spray bottle until a lake 1–2 cm deep has formed in one side of the container.
- 4 The water table is the top saturated level. Observe the water table in the aquifer (stones) and the level of the lake.
- 5 Insert the tube of the pump into the higher rocky side of your model. This represents a bore to access groundwater.
- 6 Pump water into a cup or beaker and observe the level of the groundwater and lake.

Part B: Effect of pollution

- 7 Place 4 drops of red food colouring on the soil on the land end of your model and 4 drops of blue food colouring in the lake. These represent pollution sources.
- 8 Replenish your aquifer with more 'rain' and observe any movement of the colours.
- 9 Pump water into a cup or beaker and observe movement of the pollutants.
- 10 When finished, place solids in a bin and wash water down the sink. The gravel may be separated from the soil using a sieve with holes of appropriate size.

RESULTS

Record your observations in a table. You may wish to take photos during the investigation and include these in the results table.

ANALYSIS OF RESULTS

- 1 Describe the relationship between the water table and the lake in your model.
- 2 Outline the effects of pumping groundwater on the different areas of your model.
- 3 Describe the changes in pollution distribution that occurred with rain and groundwater pumping.
- 4 Using your observations, explain how pollutants from soil or surface waters may end up in groundwater.
- 5 Describe one improvement that would make your model more representative of real groundwater systems.

CONCLUSION

Summarise your findings about the effects of groundwater extraction and the movement of pollutants.

EXTENSION

This investigation modelled an **unconfined aquifer**. An unconfined aquifer is near the surface and is easily recharged by surface waters. The water table of an unconfined aquifer is at atmospheric pressure. In the real world, there are often lower layers of groundwater, called **confined aquifers**, separated by impermeable sediment or rock. The confining layers put the water under pressure so that it rises above the top of the layer when penetrated by a bore.

Create a model that contains a confined aquifer and repeat the pollution experiment. How do your results differ if you pump from the confined and unconfined areas?

Maintaining river flows

Australian rivers provide water for irrigated agriculture. The value of this production in the Murray–Darling basin was about \$8.6 billion in 2018 and continues to rise. Water extraction for irrigation has serious consequences for the ecosystem in and along the rivers. Downstream, water flow is reduced, waterways become slower and clog with sediments, the timing of water flows is changed, natural floods are prevented or diminished, and salt builds up without natural flushes to clear it. These changes result in the death of riparian vegetation and reduced breeding of native fish and birds.

Flows from sewage treatment plants can help to maintain river water levels, but these do not replace the quantities lost to irrigation. To combat the environmental damage caused by extraction, water authorities release water from dams for environmental flows. Pulses of water flush away sediments and salts. Slower releases allow natural flooding.

In addition to environmental flows, water licensing has been adjusted to reserve a portion of water for the environment. The Australian Government reinstated water licences along the Murray–Darling basin in an attempt to improve ecological health along the river system. The South Australian Murray–Darling Basin Royal Commission (2018) found that the Murray–Darling Basin plan was not based upon scientific evidence. The Commission’s report states that the amount of water allocated for the environment was inadequate and driven by political considerations.

Water pollution

Water pollution comes in many forms. In section 11.2 you learnt about water treatment options to remove some types of pollutants. The previous section on groundwater outlined the many sources of pollution that may affect groundwater and, via discharge zones, surface waters. In this section you will learn about two common types of surface water pollution: excess nutrients and plastics.

Excess nutrients

Nitrogen and phosphorus can enter waterways from fertilisers, septic systems, animal waste or incompletely treated sewage. This leads to algal blooms (Figure 11.12). A thick coat of algae forms, blocking light, causing the death of bottom-dwelling plants and hampering the vision of predators that need light to see prey. The rapid photosynthesis of the algae depletes dissolved carbon dioxide

and raises pH during the day, leaving some organisms unable to use chemosensory abilities. Dying vegetation under the algal bloom begins to decompose. Microbial decomposers thrive and deplete oxygen to the point where most organisms die, including the algal bloom that initiated the event.

Dead zones caused by eutrophication occur in freshwater lakes and coastal estuaries receiving water from nutrient-rich rivers. Some algal blooms contain cyanobacteria, which produces toxins that poison aquaculture stock, livestock, wildlife and humans.



FIGURE 11.12 Closeup of an algal bloom covering the surface of a pond, causing severe eutrophication



Algal blooms and fish kills in MDRS

INVESTIGATION 11.6

Eutrophication



Sustainability



Critical and creative thinking

INTRODUCTION

Despite efforts to treat wastewater from industry and domestic use, eutrophication is a leading cause of water pollution for many ecosystems. In this investigation you will explore the effect of small quantities of fertiliser on algal growth. You need to select appropriate measurements for your algae and quantities of fertiliser. Note that very small amounts of fertiliser may have large effects. If in doubt, start with a very low concentration, such as 1 mL of soluble fertiliser solution in 500 mL of water.

AIM

To document the effect of fertilisers on algae or floating water plants (e.g. duckweed)

HYPOTHESIS

Write a suitable hypothesis about the effect of increasing fertiliser concentration on aquatic algae.

MATERIALS

Construct a list of materials for your investigation. Consider using recycled materials such as clear 2 L soft drink bottles with the top cut off. Tap water that has been sitting in an open container overnight will be suitable for growing your algae.

Complete a risk assessment for your investigation. The first item has been added for you.

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Unknown species of algae or water plants may release toxins and / or be growing in pathogen-rich water.	Use gloves when collecting samples from local waterways. Wash hands after handling both algae and pond water.



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

METHOD

Construct a method to investigate the effect of fertilisers. Be sure to include:

- a control group (tap water only)
- at least three different fertiliser concentrations (start with very low amounts)
- a standard quantity of algae for each container in your experiment
- a method to quantify the amount of algae at the end of the experiment.
 - Filamentous algae or duckweed can be strained from water and weighed.
 - You can estimate the concentration of unicellular algae by examining it under a microscope and counting the number of cells in a low-power field of view. Repeat this several times to check for reliability.
 - You may choose to quantify the amount of light passing through the solution if your algae are evenly distributed.

RESULTS

Record your results in a table and construct a line graph of fertiliser concentration versus amount of algae.

ANALYSIS OF RESULTS

- 1 Discuss your results and the effect of fertiliser concentration on algal growth.
- 2 Too much fertiliser will cause algal death. How did your results align with this statement?
- 3 Discuss the effect of algal growth on an aquatic ecosystem.





- 4 Comment on the validity and reliability of your experiment. What challenges did you encounter when trying to control variables and quantify your results? How could you improve your experimental method?
- 5 What additional challenges are posed by a field study of eutrophication? Discuss the safety considerations of a field study versus a laboratory study.

CONCLUSION

Summarise your findings about the effect of fertilisers on algal growth.

Plastics

More than 7Mt of plastic ends up in the oceans every year, equivalent to dumping a truckload of plastic in the ocean every minute. If current levels of plastic dumping and overfishing continue, it is estimated that there will be more plastic than fish in the ocean by 2050. Whales, turtles and seabirds are regularly found

dead of starvation with their intestines full of plastic. The direct effects of plastic pollution are obvious (Figure 11.13), but **microplastics** (pieces less than 5mm long) have insidious effects on the health of animals and ecosystems. This plastic waste kills approximately 1 million seabirds and more than 100000 marine animals every year.

These staggering quantities of plastic are overwhelmingly carried to the oceans from land. Just 10 rivers carry 90% of plastics into the ocean. These are (in order) the Yangtze, Indus, Yellow, Hai He, Nile, Ganges, Pearl, Amur, Niger and Mekong rivers, shown on the map in Figure 11.14. These rivers have two things in common: a high population in the surrounding area, and poor waste management on land. The Yangtze is the longest river in Asia and the river basin is home to almost half a billion people.

Shutterstock.com/Rich Carey



FIGURE 11.13 A seahorse clings to a plastic straw among discarded bags.

FIGURE 11.14

90% of ocean plastic pollution comes from these 10 rivers.



Bags and large items are highly visible, but microplastics now outnumber plankton in many areas, reaching ratios as high as 40:1 in locations where they are trapped in ocean vortices by surface currents. Microplastics are not just a marine problem. A 2018 study by Kosuth, Mason and Wattenberg documented synthetic fibres consumed through food and drink. They found microplastic contamination (mainly synthetic fibres) in 81% of the 159 city water supplies tested from 14 countries. All commercial sea salt brands contained microplastics. They estimated that the average person ingests over 5800 particles of synthetic fibres every year, with most from tap water. If that person regularly eats fish and seafood, the microplastic consumed doubles. Microfibres from synthetic clothing are shed in the wash, but not removed in most wastewater treatment. An estimated 1Mt of these end up in the ocean each year and they account for 85% of the human material washed up on shorelines.

Microplastics come from synthetic clothing, tyre dust, paints, degraded plastic waste, microbeads in cleansers and cosmetics, and consumer items such as glitter. Microplastics do not choke large animals like humans, but the chemicals they contain can disrupt reproduction and development or cause cancer. Some of the plastic additives implicated in human health effects include phthalates, flame retardants and bisphenol A (BPA). In addition to direct toxicity, plastics absorb and concentrate other pollutants in water, such as mercury and DDT. Plastic pellets have been found to concentrate toxins up to a million times the concentration of surrounding sea water.

KEY CONCEPTS

- Groundwater is a vital resource that is connected to surface water.
- Over-extraction of groundwater reduces its availability for human use and dries up wetlands, rivers and lakes.
- Groundwater may be contaminated by liquids that infiltrate to the water table or are injected into aquifers.
- Environmental flows from dams attempt to reverse the damage caused by over-extraction of river water.
- Marine plastic pollution is a huge problem, with the majority coming from 10 rivers.
- Microplastics come from synthetic clothing, tyre dust, paint, degraded plastic waste and microbeads.
- Humans consume large quantities of microplastics in drinking water and seafood.

- 1 Outline one way in which humans directly affect water availability.
- 2 List the ways in which groundwater can affect surface water.
- 3 Explain why water authorities release water for environmental flows.
- 4 Create a flow chart showing the steps in eutrophication.
- 5 Why do most of the plastics in the ocean come from a few rivers?
- 6 List the most common sources of microplastics.
- 7 How do humans consume microplastics?

CHECK YOUR UNDERSTANDING

11.3

- ▶ Most of Earth's water is in the oceans.
- ▶ Humans use the oceans for transport, fishing and recreation.
- ▶ A significant amount of saline water is found in groundwater and salt lakes.
- ▶ Most fresh water occurs as ice in the cryosphere.
- ▶ Most liquid water is groundwater.
- ▶ Sewage is wastewater that comes from sinks, showers, toilets dishwashers and washing machines.
- ▶ Sewage treatment has three main steps:
 - primary treatment removes solids
 - secondary treatment removes carbon and nutrients
 - tertiary treatment involves disinfection.
- ▶ Pharmaceuticals are not removed by sewage treatment and may damage ecosystems.
- ▶ Treated wastewater can be used for many purposes, including watering gardens, industry and firefighting.
- ▶ Stormwater is runoff from sealed surfaces that is directed into local waterways.
- ▶ Stormwater may contain sediments, leaves, oils, household chemicals, rubbish and animal waste.
- ▶ Gross pollutant traps and artificial wetlands may be used to treat stormwater.
- ▶ Industrial water may carry any sort of pollutant.
- ▶ Pulp and paper wastewater is treated by clarification and biological treatment.
- ▶ Wastewater from coal mining is treated by sedimentation, precipitation and filtration.
- ▶ Acid mineral drainage may be treated with limestone neutralisation.
- ▶ Groundwater is a vital resource that is connected to surface water.
- ▶ Over-extraction of groundwater reduces its availability for human use and dries up wetlands, rivers and lakes.
- ▶ Groundwater may be contaminated by liquids that infiltrate to the water table or are injected into aquifers.
- ▶ Environmental flows from dams attempt to reverse the damage caused by over-extraction of river water.
- ▶ Marine plastic pollution is a huge problem, with the majority coming from 10 major rivers.
- ▶ Microplastics come from synthetic clothing, tyre dust, paint, degraded plastic waste and microbeads.
- ▶ Humans consume large quantities of microplastics in drinking water and seafood.



- 1 Outline the ways in which humans use undrinkable saline waters.
- 2 Explain the effect of continued global warming on the global distribution of fresh water.
- 3 Most of Australia's water use is for agriculture. Outline the possible consequences for water quality of agricultural waste and chemicals.
- 4 Create a flow chart showing the processes and products from sewage treatment.
- 5 Justify the use of advanced tertiary treatment to remove pharmaceuticals from wastewater.
- 6 Construct a table to distinguish between the contents and treatment options for sewage, stormwater and acid mineral drainage.
- 7 Discuss the similarities between sewage treatment and industrial water treatment.
- 8 Evaluate the use of stormwater treatment devices to improve water quality.
- 9 Analyse the benefits of water recycling, using examples.
- 10 Describe the use of physical separation methods in water treatment.
- 11 Explain the advantage of reverse osmosis for treating any type of wastewater. Suggest important disadvantages.
- 12 Discuss the challenges in managing groundwater.
- 13 Is over-extraction or pollution the greater problem for groundwater? Justify your answer using named examples.
- 14 During times of drought, water volumes for the environment and irrigation are both reduced in the Murray–Darling basin. Explain the effects this reduction may have upon the surrounding ecosystem.
- 15 What human land uses make eutrophication more likely to occur?

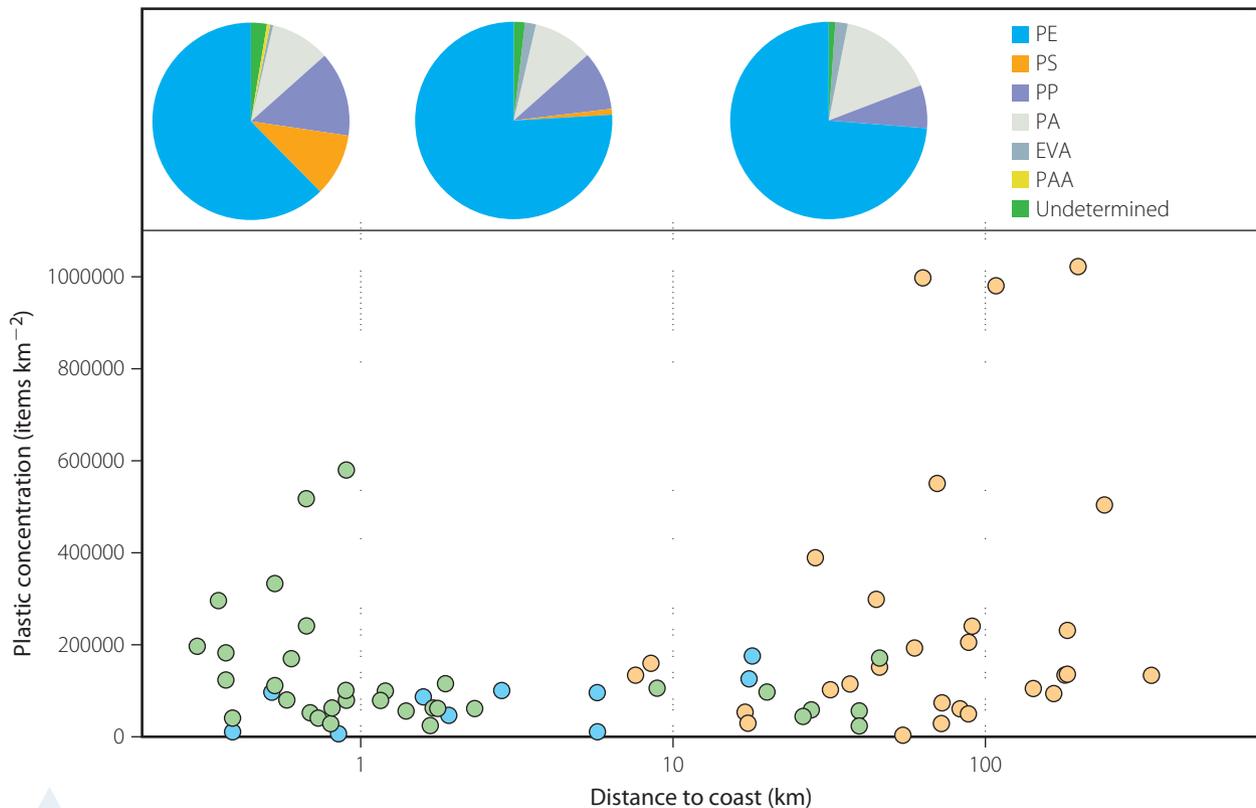
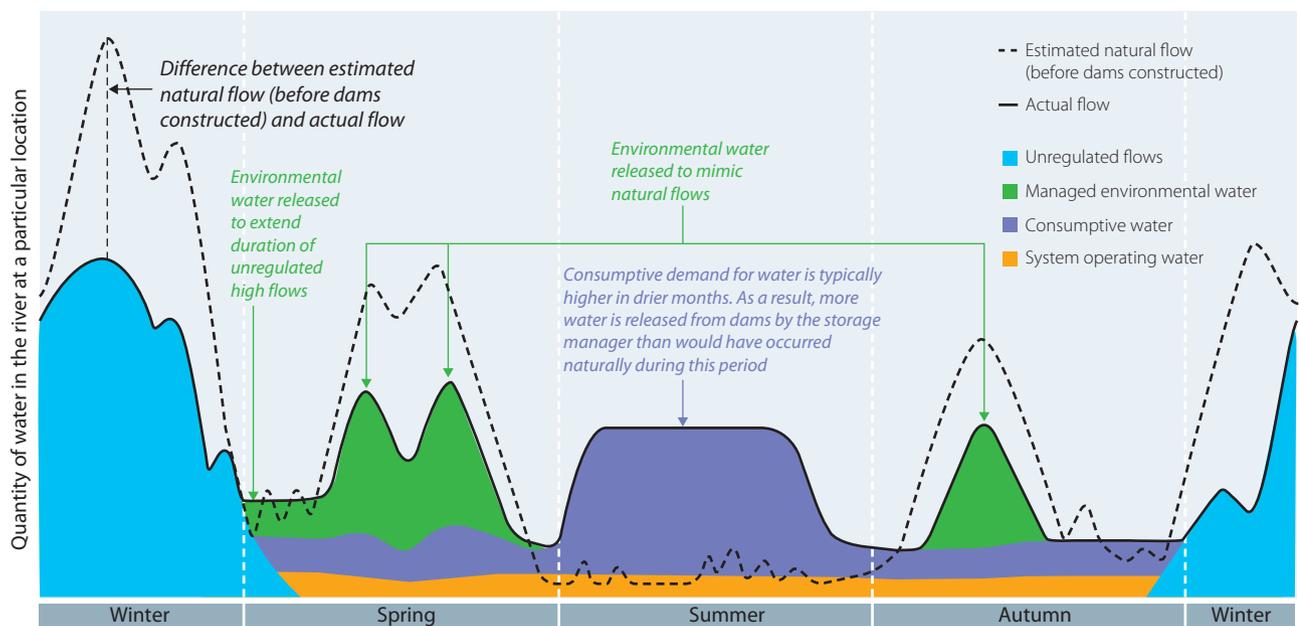


FIGURE 11.15 Concentration and composition of floating plastic debris in relation to the distance from land in the Mediterranean Sea. The pie charts show the plastic composition for each distance (<1 km, 1–10 km and >100 km). The abundance of plastics from three different studies is represented by the coloured dots.

Pedrotti ML, Petit S, Elineau A, Bruzard S, Crebassa J-C, Dumontet B, et al. (2016) Changes in the Floating Plastic Pollution of the Mediterranean Sea in Relation to the Distance to Land. *PLoS ONE* 11(8): e0161561. <https://doi.org/10.1371/journal.pone.0161561>

- 16 Most plastic found in the ocean is less than 1 cm in diameter. Assess the effects this plastic may have on marine ecosystems.
- 17 Use Figure 11.15 to answer the questions below.
 - a Which plastic is the most common pollutant, according to the pie charts?
 - b Use the pie charts at the top of Figure 11.15 to state the relationship between distance from land and plastic composition for PE (polyethylene) and PS (polystyrene).
 - c Describe the relationship between distance to the coast and plastic concentration shown by the dots.
 - d This study presents multiple samples from each distance. Explain the rationale for multiple samples based on the principles of good experimental design.
 - e Write a hypothesis for this study.
- 18 Outline three ways in which your actions can improve water quality. Identify the pollutants that will be avoided or minimised by each action.
- 19 Research by the Australia Institute in 2017 suggested that there may be 60 000 abandoned mines across Australia.
 - 20 Data summarised in 2015 from clean-ups around Australia shows that the top 8 out of 10 items recovered are plastic and 40% of coastal litter is plastic bottles. Container return schemes have been introduced in many Australian states to address this problem. Evaluate the need for and success of these schemes based upon your observations and recent data on return rates.
 - 21 The Office of Environment and Heritage (OEH) manages water in New South Wales. Figure 11.16 summarises the natural and managed water levels in a river. Use this information to answer the questions below.
 - a What time of year has the highest natural river flow?
 - b Outline the natural variation in water flow before dam construction.
 - c Why does the OEH (Office of Environment and Heritage, which manages water in NSW) release water from dams?



Graph from "What does environmental watering involve?", Victorian Environmental Water Holder, June 2015

FIGURE 11.16 OEH water management is designed to supply both human needs and the environment.

d Environmental water releases trigger an increase in plant and animal life in wetlands. Use what you have learnt in this chapter as well as Figure 11.16 to explain how water releases support wetlands directly and indirectly.

22 Use the comparative information in Table 11.4 to answer the questions below.

TABLE 11.4 Personal water use with standard or water-efficient household appliances

HOUSEHOLD APPLIANCE	STANDARD WATER USE (L PERSON ⁻¹ DAY ⁻¹)	WATER-EFFICIENT APPLIANCES (L PERSON ⁻¹ DAY ⁻¹)
Toilet	50	33
Bath and shower	50	19
Hand basin tap	10	1
Kitchen		
Tap	7	1
Dishwasher	3	2
Laundry		
Tap	5	1
Washing machine	25	10
Total	150	67

Von Weizsacker, Ernst, Hargroves, Karlson, Smith, Michael, Desha, Cheryl, & Stasinopoulos, Peter (2009) Factor Five: Transforming the Global Economy through 80% Improvements in Resource Productivity. Earthscan/Routledge, London.

- a** Replacing which standard household appliance with a water-efficient version will have the greatest effect on your personal water efficiency? Identify the appliance and calculate the yearly water savings.
- b** Calculate the difference in bathroom water use for a week with standard appliances and water-efficient appliances. What would be the total if a composting toilet that uses no water was installed?
- c** Should legislation be introduced to phase out standard taps? Justify your answer using examples of water savings and global water availability.

12 Soil

OUTCOMES

In this chapter you will learn about:

- the causes of saline soils
- rehabilitation of salt-affected areas [S ICT L AAEA](#)
- methods to prevent soil erosion [S CCT ICT](#)
- the origin and effects of soil contamination. [S ICT L AAEA](#)





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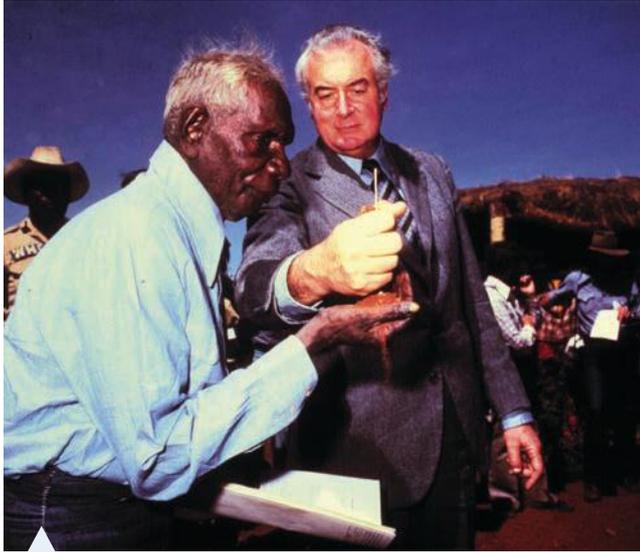


FIGURE 12.1 Prime Minister Gough Whitlam pours soil into the hand of traditional landowner Vincent Lingiari, 1975.

In 1975 Prime Minister Gough Whitlam symbolically returned Gurindji land to its traditional owners by placing a fistful of soil in Vincent Lingiari's hand (Figure 12.1). The promise of native title, represented by that handful of soil, resonated throughout Australia and the story was immortalised in Paul Kelly and Kev Carmody's song 'From little things big things grow'.

Australia's soils are some of the oldest in the world, derived from ancient and highly weathered rocks. Land management practices brought by European settlers have led to problems such as salinity and acidification. By learning the causes and consequences of land degradation, Australians have

begun to rehabilitate our precious soil so that we can preserve ecosystems, protect human health and continue producing food far into the future.

12.1 Causes of saline soils

The glacier that covered much of Gondwana 300 million years ago ground down rocks to create the last large areas of new soil on the continent. Australia is the lowest and flattest continent. The combination of these old soils and flat topography means that salts have accumulated in Australia for many millions of years. A 1.2 million km² drainage basin leads this salt inland to Kati Thanda–Lake Eyre, which is 15m below sea level, further adding to the problem.

Salt comes from a variety of sources.

- ▶ **Connate** or fossil salt was deposited in ancient oceans when sedimentary rocks were forming. Large areas of Australia were submerged during its geological history, leaving a legacy of salt-bearing rock.
- ▶ **Aeolian** or wind-blown salt is carried inland from sea spray or salt-bearing sedimentary deposits.
- ▶ Weathering of rock releases salts as minerals break down.
- ▶ Rain moves salt originally from sea spray or pollution to inland areas.

Primary salinity occurs naturally in salt lakes, salt swamps and natural salt scalds (dried salt crusts on the land). Secondary salinity occurs when human actions cause salinisation of water and/or soil.

Humans have caused secondary salinity since the advent of agriculture in Mesopotamia. Ancient Sumer was one of the first sites of wheat cultivation and one of the first places to suffer widespread **salinisation**. By 2000BCE, the ground was white with salt and the fortunes of the Sumer declined in conjunction with the fertility of the soil.

Both land clearing and irrigation can lead to salinisation, as shown in Figure 12.2. The cost of salinity

Department of Primary Industries and Regional Development



FIGURE 12.2 Dryland salinity causes plant death and salt scald in agricultural land.

in Australia is difficult to measure. In 1999, the Australian Government estimated that salinity cost Australia \$130 million annually in lost agricultural production. A 2003 study estimated annual losses at \$304 million in the Murray–Darling basin alone. This estimate included \$98 million in lost agricultural production and \$143 million to households, commerce and industry. It is estimated that \$519 million per year of agricultural production has been lost in Western Australia since 2009–10. The variability in estimates makes it clear that salinity has a significant cost to Australia that is both challenging to quantify and continuing to rise.

Dryland salinity

In natural and well-managed systems, trees and deep-rooted **perennial** (year round) vegetation use most of the water that enters the soil. Water is returned to the atmosphere through transpiration and evaporation from leaves and soil. The net movement of water from areas with vegetation is known as **evapotranspiration**, recognising the role of both processes. There is minimal run-off and infiltration, so the water table remains stable, as shown in Figure 12.3a.

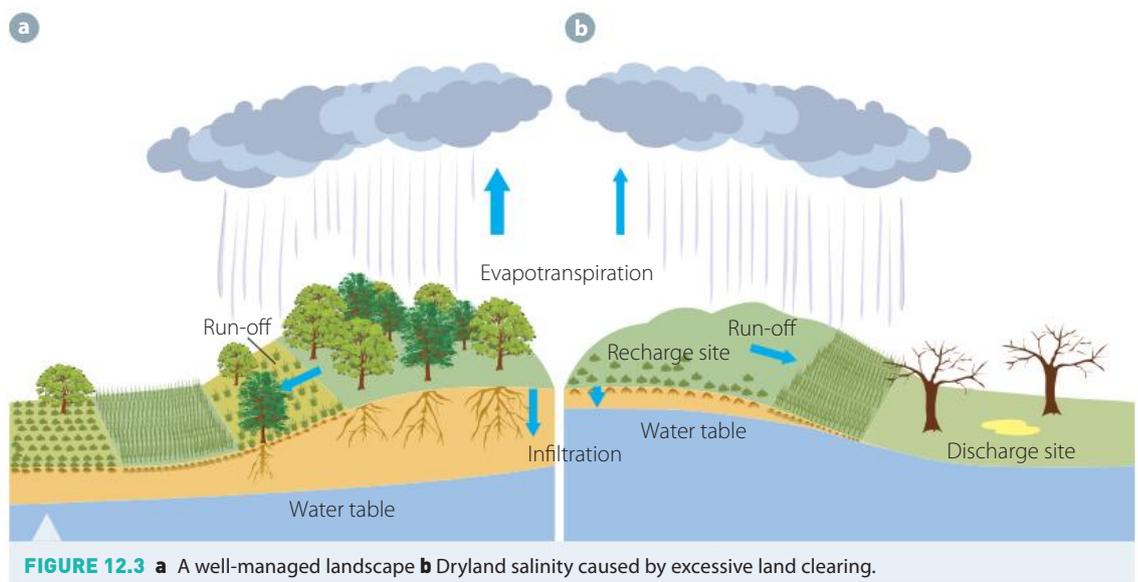


Figure 12.3b shows the changes in water balance that follow excessive land clearing. Native vegetation has been replaced by shallow-rooted annual plants, which represent most agricultural crops. This reduces evapotranspiration, increasing run-off and infiltration. As a result, the water table rises. The rising water table dissolves connate salts and brings them closer to the surface. Salinity caused by land clearing is known as dryland salinity. Land clearing at nearby mine sites can add to **recharge** (filling) of the water table.

Consequences of this salinity are that deep-rooted trees are killed when the rising saline groundwater reaches their root zone. Shrubs and herbs are affected next because they have shallower roots. The water eventually reaches the surface in discharge areas, leading to waterlogged soil and salt scalds. Only salt-tolerant species can survive in these areas and the loss of salt-sensitive plants leaves the soil vulnerable to erosion.

Saline groundwater may also mix with surface waters, causing increased salt concentrations. Saline water supplies may kill some aquatic species and contribute to the ill health of domestic and native animals that drink surface water.

The ultimate consequences of dryland salinity include decreased agricultural productivity and changes to ecosystems with a loss of biodiversity. Plant health is damaged by toxic ion levels, reduced availability of key trace elements and increased difficulty with water absorption. This is because the



increased concentration of ions in the soil compared to inside the plants' cells ultimately draws water out of the cells via **osmosis**. Soil structure is degraded by salt crystals and topsoil is lost to erosion. These changes affect large areas and are most effectively addressed with a regional approach.

Irrigation salinity

Approximately 60% of Australia's fresh water use is for irrigation. The value of Australia's irrigated agriculture for 2014–2015 was \$15 billion. (Department of Agriculture and Water Resources, 2018). However, inefficient use of this water leads to irrigation salinity.

Irrigation salinity may be caused by excessive use of irrigation water, inefficient water use, poor drainage, or seepage from irrigation channels, drains and water storages. The effect is worse if the irrigation water comes from salty sources.

Irrigated land has generally been cleared, so inefficient irrigation leads to a greater volume of water infiltration than land clearing alone. The increased volume of infiltration causes the water table to rise more rapidly, resulting in salinisation of soil and waterways. These changes affect small areas and can be effectively addressed with new irrigation methods and a community approach.

Urban salinity

Urban salinity occurs in towns and cities as a consequence of urban development. Land is cleared to build houses, roads, shops, schools and sporting facilities. Sealed surfaces are drained to local waterways, but stormwater pipes may leak water into the ground. Sewer and water supply pipes can also contribute to a rising water table. Evapotranspiration from lawns moves little water compared to areas covered in trees. Increased infiltration from grassy areas and overwatering of gardens also increase the level of the water table. Underground infrastructure may interrupt the natural flow of groundwater, causing it to accumulate. In addition, cities near agricultural lands are more susceptible to urban salinity because of dryland and/or irrigation salinity nearby.

Salinisation damages roads, underground pipes, bridges, buildings and public amenities such as sports fields and

parks. The saline water soaks into porous structures and the salt is left behind as it evaporates. This leads to structural weakness and crumbling. Figure 12.4 shows the effect of salinity upon brick structures. Public green spaces are affected by waterlogging and salt scalds.

Urban salinity results in significant maintenance costs, higher construction costs and reduced water quality. More than 200 towns in the Murray–Darling basin are at risk from urban salinity, as are areas of western Sydney.



FIGURE 12.4 Saline groundwater soaks the foundations of brick structures and evaporates, leaving salt and eventually causing the brick to crumble.

KEY CONCEPTS

- Australian soils have been accumulating salt for millions of years.
- Sources of salt include connate deposits, aeolian deposits, weathering of rocks and salt in rainfall.
- Primary salinity is a natural event. Secondary salinity results from human activities.
- Land clearing and irrigation cause the natural water table to rise, dissolving connate salts and bringing them to the surface.
- High salinity decreases agricultural productivity, degrades land and damages human structures.

- 1 Why is Australia particularly vulnerable to salinity?
- 2 Explain why Australian rocks contain connate salts.
- 3 Distinguish between primary and secondary salinity.
- 4 Why does deep-rooted perennial vegetation help to prevent salinity?
- 5 Outline the impact of soil salinity on agriculture.
- 6 Identify sources of excess water in urban areas.
- 7 Describe the effects of salinity on urban structures.

12.2 Rehabilitation of salt-affected areas

Regular monitoring is needed to determine the extent of a salinity problem and the effectiveness of rehabilitation strategies. Bore holes allow land managers to measure the depth to the water table. A piezometer may be used to measure water pressure and depth. Alternatively, a tape measure attached to a bell-shaped plover may be used. The plover is dropped into the bore hole and makes a 'plop' sound when it strikes the water surface. The depth to the water table is read from the tape measure when the plop is heard. Fox-whistle monitors are similar but make a whistling noise when they reach the water table.

Dissolved salts promote electrical conduction in soil and water. Soil-testing laboratories can determine the amount and type of salts in soil. Water samples taken from bore holes may be tested with a conductivity meter, also called a total dissolved solids (TDS) meter.

INVESTIGATION 12.1

Salinity in evaporating water

INTRODUCTION

Water used for irrigation may come from local rivers or rainfall collected in dams. The rate of water evaporation from these bodies of water is influenced by temperature and wind. As a result, Australian rivers and dams may become more saline in the summer and times of drought. This affects the suitability of the water for drinking and irrigation.

Salinity can be measured using a total dissolved solids (TDS) meter. This gives a reading in milligrams per litre (mgL^{-1}), which is the same thing as parts per million (ppm). The preferred unit is mgL^{-1} . Salinity can also be measured by electrical conductivity in units of decisiemens per metre (dSm^{-1}).

AIM

To determine the effect of evaporation on the salinity of water

HYPOTHESIS

Write a suitable hypothesis for your investigation.

MATERIALS

- Saline solution containing 0.30gL^{-1} NaCl
- 250mL beaker
- 100mL measuring cylinder
- TDS meter
- Labels



Sustainability



Numeracy



» Complete a risk assessment for your investigation.



WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

METHOD

- 1 Label the 250 mL beaker with the names of the people in your group.
- 2 Use the measuring cylinder to measure 200 mL of saline solution into your 250 mL beaker.
- 3 Use the TDS meter to record the TDS value of the saline solution for the start of your experiment (day 0).
- 4 Place your beaker in a sunny location where it can remain undisturbed for 1–2 weeks.
- 5 During each class for the next 2 weeks, record the number of days from the start of the experiment and the TDS value for your beaker.
- 6 After your final measurement, measure the final volume of liquid in your beaker and dispose of the salt solution down the sink.

RESULTS

- 1 Record your results in a carefully planned table.
- 2 Construct a graph of days versus TDS.

ANALYSIS OF RESULTS

- 1 State the relationship between evaporation time (days) and salinity (TDS).
- 2 Explain this relationship.
- 3 Calculate the evaporation rate. $\text{Evaporation rate (mL d}^{-1}\text{)} = (200 - \text{final volume}) \div \text{days of experiment}$.
- 4 What factors might speed up or slow down the evaporation rate?
- 5 Use Table 12.1 to compare the possible uses of your water at the beginning of the experiment and the end of the experiment.

TABLE 12.1 Salinity of water and suitable uses

SALINITY (mg L ⁻¹)	HUMAN USE	IRRIGATION USE	LIVESTOCK USE
0–180	Safe to drink	Safe to use	Safe for all livestock
180–480	Safe to drink	May cause leaf scorch	Safe for all livestock
480–1500	Can be drunk, but people prefer lower range	Requires special management and salt-tolerant plants	Safe for all livestock
1500–3600	Below 1800 can be consumed, but not recommended	May be used occasionally on very salt-tolerant crops	3600 is the limit for poultry and pigs.
3600–6000	Unsafe	Unsuitable	May be used for beef cattle and adult sheep
Over 6000	Unsafe	Unsuitable	Beef cattle use up to 10 200; adult sheep use up to 13 800

Adapted from Agriculture Victoria AgNote AG1402 version September 2018. © The State of Victoria Department of Economic Development, Jobs, Transport and Resources 2017. Licensed under Creative Commons 3.0

- 6 Graph your data again with an x-axis (evaporation time) extending to 30 days.
- 7 Extrapolate from your data to predict the salinity at 30 days.
- 8 Outline the possible uses for the predicted concentration of saline water at 30 days.
- 9 Rainwater in New South Wales has an average salinity of 100 mg L⁻¹. This rainwater may be collected in dams for use on farms. In drought conditions, there may not be rain for several months. Discuss the implications for farmers who must use dam water to irrigate their crops and water livestock. Refer to Table 12.1 and the results from your investigation in your answer.



» EXTENSION

Investigate the rate of evaporation in different conditions such as:

- location (windowsill, cupboard)
- air flow (different distances from a fan)
- temperature (incubator, refrigerator)
- surface area (beaker, pie plate)

Managing dryland salinity

Restoring vegetation is key to managing dryland salinity. Deep-rooted perennial vegetation planted in recharge areas will decrease infiltration of rainwater to the water table. Lines of trees between paddocks have a dual role, acting as a wind break and reducing infiltration. Alley cropping uses crops sown between belts of trees or perennial shrubs. This practice can provide shelter for crops and stock. However, alleys may prove too narrow for large machinery.

Cropping systems that incorporate perennial vegetation with annual crops can help to maintain water balance. Lucerne is a perennial pasture crop that is frequently used to manage salinity and increase absorption of rainfall. Intercropping involves sowing an annual crop into a stand of lucerne. This allows farmers to harvest a crop and still maintain perennial pasture for stock. Lucerne not only has a deep root system but is also a legume that fixes nitrogen and provides a natural boost to crop growth.

In discharge areas, salt-tolerant species are planted to preserve soil and reduce the water table. Saltbush (Figure 12.5), wheatgrass and *Puccinellia* grass are examples of perennial plants that can grow in discharge areas. During regrowth of pasture, soil should be mulched to prevent erosion. Gypsum and/or fertilisers may help new pasture to establish. Once the area is revegetated, carefully managed sheep grazing is used to maintain profit and vegetation cover.

Engineering solutions may be appropriate for some sites. Banks and subsurface drains can be used to intercept subsurface water and direct it away from the site. Groundwater may be pumped into evaporation basins if suitable areas are available.

Managing irrigation salinity

Investment in irrigation-monitoring technology allows farmers to minimise water use and avoid recharge of the water table. Automated irrigation systems can monitor soil water levels and plant uptake, adjusting the volume of water throughout the life of a crop. Improvements to soil structure will help to retain water in the plant root zone where it can be absorbed. As with dryland salinity, gypsum can be used to improve soil structure and alleviate the effects of saline water.

It is vital to choose an appropriate irrigation strategy for the local soil and crop. Flood irrigation is useful for cracking clay soil but is wasteful in high-frequency irrigation systems. Sprinklers provide good control and flexibility. However, evaporation increases the salinity of water on leaves, leading to leaf burn. Leaf burn occurs because salt prevents water absorption and accelerates water loss, leading to a dry,



FIGURE 12.5 Saltbush is a hardy plant that can be used to rehabilitate saline recharge areas and as feed for stock.

Shutterstock.com/THPStock

burnt appearance around leaf tips. Regardless of the irrigation strategy employed, regular maintenance is important to reduce loss of water through seepage.

Managing urban salinity

Catchments in urban areas need to be managed as described for dryland salinity. Within the urban area itself, large trees and shrubs not only reduce the water table but also help to reduce local temperatures and provide habitat for wildlife. Gardens and public areas should be watered only when needed. Native gardens that do not need supplementary water are easier to maintain and help restore water balance.

Leaking stormwater channels and water pipes need to be replaced with corrosion-resistant materials and stormwater systems should be designed to move water to local waterways efficiently. Septic tanks should be eliminated and houses connected to piped sewerage systems when possible.

INVESTIGATION 12.2



Sustainability



Information and communication technology capability



Literacy



Asia and Australia's Engagement with Asia

Case study of rehabilitation

AIM

To prepare a case study of rehabilitation of a salinity-affected area

METHOD AND RESULTS

- 1 Search the Internet for a report on the rehabilitation of a specific site affected by salinity. The weblinks provide some suggestions, or find information on a site of your choosing.
- 2 Prepare a summary of your case that includes:
 - site name
 - a map showing the location of your site
 - a description of land use at the site
 - the primary and secondary causes of salinity
 - an outline of the rehabilitation strategies used at the site.

DISCUSSION

- 1 Explain the type(s) of salinity affecting your chosen site and the surrounding area.
- 2 Explain the scientific basis for the rehabilitation strategies used in the area.
- 3 Evaluate the result of the rehabilitation program, including cost, ecological benefit and preservation of topsoil.

CONCLUSION

Summarise the method(s) of rehabilitation used at your site.

EXTENSION

The 2004 Aceh tsunami inundated approximately 47 000 hectares of coastal land around the Indian Ocean. Research the rehabilitation efforts coordinated by the Food and Agriculture Organization of the United Nations. How does this salinity differ in both cause and treatment to Australia's inland salinity?

Temora NSW

Brymaroo QLD

Case studies of grazing saltlands from Land & Water Australia

Wagga Wagga

- Depth of the water table and water salinity are monitored to check the progress of rehabilitation.
- It is vital to establish vegetation in both recharge and salt-affected areas.
- Engineering solutions such as drainage and evaporation basins may be useful.
- Efficient irrigation systems reduce water table recharge.
- Urban salinity is treated by appropriate planting and maintaining watertight infrastructure.

- 1 How are bore holes used to monitor ground water?
- 2 What are the advantages of planting salt-tolerant vegetation in discharge areas?
- 3 Explain why lucerne is commonly used for rehabilitation.
- 4 Identify engineering solutions that can combat dryland salinity.
- 5 How do automated watering systems help to reduce irrigation salinity?
- 6 Outline the role of vegetation in managing urban salinity.

12.3 Methods to prevent soil erosion

During the 1930s, the Great Plains of the United States lost millions of tonnes of topsoil because of excessive land clearing, drought and wind. On 14 April 1935 alone, more than 2.5Mt of topsoil was blown away in an event called Black Sunday. Known as the Dust Bowl, this period was a national tragedy that was combatted by planting 200 million trees as windbreaks and restoring native prairie grasses. Eastern Australia experienced severe dust storms in October 2002 and September 2009. The storms raised public awareness of the severity of wind erosion during drought.

Soil is a valuable resource that is renewed only slowly. The global average for soil formation is 114mm per 1000 years. However, the average rate of soil formation for New South Wales is only 10mm per 1000 years. Rates of erosion in most parts of Australia are more than 10 times the rate of soil formation.

Soil erosion is usually caused by wind and water (Figure 12.6). In agricultural fields, erosion removes the uppermost layer of soil, which is rich in organic material. The soil is washed or blown into local waterways, causing siltation and reducing water quality. Fertilisers in agricultural soil contribute to eutrophication of waterways. Pesticide residues can cause the death of aquatic organisms.

Soil erosion has affected the Great Barrier Reef. Sediments have smothered coral reef organisms and reduced light levels for photosynthesis. In addition,



Susan Filan

FIGURE 12.6 Stormwater flow has eroded this hillside, exposing deep tree roots.



FIGURE 12.7 Fertiliser and sediment run-off near the Great Barrier Reef contribute to outbreaks of the crown-of-thorns starfish. These starfish feed on coral, resulting in significant losses over time.

fertiliser run-off can lead to algal blooms and outbreaks of the crown-of-thorns starfish (Figure 12.7).

Preventing erosion in urban areas

Erosion controls vary with topography and land use. In urban areas, steep slopes and stormwater ditches are at high risk of erosion. In these locations, space constraints may mean that the only viable solution to prevent landslides is to pave water channels or build retaining walls, as shown in Figure 12.8.

Tree planting and vegetation can be used to control erosion, sometimes in conjunction with barriers, as shown in Figure 12.9. The plant roots hold the soil together. Vegetation reduces the force with which rain drops hit the soil, slows water flow and protects soil from wind. In areas with high

pedestrian traffic, it may be difficult to maintain grass cover. In these cases, mulch is an effective ground cover to preserve soil.

Soil disturbance is inevitable at construction sites. Sediments can be retained onsite by using temporary barriers, hay bales and/or sand bags (Figure 12.10). Water may be sprayed for dust control.



FIGURE 12.8 Paved stormwater channels prevent erosion.



FIGURE 12.9 Vegetation protects soil from wind and water erosion.



FIGURE 12.10 Erosion control barriers at a new road construction site

INVESTIGATION 12.3

Soil erosion field study

INTRODUCTION

Soil erosion can occur in any environment where soil is exposed to wind, water and other forms of disturbance. Hillsides are more vulnerable to erosion because gravity accelerates water run-off. Heavy pedestrian or animal traffic can wear paths into soil and rock.

AIM

To document local sites vulnerable to erosion and the methods used to control erosion

MATERIALS

- Digital camera
- Computer with access to Google Maps



WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Sunburn	Wear appropriate clothing, hat and sunscreen.
Traffic	Use footpaths and marked crossings where possible. Be aware of traffic in surroundings.
Slip, trip or fall on unstable hillsides	Choose pathways carefully in areas at high risk for erosion. Avoid loose surfaces such as gravel.



What other risks are relevant to your local area? How will you manage these risks?

METHOD

- 1 Find your school or home on Google Maps. Zoom in so that you can see buildings and features well in satellite view.
- 2 Clip or copy an image of the local area and create a document with this map at the centre. Predict which areas may be vulnerable to erosion.
- 3 Walk around your school campus or neighbourhood looking for areas (at least three sites) where erosion may occur. You may find it helpful to take a printed copy of your map.
- 4 Label each erosion site on your map and take a photograph showing the erosion and/or prevention measures. Note the risk factors that you identified in choosing each site.
- 5 Identify the local waterway to which stormwater is diverted.

RESULTS

- 1 Create an A3 poster featuring the map and your photos illustrating the labelled erosion sites.
- 2 Construct a summary table with the site, risk factors and erosion control methods (if any). Display the table with your poster.

ANALYSIS AND DISCUSSION

- 1 Explain why the sites you documented are at risk of erosion.
- 2 Evaluate the effectiveness of erosion controls in your area.
- 3 Analyse other options for erosion control at two sites in your area.
- 4 Speculate upon the amount of sediment that may be washed into the local waterway during heavy rainfall. »



CONCLUSION

Summarise the causes and controls for erosion in your local area.

EXTENSION

Research erosion control regulations for construction sites in your local government area.

Preventing erosion on agricultural land



Fixing fantasy farm

Tree planting and deep-rooted perennial plants combat both salinity and erosion in Australia's agricultural areas. Vegetation significantly reduces run-off of water and subsequent erosion. Experiments near Ipswich, Queensland, showed that land with only 6% vegetation cover had 70% of rainfall run-off and a soil loss of 22 t ha^{-1} . When 87% of the land was covered, only 3% of rainfall ran off and soil loss was reduced to only 0.03 t ha^{-1} (Table 12.4 on page 322).

Heavy grazing and tracking by animals can reduce vegetation cover and lead to erosion. Stock rotation involves periodically moving grazing animals to different areas, allowing vegetation to recover and regrow. Farmers may also fence high-risk areas such as steep hills and creeks to exclude stock. These areas are easily destabilised by the hard hooves of cattle and sheep.

Control of pest animals is vital. Feral goats graze areas intensively, leaving bare, trampled soil that is easily eroded. Rabbits not only graze intensively, but also dig burrows that cause erosion and ground collapse. You will learn more about damage done by rabbits in Chapter 13.

Tillage, when soil is turned over and left bare, kills weeds and loosens soil. However, tillage also leaves soil vulnerable to erosion. More than 70% of Australian pasture and crop land is not tilled. Herbicide is used for weed control and new crops are sown in the stubble of the previous crop, as shown in Figure 12.11.

Contour ploughing, strip cropping and controlled traffic farming are used in addition to soil cover. For contour farming, rows of crops are planted across the slope of the land. This disrupts run-off and increases water infiltration, thus decreasing erosion.

Strip cropping involves creating alternating strips of different crops or of crops and grass across a floodplain or slope. This practice ensures that there is always soil cover and always a crop in the growing phase. The plants slow water flow, trap sediment and protect the soil from wind.

Controlled traffic farming establishes permanent wheel tracks called tramlines. As Figure 12.12 shows, most of the field is used for plant growth, but a small area is compacted by wheels. Water erosion is reduced because of increased infiltration in

areas covered by vegetation. The compacted tramlines reduce tyre resistance and slip compared to bare soil. This, in addition to preventing erosion, results in fuel savings of up to 25%.



FIGURE 12.11 Corn planted in stubble of the previous crop



FIGURE 12.12 Tramlines visible in a wheat field

INVESTIGATION 12.4

Preventing soil erosion

AIM

To compare the effectiveness of different types of ground cover in preventing erosion

HYPOTHESIS

Write a suitable hypothesis for your investigation.

MATERIALS

You will use three bottles like those shown in Figure 12.13. Construct a materials list for your investigation. Consider how you will measure the effectiveness of erosion controls. Make sure you identify quantities of each material that you need.

Complete a risk assessment for your investigation.



FIGURE 12.13 Bottles prepared for experiment with closed ends elevated.

Susan Flinn



Sustainability



Critical and creative thinking

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?

HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?



METHOD

Construct a method to test your hypothesis.

RESULTS

Record both quantitative and qualitative observations in a carefully planned table.

DISCUSSION

- 1 Identify the independent, dependent and controlled variables in your experiment.
- 2 Evaluate the validity and reliability of your results.
- 3 Discuss your results, with particular attention to the volume of run-off and the amount of sediment.
- 4 Look back to Investigation 12.3. What do your results indicate about the effectiveness of erosion controls in your local area?
- 5 Assess your results in comparison to the trial of vegetation cover in Queensland (page 316).

CONCLUSION

Summarise your findings about erosion prevention.

KEY CONCEPTS

- Australian soils are being eroded more quickly than they are formed.
- Erosion by wind and water removes topsoil that is rich in organic material.
- Sediments, pesticides and fertilisers from eroded soils have negative impacts on waterways.
- Erosion can be prevented by vegetation or ground cover.
- Stock management and control of feral animals help maintain vegetation.
- Minimal tillage, contour ploughing, strip cropping and controlled traffic farming all reduce erosion of agricultural land.

CHECK YOUR UNDERSTANDING

12.3

- 1 Identify the strategies used to rehabilitate the Dust Bowl areas in the United States.
- 2 What are the main causes of erosion?
- 3 Outline the impacts of erosion on waterways.
- 4 Describe the types of areas at greatest risk for erosion in urban areas.
- 5 Explain the role of vegetation in reducing erosion.
- 6 Outline the benefits of controlling domestic and feral animal grazing on farms.
- 7 Why have many Australian farmers adopted no-till farming?
- 8 Explain how controlled traffic farming can reduce erosion.

12.4 Origin and effects of soil contamination

Soil contamination is an enormous and poorly quantified problem. The Food and Agriculture Organization of the United Nations has tried to quantify the extent of the problem. Approximately 80 000 sites in Australia, 3 million sites in Europe and 16% of soils in China are thought to be contaminated. Contamination is mainly caused by human activity. Common sources of contamination include:

- industrial activities such as mining, smelting and manufacturing (Figure 12.14)
- waste from households, businesses and livestock
- wastewater leaching from landfill, mines or sewage treatment
- deposition of airborne pollutants
- agricultural herbicides, pesticides and fertilisers
- petroleum products released into the environment
- exhaust from transportation
- e-waste from old electronics
- pharmaceuticals and biological pollutants
- plastics.



FIGURE 12.14 Soil pollution around a copper mine

Pollutants from soil can enter the human body in a variety of ways: absorbed through the skin, inhaled in soil-containing dust, absorbed by food crops and eaten, or dissolved in water and consumed. Many organic compounds persist in the environment for long periods of time. One example is the pesticide DDT, which was banned in most developed countries in response to **biomagnification** and ecosystem collapse. It has been implicated in human preterm births and autism. DDT is known to disrupt the endocrine system of birds, but effects on the human endocrine system are unclear.

The World Health Organization's top ten chemicals of public health concern are mercury, lead, fluoride, cadmium, arsenic, dioxin, hazardous pesticides, asbestos, benzene and air pollution. All may contaminate soil and they are rarely found in isolation. Thus, investigating the impact of any single substance is difficult. Known health effects of soil pollutants include cancers (arsenic, asbestos, cadmium, dioxins), lower IQ (lead, arsenic), nerve damage (mercury, lead, arsenic), kidney disease (lead, mercury, cadmium) and bone disorders (lead, fluoride, cadmium).

Fluoride is added to the water supply to help prevent tooth decay but it is damaging to bones and teeth at slightly higher concentrations.

INVESTIGATION 12.5

Investigating local soil contamination

INTRODUCTION

The NSW Environmental Protection Agency keeps a record of contaminated land that requires regulation on account of possible health or environment risks. The most common reasons for land contamination are sites that have been used for chemical storage, such as petrol stations and dry cleaners, or heavy industrial areas where chemical manufacture has occurred. The register includes only sites that have had an EPA notice and excludes large-scale contamination such as that at mine sites.

AIM

To identify local areas of soil contamination and the possible effects of this contamination

METHOD

- 1 Go to the weblink NSW EPA Contaminated Land Record of Notices.
- 2 In the Search 1 box, choose the name of your local council in the LGA box.
- 3 Press the Search button. If no sites are listed for your council area, search for notices in a neighbouring area.
- 4 Observe the types of sites listed, for example petrol station, dry cleaner, gasworks.
- 5 Click on the link to one of the local sites.
- 6 Click on the notice number for a Declaration of Significantly Contaminated Land.
- 7 Copy Table 12.2 and use it to record the nature of the contamination (point 2 in the report) and the nature of harm the contamination might cause (point 3 in the report).
- 8 Repeat the process for another site in your local area.
- 9 Search for health risk information about one of the contaminants in your local area. A good starting place is the weblink Department of Health's National Industrial Chemicals Notification and Assessment Scheme.

RESULTS

TABLE 12.2 Local soil contamination

LOCAL GOVERNMENT AREA	
SITE NAME	
TYPE OF SITE	
NATURE OF CONTAMINATION	
HARM IT MAY CAUSE	

Outline the health dangers of one chemical found at a contaminated site in your local area.

ANALYSIS AND DISCUSSION

- 1 What type of contaminated sites occur in your local area?
- 2 Does the contaminant you researched pose a threat to human health, the environment or both?
- 3 Explain why the contaminant you researched would be associated with the type of site where it is found.
- 4 Identify an unreported site in your local area that may have contaminated soil. Predict the type of contamination based on the type of site.

CONCLUSION

Summarise the sources and possible effects of soil contamination in your local area.

EXTENSION

Sydney's Homebush Bay and Rhodes Peninsula were the subject of a 25-year cleanup after closure of the Union Carbide factory. Research the steps that were taken to reclaim this area and evaluate the result of the cleanup.



NSW EPA Contaminated Land Record of Notices



Hazardous Chemical Information System

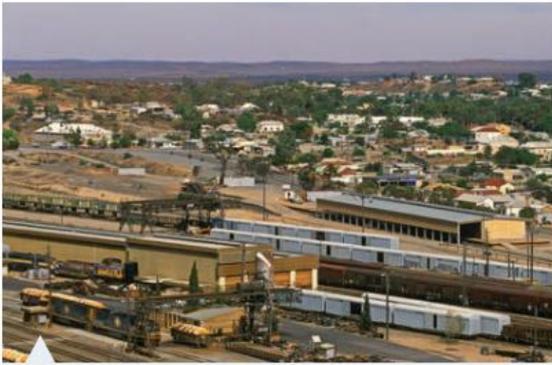


FIGURE 12.15 The town of Broken Hill has grown around one of the world's richest deposits of silver, lead and zinc. Past and present mining have resulted in hazardous levels of lead in dust throughout the town.

Heavy metals in soil

A variety of elements with metallic properties are called 'heavy metals' when discussing health impacts. This is not a scientific description, since arsenic is a metalloid. The soil contaminants known as heavy metals include arsenic, lead, cadmium, chromium, copper, mercury, nickel and zinc.

Lead is the world's largest single soil contaminant as a result of its use in industry, leaded petrol, lead-based paint, lead mining and smelting. Lead from mining is a major hazard in Broken Hill (Figure 12.15). Effects of acute short-term exposure include nausea and vomiting, muscle pain, fatigue and seizures. Long-term effects of lead include anaemia, kidney disease, nerve damage and impaired brain development.

Arsenic has been used in pesticides and as a wood preservative. It can naturally concentrate in drinking water and is taken up by rice that is irrigated with water containing arsenic. Acute exposure may cause nausea, vomiting, diarrhoea, brain dysfunction, altered heart rhythm and nerve pain. Long-term exposure may lead to skin changes, diabetes and cancer.

Cadmium is frequently released by smelting of iron, lead and copper ores. It is the most common heavy metal contaminant in China's soils and, like arsenic, it may be taken up by plants and consumed by people. Short-term exposure can cause lung inflammation. Chronic exposure may result in lung cancer, kidney damage and softening of the bones.

INVESTIGATION 12.6

Sustainability

Information and communication technology capability

Literacy

Asia and Australia's engagement with Asia

Numeracy

Heavy metal pollution in the Asia–Pacific region

INTRODUCTION

Pollution accounts for 16% of deaths worldwide. In China, approximately 20% of agricultural soil is contaminated. Cadmium, nickel and arsenic in areas with heavy industry are China's most common soil pollutants. Lead from leaded petrol and paints contaminates the soil of Australia's major cities. Up to 40% of Sydney's gardens have dangerous lead levels, particularly in older suburbs. Mining areas such as Broken Hill (New South Wales) and smelting sites such as Port Pirie (South Australia) have high levels of lead-containing dust. Lead is especially dangerous for children because it interferes with brain development.

AIM

To explore the impact of lead contamination of soil in Australia and the Asia–Pacific region

METHOD

- 1 Use the weblink provided or other sources to find data on deaths from lead exposure for at least four countries in the Asia–Pacific region.
- 2 Copy Table 12.3 and use it to record your findings. Some data is included for you.
- 3 Record the GDP and deaths due to lead exposure for each of your chosen countries.
- 4 Look up and record the population of each country in millions.
- 5 Calculate the total deaths attributed to lead for each country.
- 6 Make a graph of GDP against deaths (per million).
- 7 Make another graph of GDP against total deaths.

Global Alliance on Health and Pollution world map

Turn on Pollution Deaths, then go to Settings and choose Pollution type: Soil.

» RESULTS

TABLE 12.3 National data and deaths due to lead

COUNTRY	GDP (US\$ PER CAPITA)	DEATHS DUE TO LEAD (PER MILLION)	POPULATION (×1000 000)	TOTAL DEATHS DUE TO LEAD (= DEATHS × POPULATION)
Australia		97		
China				64 837
Indonesia		66		
Malaysia				537

ANALYSIS OF RESULTS

- 1 Describe the relationship (if any) between GDP and deaths per million due to lead exposure.
- 2 Describe the relationship (if any) between GDP and total deaths due to lead exposure.
- 3 Identify significant outliers in each of your graphs and explain why they are outliers.

DISCUSSION

- 1 Discuss the relationship between the GDP of a country and deaths from lead exposure.
- 2 What factors besides GDP might affect lead exposure in a country?
- 3 Leaded petrol was sold in Australia from 1932 to 2002. This was the largest source of atmospheric lead pollution in the southern hemisphere. Explain how the use of leaded petrol may affect lead exposure deaths.
- 4 The data provided in Table 12.3 are from 2015. Justify which values you would expect to change and which you would expect to stay much the same.

CONCLUSION

Summarise the impact of lead exposure on deaths in Australia and the Asia–Pacific region.

EXTENSION

Mining areas such as Broken Hill (New South Wales) and smelting sites such as Port Pirie (South Australia) have high levels of lead-containing dust. Choose one of these cities and research the main way people are exposed to lead. Summarise the health effects of lead and explain why lead is particularly dangerous to babies and young children. Describe what public health measures are being undertaken to reduce the risk to the population of your chosen city.



LeadSmart

KEY CONCEPTS

- Soil contamination is a global problem that is caused by human activity.
- Multiple substances may contaminate soil, including pesticides, heavy metals and plastics.
- Soil pollution can cause cancer, low IQ, nerve damage, kidney disease and bone disorders.
- The so-called ‘heavy metal’ pollutants include lead, cadmium, chromium, copper, mercury, nickel, zinc and arsenic, a metalloid.
- Lead is the greatest single soil pollutant in the world.
- Arsenic and cadmium can be absorbed by plants and eaten, resulting in cancer and other health problems.

- 1 What are some examples of substances that you use that may cause soil pollution?
- 2 How does soil pollution enter the human body?
- 3 Summarise the human health effects caused by soil contamination.
- 4 List the World Health Organization’s top ten chemicals of public health concern.
- 5 Identify sources of heavy metal soil pollution.

CHECK YOUR UNDERSTANDING

12.4

12 CHAPTER SUMMARY

- Australian soils have been accumulating salt for millions of years.
- Sources of salt include connate deposits, aeolian deposits, weathering of rocks and salt in rainfall.
- Secondary salinity results from human activities.
- Land clearing and irrigation cause the natural water table to rise, dissolving connate salts and bringing them to the surface.
- High salinity decreases agricultural productivity, degrades land and damages human structures.
- Water table depth and water salinity are monitored to check the progress of rehabilitation.
- It is vital to establish vegetation in both recharge and salt-affected areas.
- Engineering solutions such as drainage and evaporation basins may be useful.
- Efficient irrigation systems reduce water table recharge.
- Urban salinity is treated by appropriate planting and maintaining watertight infrastructure.
- Australian soils are being eroded more quickly than they are formed.
- Erosion by wind and water removes topsoil, which is rich in organic material.
- Sediments, pesticides and fertiliser from eroded soils have negative impacts on waterways.
- Erosion can be prevented by vegetation or ground cover.
- Stock management and feral animal control help to maintain vegetation.
- Minimal tillage, contour ploughing, strip cropping and controlled traffic farming all reduce erosion of agricultural land.
- Soil contamination is a global challenge caused by human activity.
- Multiple substances may contaminate soil, including pesticides, heavy metals and plastics.
- Soil pollution can cause cancer, low IQ, nerve damage, kidney disease and bone disorders.
- The so-called 'heavy metal' pollutants include lead, cadmium, chromium, copper, mercury, nickel and zinc and arsenic, a metalloid.
- Lead is the greatest single soil pollutant in the world.
- Arsenic and cadmium can be absorbed by plants and eaten, resulting in cancer and other health problems.

12 CHAPTER REVIEW QUESTIONS



- 1 Irrigation salinity occurs most frequently in areas that have been cleared for the planting of annual crops. Assess the likelihood of irrigation salinity in an orchard that is irrigated.
- 2 Explain why ancient Mesopotamia was so drastically affected by salinity.
- 3 A town in the Murray–Darling basin is affected by urban salinity. Propose three steps the town council can take to reduce the salinity in their area.
- 4 Create a table comparing four aspects of dryland, irrigation and urban salinity.
- 5 The Australian Government has provided communities with grants to plant 20 million trees by 2020. Justify the program benefits for soil quality and preservation.
- 6 A school in the Blue Mountains is building a new multipurpose hall on a sloping site. Justify two strategies that may be used to control erosion during construction.
- 7 Farming of root vegetables requires soil disturbance for harvest. Explain one method of minimising erosion on farms that grow root crops.

- 8 The amount of erosion was measured at three sites at Mt Mort near Ipswich, Queensland, after a storm dumped 54 mm of rain. The results are shown in Table 12.4.

TABLE 12.4 Erosion after a storm in Mt Mort, Queensland

SITE	A	B	C
VEGETATION COVER (%)	87	69	6
TOTAL RUNOFF FROM STORM (mm)	1.5	14	38
RAINFALL THAT RAN OFF (%)	3	26	70
SOIL LOSS (t/ha)	0.03	0.3	22
DEPTH OF SOIL LOST (mm)	0.002	0.02	1.7

© The State of Queensland 2018

- a If the soil formation rate on Mt Mort is 30 mm per 1000 years, calculate the number of years required to replace the soil lost at each site in this storm.
- b Heavy rains like this are likely to happen at least once per year. Recommend a soil management strategy for farmers in Mt Mort.

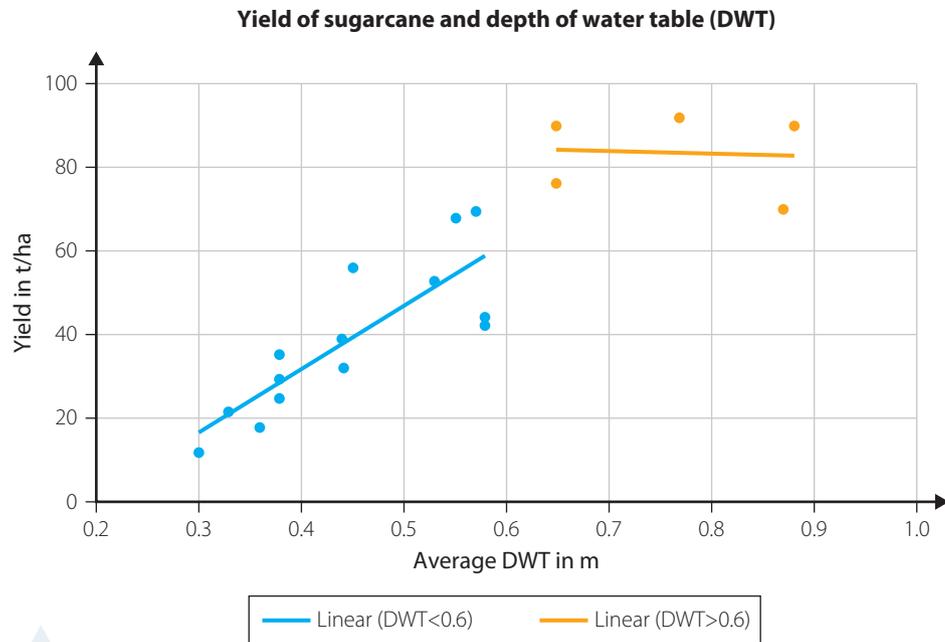


Figure. Overview of economic activities causing soil contamination in some WCE and SEE countries (pct. of investigated sites). Created 12 November 2009, The European Environment Agency (EEA)

FIGURE 12.16 Relationship between depth of water table in metres (m) and sugarcane yield in tonnes per hectare (t/ha)

- 9 Figure 12.16 shows the relationship between sugarcane yield and water table depth, based upon studies in Queensland.
 - a Describe the trend in the graph.
 - b Identify the minimum water table depth that will provide maximum sugar cane yield.
 - c A sugarcane farmer notices that the water table has risen from 0.8m below surface last year to 0.7m this year. Evaluate the possible outcomes in the next five years if no action is taken to address the rising water table.
- 10 Lead is the most widespread soil contaminant worldwide.
 - a Explain why lead pollution is so common.
 - b Predict the human health effects that would be observed in areas of higher lead contamination.
- 11 Why can soil pollutants be found far from where they were produced or released?
- 12 Discuss the difficulty in proving that a soil pollutant causes a specific human health problem.
- 13 The VegeSafe program run by the Environmental scientists at Macquarrie University, offers low-cost soil testing for heavy metals. What advantage is there to knowing about contamination in soil around your home?
- 14 Figure 12.17 shows causes of soil contamination in Europe.
 - a Use information in the graph to determine how much soil pollution is the result of waste treatment, disposal and storage.
 - b Calculate the percentage of soil pollution attributable to industry.
 - c Discuss the risk and benefit of reducing industrial production to reduce environmental contamination.

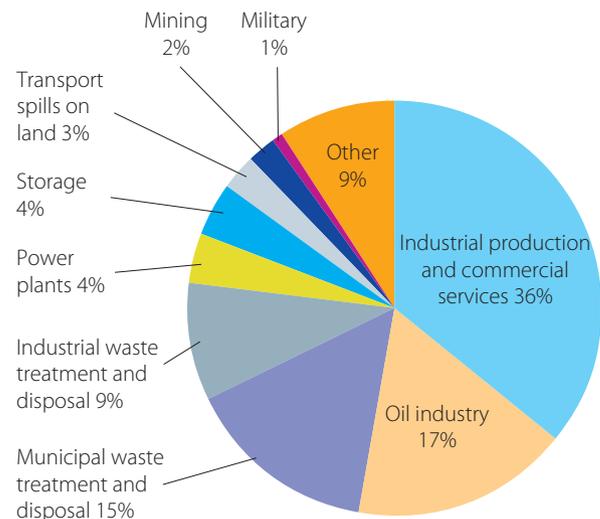


FIGURE 12.17 Causes of soil contamination in Europe as determined by the European Environment Agency

Figure. Overview of economic activities causing soil contamination in some WCE and SEE countries (pct. of investigated sites). Created 12 November 2009, The European Environment Agency (EEA)

- 15 Soil formation in Java, Indonesia, occurs at approximately 110mm year^{-1} . Many agricultural areas are on volcanic slopes. Farmers grow rice and other crops, sometimes harvesting three crops per year, using natural rainfall. More than 70% of agricultural areas in central Java have a high or very high erosion hazard rating.
 - a Outline factors that may affect Java's vulnerability to salinisation.
 - b Describe the factors that may influence erosion in Java.
 - c Is salinity or erosion likely to be the greater risk in Java? Justify your answer.
 - d Contrast key factors influencing soil management in Java with those in New South Wales.

16 Phytoremediation is the use of plants to absorb soil pollutants. In 2001, researchers noticed that the Chinese brake fern absorbs arsenic from soil. Figure 12.18 shows their data for the concentration and location of the arsenic in plant tissues.

- a** Where in the fern is the arsenic concentrated?
- b** Based upon this data, propose an optimal harvest time to gain maximum arsenic removal in the shortest time.
- c** Assess the effectiveness of planting brake fern to facilitate phytoremediation in areas contaminated by arsenic.

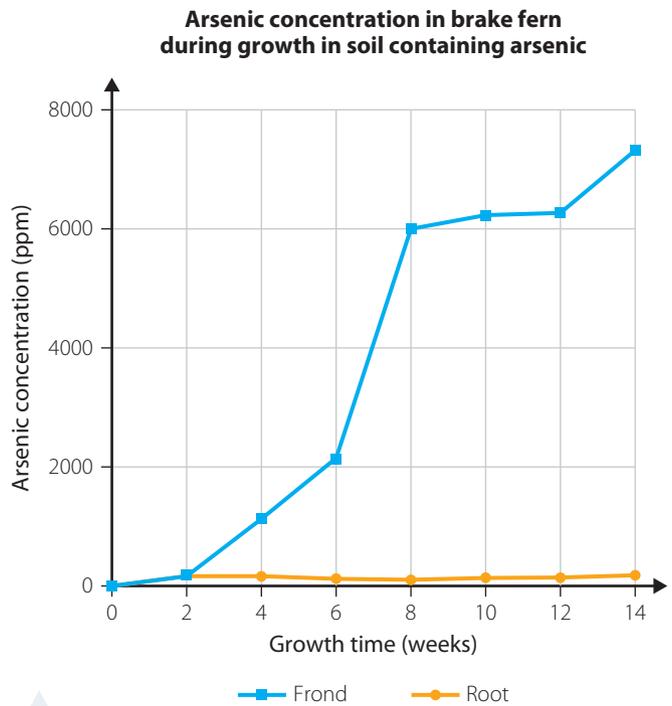


FIGURE 12.18 Arsenic concentration in brake ferns grown in soil containing 97 parts per million (ppm) of arsenic

FROM CONTAMINATION TO BEAUTIFICATION: FERNS REMOVE ARSENIC FROM SOIL FOR STUDENTS p. 2. <https://fcit.usf.edu/florida/teacher/science/mod1/resources/fern-student.pdf>, The Florida Center for Instructional Technology, fcit.usf.edu

13 Introduced species

OUTCOMES

In this chapter you will learn about:

- the abiotic and biotic effects of introduced species
- how to plan and carry out an investigation about an introduced species in your local area in relation to: **CCT EU ICT N DD**
 - why the species was introduced
 - the effects of the introduced species on the living and non-living environments
 - how the introduced species affected the area in which it was living
 - how humans have contributed to the successful survival of introduced species
 - controlling introduced species
 - the cost of introduced species on the economy
 - different viewpoints about the introduced species **ATSIHC IU**
- the ways that human activities can favour introduced species and disturb the ecological balance of natural systems **S CCT EU**
- the ways that introduced species contribute both directly and indirectly to the decline and extinction of native species. **S CCT CC WE**





The red fire ant (*Solenopsis invicta*) is native to South America, where it has many natural predators including armadillos, antlions and horned lizards. The first sighting of a fire ant in Australia was in Brisbane in 2001, where it is thought to have arrived via a shipping container from America (Figure 13.1). In 2014, red fire ants were discovered at Port Botany but were quickly contained.

Fire ants are one of the most **invasive species** and have a very painful sting. In severe cases they can cause anaphylactic shock and death. They have no natural predators in Australia and are known to swarm over and feed on small native animals such as frogs, insects, mammals and birds. Their predation of native species removes pollinators from the ecosystem, disrupting food chains and food webs. Since 2001, several million dollars has been spent on unsuccessful attempts to eradicate red fire ants from Australian ecosystems.

Red fire ants are an example of an accidentally **introduced species**. There are many examples of species that have been deliberately introduced by humans into Australia.



istockphoto.com/thamepic

FIGURE 13.1 The red fire ant (*Solenopsis invicta*) was introduced into Australia in 2001.

13.1 Effects of introduced species

The **environment** is the physical component of the ecosystem, such as the rocks and sand in the desert or the water in a lake. An **ecosystem** is the non-living and living components and their interactions; for example, a lake includes the fish, the plants, the water and all the interactions between them. Both the environment and ecosystem are affected by abiotic and biotic factors. **Abiotic** factors refer to non-living things such as the pH of the soil and the temperature and turbidity of the water. **Biotic factors** involve the living or once-living part of an ecosystem, such as animals feeding on plants, fungi decaying logs and bacteria breaking down dead animal tissue. Introduced species in Australia have had effects on both the biotic and abiotic factors of Australian ecosystems.

Terrestrial ecosystems

Terrestrial ecosystems are those that occur on land; for example, a desert ecosystem or a rainforest ecosystem.

Introduced plants

Many **exotic species** of plants have been introduced into Australian terrestrial ecosystems. Many of these were grass plants introduced to provide food for the early European settlers, such as wheat, oats and rye, originally from the Middle East (Figure 13.2). Sorghum, a type of cereal used for stock feed, is from north Africa. Maize and rice, two other types of grass cultivated in Australia, originated in America and Asia respectively. Most of the fruit trees in Australia, such as apples, oranges, pears and lemons, have come from Europe, Asia or North America. Plants are also introduced for building materials, such as radiata pine (*Pinus radiata*) from California, where it is known as the Monterey pine.

Abiotic effects of introduced plants

Introduced fruit and ornamental plants have specific nutrient and mineral requirements for optimal growth. Most Australian soils have very low levels of nutrients; the exception is soils in the eastern third of the country where there have been basaltic eruptions in the last few million years. Humans have adjusted nutrient levels to suit exotic plants by the addition of nitrogenous and phosphorus fertilisers. Native plants that are well adapted to the low nutrient levels in soils can be adversely affected by changing the nutrient levels.

Leaf litter dropped from introduced plants has been shown to alter soil chemistry significantly. Radiata pine forests cover vast regions in the eastern third of New South Wales and Victoria. Pine trees continually drop their needles (Figure 13.3) and the breakdown of these acidifies the soils and water runoff into local creeks.

Biotic effects of introduced plants

In addition to soil chemistry, introduced plants can outcompete their native counterparts in a variety of ways. Introduced plants such as *Lantana camara* grow in dense thickets at much faster rates than many native species (Figure 13.4). The result of this growth is that sunlight is blocked from reaching the ground so that low-growing natives in the understorey have little chance of survival.

Many introduced plants have shallow root systems, enabling dense concentrations of introduced plants to take ready advantage of available soil water, depriving natives with mostly deeper roots of this necessary resource. This not only affects the plants, but also the animals that depend on those plants.

Prickly pear

The most famous introduced plant species in Australia is the prickly pear (genus *Opuntia*). The prickly pear infestation of Australia began in 1822, when Dr William Bell Carlyle acquired the American cactus on a stopover in India and brought it in as a pot plant. He used the prickly pear as fences on his property



FIGURE 13.2 Wheat fields now cover areas once covered by native plants.

Shutterstock.com/tolajla



FIGURE 13.3 Pine needles dropping from pine tree plantations affect the pH of soils and nearby waterways.

Shutterstock.com/Brian S



FIGURE 13.4 *Lantana camara* grows in dense clumps, shading out native understorey plants.

Shutterstock.com/Alex Farias



Prickly pear control

Watch this silent 1926 newsreel about early attempts to control the prickly pear.



FIGURE 13.5 The characteristics of the prickly pear made it appear an ideal living fencing material in early Australia.



FIGURE 13.6 Hard-hoofed sheep compact the soil. Compare the grass growing outside the fence to that in the paddock.



FIGURE 13.7 Ground disturbance around the entrance to a rabbit warren.

near Scone, New South Wales. It was such a success as a fence that he gave cuttings to his neighbours and friends. In less than 100 years the prickly pear had spread to cover 24 million hectares of Australia (Figure 13.5).

Conditions in that part of Australia are ideal for prickly pears and they quickly flourished, outcompeting native plants for space and water. Prickly pear seeds are spread by birds, which eat the fleshy fruits and deposit the seeds far and wide in their droppings. This leads to infestation of pasture crops and subsequent economic costs.

Many methods of biological control were trialled to reduce the numbers of the prickly pear, including the introduction of 18 insect species into Australia. The most successful was another introduced species, the Argentinian stem-boring moth *Cactoblastis*, whose larvae eat the cactus plant. It was so successful that millions of hectares of previously infested land were returned to grazing.

Introduced animals

The addition of stock to Australia also has a large impact on native plants. Before 1788 there were no hard-hoofed **herbivores** in Australia. Native Australian herbivores such as the kangaroo and wallaby have soft feet that do not disturb the fragile soil structure.

Abiotic effects of introduced animals

Soil crusts are formed by lichens, mosses, liverworts, algae and fungi in the first 4mm of soil. The crusts are important in stabilising the soil, preventing erosion and evaporation, fixing nitrogen and assisting with water filtration. The First Fleet arrived in 1788, bringing cows, horses, sheep and goats. Hard-hoofed animals such as these break up the soil crusts, leading to water and wind erosion and loss of nutrients. This is further exacerbated by soil compaction in many areas.

Soil is made up of minerals, organic matter, water and air spaces. Oxygen and water need to move through the air spaces to the root cells of plants. Compaction of the soil reduces the size of the air spaces, thereby reducing the movement of oxygen and water in the soil. This, as well as harming plants, leads to increased water runoff and erosion of the soil surface down to many centimetres. Soil compaction also affects the germination rates of seeds through lack of water and oxygen movement into the soil (Figure 13.6).

Another introduced species, the rabbit, favours land with sandy soil so they can dig their warrens (Figure 13.7). This sandy soil that has been excavated is easily eroded by wind and rain. Rabbits eat vegetation down to ground level, further exposing the sandy soils to erosion as a secondary effect. In regions of heavy rabbit infestation, eroded soil runs into creeks and rivers, which suffer from significant siltation as a result.

INVESTIGATION 13.1

Soil compaction and water infiltration

AIM

To investigate the effect of compaction of soil on the rate of infiltration of water

MATERIALS

- 2 × 250 mL beakers
- 2 × 100 mL measuring cylinders
- 2 retort stands
- Bosshead and clamp
- 2 large filter funnels
- Filter paper to fit funnels
- Plastic spoon
- 200 mL water
- 2 stopwatches
- Electronic balance
- 100 g soil
- Disposable gloves
- Facemask
- Small container to compress soil (such as a 50 mL beaker)



Numeracy



Information and communication technology capability

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Soil contains microbes that could make you ill.	Wash your hands at the end of this investigation. Wear gloves and a face mask when handling soil.
Glassware can break and cause cuts.	Take care when handling glassware and do not leave it near the edge of the bench. If breakages occur, inform your teacher.



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

METHOD

- Set up the apparatus as shown in Figure 13.8 twice so you have two identical sets of equipment.
 - Place a filter paper in a filter funnel.
 - Using the bosshead and clamp, attach the filter funnel to the retort stand.
 - Place a beaker under the filter funnel.
- Place approximately 50 g soil in a weigh boat and measure its mass using the electronic balance.
- Place the soil in one of the filter funnels.
- Repeat for the other 50 g of soil, placing it in the other filter funnel.
- Using the provided container, carefully compress one of the soil samples in the funnel.
- Measure 100 mL of water into each of two measuring cylinders so each contains 100 mL water.

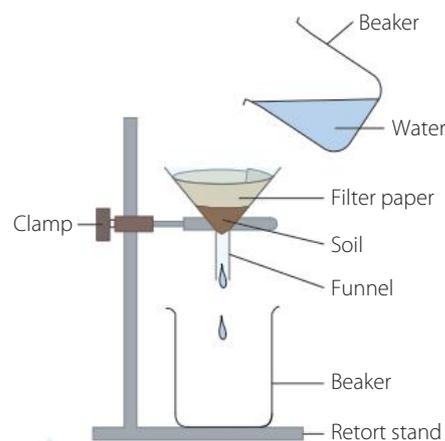


FIGURE 13.8 Equipment set-up



- » 7 Choose how you are going to measure rate. You could choose the time it takes:
- a to get 50 mL
 - b for the first drop
 - c to stop dripping.
- 8 Pour water over the first soil sample and start the first stopwatch.
- 9 Pour water over the second soil sample and start the second stopwatch.

RESULTS

Draw a suitably formatted table to record time (s) and mL infiltrated for each soil sample.

ANALYSIS OF RESULTS

- 1 Calculate the rate of infiltration by mL/time (s) for each soil sample.
- 2 Identify the independent and dependent variables in this investigation.
- 3 Use the graphing software on your computer to generate a graph for each funnel.
- 4 Using the graphs that you have generated, describe the trend in each graph.
- 5 What differences did you observe between the funnels? How do you explain the differences, if any?
- 6 How did you control any variables during this experiment?
- 7 Did you experience any problems with the method? If so, how could you alter the method to reduce the effect of these problems on the result?

CONCLUSION

What did you find out about soil compaction and water infiltration of soil? How could this affect plants growing in that soil?

AAP Image/Mark Marathon



FIGURE 13.9 Feral cats pose a risk to Australian wildlife.

Biotic effects of introduced animals

Before Europeans arrived in 1788, the largest mammalian predators on the Australian mainland were the dingo (an introduced species from Asia) and quolls. In Tasmania, the largest predators were the Tasmanian devil and the thylacine. The introduction of the domestic cat (Figure 13.9) and the red fox changed the ecological balance by introducing very aggressive predators to native animals such as the bilby, bandicoot, bettong and numbat. Few, if any, of the native species of small to medium-sized marsupials have behaviours that allow them to avoid

predation by feral cats and foxes. Foxes in particular are very adaptable predators; there is a resident population of foxes in most large Australian cities. Feral cats also carry exotic parasitic diseases such as toxoplasmosis and sarcosporidiosis, which can be transmitted to native animals.

The cane toad (Figure 13.10) has a special place in the history of Australian ecosystems. Native to South and Central America, the cane toad was introduced into coastal Queensland in 1935 from Hawaii. The toad was introduced to control beetle pests in the Queensland sugarcane fields. To date, the toad has progressed along the coastal fringe of Australia from Port Macquarie in New South Wales to Broome in Western Australia. The adult toads can reach a large size and will eat basically anything that they can fit into their mouths. As such, they have displaced many native species either by direct predation or

by outcompeting them for food. The toads and their tadpoles are toxic to most predators. In most parts of the toads' range, populations of larger predators such as quolls, goannas and many of the larger snakes have been severely affected. Some of these species have recovered a little, but not all.

Many introduced bird species, such as feral pigeons, sparrows, starlings and Indian mynahs, actively exploit urban environments and the surrounding bush areas, pushing native birds out of parts of their original range. The competition is not just for food but often also for available nesting sites.

Introduced herbivores such as deer, cattle, buffalo, horses, donkeys, goats and camels all compete with large native animals for food and water resources. Rabbits and hares are generally restricted to the southern two-thirds of the country, where they compete with native animals for food resources. During times of drought, the introduced species can often survive on plants that native species do not consume. This gives the introduced animals a survival advantage, so they can quickly increase their numbers when conditions improve.



FIGURE 13.10 A mature adult cane toad

KEY CONCEPTS

- The environment is the non-living component of the ecosystem.
- The ecosystem is the non-living and living components and their interactions.
- Abiotic factors are the non-living components of the ecosystem.
- Biotic factors are the living components of the ecosystem.
- Terrestrial ecosystems occur on land.
- Abiotic effects of introduced plant species include changing the soil and water chemistry.
- Abiotic effects of introduced animal species include disrupting the soil crust and soil compaction, leading to erosion and potentially siltation of waterways.
- Biotic effects of introduced plant species include outcompeting native plants for space, light, water and nutrients.
- Biotic effects of introduced animal species include outcompeting for space, water and food; predation upon and poisoning of native species and introducing exotic diseases.

- 1 What is meant by an introduced species?
- 2 Distinguish between the terms biotic and abiotic; environment and ecosystem.
- 3 Describe the reason for introduction and continuing effects of three deliberately introduced species.
- 4 List three biotic effects of named introduced species on Australian terrestrial ecosystems.
- 5 List three abiotic effects of named introduced species on Australian terrestrial ecosystems.

CHECK YOUR UNDERSTANDING

13.1A

Aquatic ecosystems

Aquatic ecosystems are based on a body of fresh water such as a pond, lake or river.

Biotic and abiotic effects

Australia is a dry continent. Australian rivers have much lower flow rates than rivers in most other countries and the water in the rivers is significantly warmer on average. Higher temperatures mean that the level of dissolved gases in the water is low in many instances. Oxygen in the water comes from photosynthesis in aquatic plants growing on the bottom of the river.



River system
food chain



FIGURE 13.11 European carp stir up sediment on the bottom of waterways, reducing light penetration.



FIGURE 13.12 Water hyacinth completely covering the surface, blocking light penetration and reducing water flow in a small river



FIGURE 13.13 A Northern Pacific seastar on a Tasmanian beach.

European carp (Figure 13.11) is a popular eating fish in Europe. It was introduced into Australia more than 100 years ago and is now found in every state. Carp are bottom-feeding fish that stir up the sediments on the base of the river channel, increasing **turbidity**. A lack of sunlight reaching the plants on the river bottom reduces their ability to photosynthesize, causing a lowering of oxygen levels. While carp do not actively prey on adult fish, they will eat the eggs of other fish as they progress through the mud on the bottom of river systems. This disturbance of the mud also poses problems for many of the native predatory fish such as Murray cod because they are visual predators and poor visibility in the river waters limits their ability to hunt.

During the 19th century, large numbers of salmon and brown trout from Europe, along with rainbow trout from North America, were released into Australian river systems to improve the recreational fishing industry. Trout are voracious feeders and they have led to local extinctions of many of the native galaxias species due to competition for food.

Introduced floating aquatic plant species such as water hyacinth and alligator weed can also block sunlight penetrating the water. The slow flow rate of Australian rivers does little to break up large mats of floating vegetation so, given enough time, these plants can extend right across the river (Figure 13.12).

Marine ecosystems

Marine ecosystems occur in the oceanic waters around Australia, including the many estuary systems. They are home to species that are adapted to the high levels of salt in the water.

Biotic and abiotic effects

A large variety of marine organisms have turned up in Australian waters in the last 30 or so years that were not seen before the early 1980s. Many of these species have arrived as larvae in the ballast water systems of ships travelling to Australia from other ports. Most notable is the appearance of the Northern Pacific seastar in the Derwent River in Tasmania in the late 1980s (Figure 13.13). The seastar is a voracious feeder on clams and scallops and is thought to have directly led to the disappearance of two species of bottom-dwelling fish in the Derwent River. The seastar had managed to make its way to Port Phillip Bay, near Melbourne, by the early 2000s. It is currently severely affecting the scallop fishery in Port Phillip Bay.

Caulerpa taxifolia, an alga, has been observed encrusting rocky areas around the mouth of Botany Bay. This alga is gradually replacing native algae and sea grasses that form the habitat and food source for a range of fish. As the *Caulerpa* beds expand due to rapid reproduction and lack of predation, the native algae and sea grasses and the fish that depend upon them are gradually declining in numbers.

- Aquatic ecosystems are based on a body of fresh water.
- Introduced fish species affect aquatic ecosystems by:
 - increasing turbidity, which lowers the amount of light reaching photosynthetic plants, limiting oxygen production
 - decreasing availability of food for native species.
- Introduced plant species block light reaching photosynthetic plants, limiting oxygen production.
- Marine ecosystems are based on a body of salt water.
- Introduced species affect marine ecosystems by outcompeting native species for food.

- 1 Distinguish between aquatic and marine ecosystems.
- 2 Explain how two named introduced species affect the oxygen levels of aquatic ecosystems.
- 3 State the effect that two introduced species have on a marine ecosystem.
- 4 List three biotic effects of introduced species on Australian aquatic or marine ecosystems.
- 5 List three abiotic effects of introduced species on Australian aquatic or marine ecosystems.

CHECK YOUR UNDERSTANDING

13.1B

13.2 Case study of an introduced species

The European rabbit (*Oryctolagus cuniculus*), shown in Figure 13.14, is native to Spain and Portugal, France, Gibraltar and north-western Africa. It is a highly adaptable herbivorous species and has proven to be one of the most invasive introduced animal pest species, spreading across Australia faster than any other introduced mammal in the world. Its current population in Australia is thought to be greater than 200 million.

Reason for introduction

Rabbits were brought to Australia on the First Fleet when it arrived in Sydney Harbour in 1788. These rabbits were domesticated and there is no evidence that they escaped into the Australian bush. There are few, if any, records of other attempted introductions until 1859. This does not mean that there were no other attempts to bring rabbits to Australia between 1788 and 1859. The first reports of wild rabbits occurred in northern Tasmania in 1827 so they must have been imported to that colony between its foundation in 1803 and the recording of feral rabbits in 1827.

In Britain, the rabbit was considered a game animal by wealthy landowners and poor people alike, and it featured regularly as part of an evening meal. For many years in Australia, rabbit meat was considered to be a poor man's food by much of the population.

The first recorded release of wild rabbits from Europe was in 1859 by a farmer named Thomas Austin in Winchelsea, Victoria. The reason for the release was so that the rabbits could be hunted for sport. The initial release was of 24 breeding rabbits. In 1866 (a mere 7 years later), over 14000 rabbits were shot on Austin's property in one hunting expedition.



FIGURE 13.14 Feral rabbit



Invasive species

Biotic effects of the species

Rabbits cause substantial damage to vegetation. When food is plentiful, rabbits are selective feeders, preferring native drooping sheoak (*Allocasuarina verticillata*), buloke (*Allocasuarina luehmannii*) and sweet bursaria (*Bursaria spinosa*). Rabbits will graze on native pasture and agricultural pasture; 12–16 rabbits can eat the same amount of food as one large merino sheep. When food becomes scarce, either due to drought conditions or increasing population pressure, rabbits will excavate below the ground surface to feed on underground shoots and seeds. When the rabbits feed in this way, they reduce the amount of grasses by either consuming the plants as they appear aboveground, or by stopping the seeds from germinating. When there is limited grass feed, rabbits will then start to strip leaves from low shrubs and even strip bark from tree trunks, effectively ringbarking the tree.

Rabbits dig warrens in the ground, preferring sandy soil. As they dig their warrens, they expose tree roots to the air, leading to disease infestation and dehydration of the plant. By removing the majority of available vegetation, rabbits affect herbivorous native animals by outcompeting them for available food resources. Consumption of seeds by rabbits can adversely affect birds that rely on those seeds for nourishment. When rabbit populations are high, there is a marked reduction in the overall biodiversity of an area. There are at least 156 species that are threatened as a direct result of competition by rabbits for space, food and water, as well as land degradation.

Another consequence of rabbits moving into a region is that they will tend to attract other introduced predators, such as red foxes, dingoes and feral cats. Red foxes were also introduced for recreational hunting. Today, the range of the red fox mimics that of the rabbit. A flow-on effect of the interaction between the rabbit and the red fox is that the foxes will take large numbers of smaller native animals and birds if rabbits are not readily available.

Abiotic effects of the species

Removal of grass and tree cover by rabbits leaves the soil vulnerable to wind and water erosion. Warrens are constructed by excavating a series of tunnels and underground chambers. The soil that is removed is dumped around the entrances to the burrows, where it can be moved by prevailing winds. Removing much of the native vegetation in an area exposes the sandy soil to wind erosion and leads to soil loss. When rain arrives in an area inhabited by large numbers of rabbits, much of the loose soil is transported by flowing water to streams and rivers, leading to siltation problems. Where rabbits kill trees or prevent their regeneration, the water table can rise, creating waterlogging or contributing to salinity.

The link between the loss of trees and salinity is discussed in Chapter 12.

Affected areas

Due to their adaptability, rabbits quickly spread across both rural and suburban Australia, and now 70% of the Australian landmass, as shown in Figure 13.15. From their introduction in Victoria in 1859, they reached the New South Wales–Queensland border by 1886 and were seen in Western Australia and Northern Territory by 1900. They had spread to their current range by 1980.

The Australian environment is a perfect fit for the lifecycle of the rabbit. Mild winters, unlike those in Europe, allow the rabbit to breed all year round. Because rabbits reach breeding age at four months, each female can produce four litters of 8–10 kittens each year. This means that a rabbit born in January can have approximately 670 descendants before the same time next year.

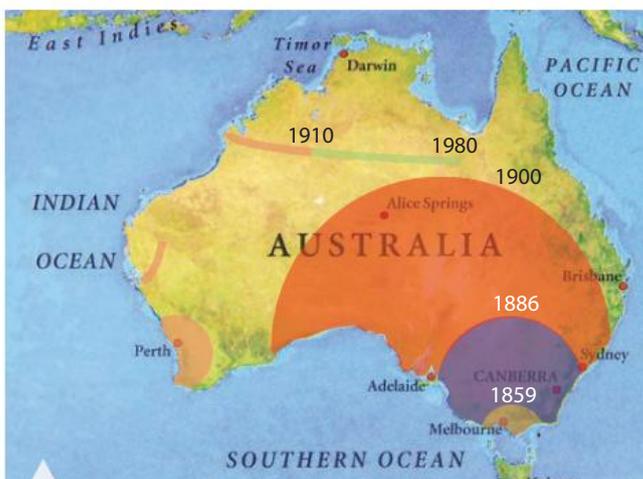


FIGURE 13.15 The spread of the European rabbit across Australia

Sandy soils found across much of Australia mean rabbits can easily dig underground warrens. Heavy clay soils restrict their ability to dig warrens, but these soils are not particularly common in the southern half of the country.

The main control on the spread of the rabbit prior to human efforts is the temperature of the warrens. Once the temperature of the breeding burrows exceeds 28°C, rabbits are unable to breed. As a result, the northern limit of the rabbit is around the Tropic of Capricorn. Some rabbit populations exist north of this in Queensland on elevated mountain ranges where overall temperatures are slightly lower.

Between 1901 and 1907, the Western Australian Government constructed a series of fences running the length of the state to restrict the rabbit. This rabbit-proof fence has had some success in keeping large numbers of rabbits out of the agricultural regions in the western third of the state, but rabbit populations are regularly found inside the fence. The fence is still maintained and is regularly patrolled by rangers who make repairs when breaks are located.

Human impacts

Thomas Austin experienced great success from stocking his Winchelsea farm with rabbits, along with hares, blackbirds, partridges and sparrows, and offering it to wealthy settlers for game-shooting parties. He increased his flock of rabbits by breeding them with local domesticated rabbits, which had the result of increasing **hybrid vigour**. Other landholders witnessed Austin's success and brought rabbits into western Victoria and South Australia as they tried to cash in on the recreational hunting trade.

Rabbits were deliberately introduced onto islands around Australia. It was thought that they would be a food supply for survivors of shipwrecks.

Many farmers did little about controlling the rabbits on their farms until the rabbits started to out-compete sheep and foul pasture, interfering with wool production. This delay in action meant that rabbits were able to spread to further corners of Australia in large numbers.

Humans have further assisted the spread of rabbits by clearing bushland and planting large expanses of pasture crops such as canola and vegetables. Rabbits can eat all the emerging seedlings in a crop, costing Australian agriculture significant amounts in lost production. Rabbits take advantage of the ploughed fields, finding it is easier to dig warrens.

Control

Various methods have been used to control rabbit populations, with varying degrees of success. Destruction of warrens either by bulldozers or gassing has had limited success. Baiting with carrots laced with a mammalian toxin known as 1080 has had some success. However, there is a very real danger that native species such as wombats, wallabies and kangaroos will eat the poison-laced food.

The myxoma virus causes a disease called myxomatosis that occurs only in rabbits. This virus was deliberately introduced into Australia in 1950. Initially, the virus had a mortality rate of above 90%, meaning that if a population of rabbits was infected, more than 90% died. The remaining rabbits possessed a natural resistance to the myxoma virus due to genetic variability in the population that allowed them to survive. These survivors interbred, producing successive generations and the resistance to the disease gradually increased due to **natural selection**. Another problem in using the myxoma virus is that it is spread by mosquitoes. Having mosquitoes as the disease vector proved effective in parts of the country where there was sufficient rainfall for bodies of standing water to be available for mosquito breeding. However, during times of drought and in the dry interior, the disease was much less effective due to the lack of mosquitoes. Myxomatosis still keeps rabbit numbers down by as much as 75% of what they were before the introduction of the virus.

A second introduced virus, calicivirus, causes rabbit haemorrhagic disease. This virus was still being tested at a laboratory on Wardang Island off the coast of South Australia when it was released to the mainland. There is some suspicion that the virus was deliberately released before the tests had been completed. Its impact on desert rabbit populations was immediate. Areas that had been infested with rabbits for over a hundred years were quickly cleared as the virus spread. The vector in this case was flies, which are much more common than mosquitoes in inland Australia and do not depend on bodies of water for reproduction.

Once again, rabbits have begun to show signs of resistance to this disease. Efforts are being made to find other diseases, or to produce improved strains of these two diseases, to reduce rabbit numbers further.

Control methods have had a significant effect when you consider that the Australian rabbit population was estimated to be 10 billion in 1920. Current estimates are around 200 million.

Economic impact

Rabbit control is a significant cost to farmers, but taking no action is costlier. The cost of lost productivity per rabbit can be estimated and depends on the commodity being farmed (Table 13.1). Lost productivity can be in terms of reduced quality or amount of wool on sheep or lower liveweight of cattle due to grazing competition with rabbits, as well as devastation of food crops or forestry plantations due to rabbit grazing. It has been estimated that the total annual cost of rabbits in lost agricultural production is \$206 million each year.

TABLE 13.1 Estimated cost to agriculture per rabbit

ENTERPRISE	APPROXIMATE COST / RABBIT / YEAR (\$)
Wool	1.85
Store cattle (property bred)	2.40
Trading cattle (grow out for 12 months)	2.85
Stud cattle	13.90
Broccoli (per hectare)	9.90
Lettuce (per hectare)	2.35
Lucerne (irrigated per hectare)	6.80
Wine grapes (per hectare)	65.60

Table 5: Approximate cost of rabbits to agricultural enterprises, from 'Rabbit control in Queensland - A guide for land managers', © The State of Queensland, Department of Primary Industries and Fisheries 2008. This information was produced in 2007 (2008) and has not been updated. Costs and impacts in this table are out of date and readers are advised to check with a relevant authority to obtain up-to-date pricing

Differing views

Views about rabbits have changed over the years. Early settlers deliberately introduced rabbits into Australia for sport and a source of food. During the Great Depression of the 1930s, rabbits were a cheap source of fresh, lean meat and Rabbitohs, or rabbit sellers, were common. As the rabbit population increased rapidly and began to threaten agricultural productivity, this view changed. Many control techniques have been trialled to reduce population numbers, including trapping, destroying warrens, bounties, poisons and biological control such as myxomatosis and calicivirus.

Rabbits are now farmed commercially, but their numbers and enclosures are strictly governed. Rabbit meat is still sold in specialty butcher shops in most cities within Australia. People with a taste for rabbit meat are very supportive of farmed rabbit populations. Hat makers such as Akubra need a regular supply of rabbit pelts to manufacture their range of hats. The iconic hat of the Australian Defence Force, the 'slouch hat', is made from rabbit pelts.

Views of Aboriginal and Torres Strait Islander peoples

Rabbits have not colonised northern Australia in large numbers because high temperatures limit their breeding. As a result, there is little recorded information on the views of Torres Strait Islander peoples' views towards rabbits. Where feral rabbits were available, they made up part of the diet of some Aboriginal groups. Aboriginal people did not separate the environmental impact of rabbits from native animals because they consider the ecosystem to be an integrated whole, with no species 'belonging' more than another (Rose 1995). Indeed, some Aboriginal people were able to take advantage of the large numbers of rabbits. A government report from 1930 indicates that Aboriginal people in northern South Australia were earning a living through rabbit trapping and selling skins and carcasses.

In 1995, 95% of the rabbit population of drier parts of Australia died when the calicivirus escaped from Wardang Island. This severely affected the supply of rabbits for Aboriginal people, reducing their access to this food supply. Today, the Australian Government shares responsibility for management of Indigenous Protected Areas (IPA). Two IPAs in northern New South Wales are Wattleridge, which covers 648ha, and Tarriwa Kurrukun, which covers 930ha. These IPAs are owned by the Banbai Aboriginal nation. The Banbai Rangers manage the feral rabbit population on these lands through shooting and trapping.

References

Rose, B. 1995. Land management issues: attitudes and perceptions amongst Aboriginal people of central Australia. Report for Central Land Council, Alice Springs.



INVESTIGATION 13.2

Investigating an introduced species

Since the arrival of the First Fleet in Australia in 1788, over 2800 weed species, 25 mammal species, 20 bird species, four reptile species, one frog species, 34 fish species and anywhere between 100–400 marine species have been introduced into Australia.

Your task is to produce a case study of no more than 1000 words on one of these introduced species. You may not choose the European rabbit because this has been provided above.

Before choosing your introduced species, do some research to make sure that there is sufficient information available to address each of the areas below. While you are conducting your research, make sure that you record all your reference materials so you can provide a reference list at the end of your case study. Add relevant photos or diagrams.

- 1 Name the introduced species and give a brief introduction of where it is from.
- 2 Explain when, how and why the species was introduced into Australia.
- 3 Describe the biotic and abiotic effects of the species on the ecosystem.
- 4 Describe the spread of the species and produce a map to identify the current range of the species.
- 5 Describe how human activities have contributed to the spread of the species.
- 6 Detail the methods, past and present, that have been employed to control the species.
- 7 Outline the economic impacts of the introduced species.
- 8 Compare differing viewpoints about the harms and benefits of the species, including the viewpoints of Aboriginal and Torres Strait Islander peoples.
- 9 Provide a reference list to show the sources of your material. Refer to page 27 to find out how to write a reference list.

- Rabbits are the most invasive introduced animal pest species in Australia.
- Rabbits were released into the environment so they could be hunted for sport.
- Rabbits graze on native plants, seeds, roots and agricultural pastures.
- Rabbits outcompete native animals for food.
- Removal of grass and tree cover by rabbits leaves soil vulnerable to wind and water erosion.
- Due to their adaptability, rabbits quickly spread across rural and suburban Australia.
- Human behaviours have encouraged the spread and population increase of rabbits.
- Various control methods have been tried, including physical destruction of warrens, poison and biological controls.
- It has been estimated that the total annual cost of rabbits in terms of lost agricultural production is \$206 million.

CHECK YOUR UNDERSTANDING

13.2



Numeracy



Difference and diversity

- 1 Explain why rabbits were initially introduced into Australia.
- 2 Provide three reasons why rabbits have been able to spread across Australia with such speed.
- 3 List two biotic effects of rabbits.
- 4 List two abiotic effects of rabbits.
- 5 List three ways in which humans have assisted rabbits in their spread across Australia.
- 6 Assess the success of the methods to control rabbits.
- 7 Refer to Table 13.1. Assume that there are 50 warrens in a sheep paddock. Each warren contains 12 rabbits. What is the cost to the farmer for one year?
- 8 Refer to Table 13.1. Why is the cost of rabbits on wine grapes per hectare so much greater than the cost of lettuce per hectare?
- 9 Provide two different viewpoints towards rabbits. Why do you think different people had or have different viewpoints about rabbits?

13.3 Balancing the ecosystem



Sustainability

Humans use natural ecosystems for a variety of purposes, including for recreation such as bushwalking, boating and fishing. Birds, bees and small mammals pollinate food trees and crops; plants and soils clean the air and water that we use. Healthy ecosystems are essential for healthy humans. Healthy ecosystems are those where the biotic and abiotic factors are in balance; they are **sustainable** and resilient in the face of external stresses such as drought or fire. Australian ecosystems have evolved over millions of years, isolated from the rest of the world. The introduction of an exotic species can disrupt the fragile balance of an ecosystem.

Some introduced species have flourished in their new environment, to the detriment of the native species; these are called invasive species. To be successful, an invasive species needs to meet five criteria:

- 1 High reproductive success
- 2 Successful dispersal over a large range
- 3 Few or no natural predators or disease
- 4 Generalists, able to use a variety of different habitats or food types
- 5 High cost to remove

High reproductive success may be achieved by several strategies. Some short-lived species grow rapidly and reach maturity quickly, producing many seeds or offspring. Other species may reproduce more slowly but have a much longer reproductive life.

Paterson's curse, also known as Salvation Jane (*Echium plantagineum*), is an annual **herbaceous** plant about 60 cm tall with purple trumpet-shaped flowers (Figure 13.16). It was brought into Australia as a garden plant. A single plant can produce up to 10000 seeds, so it did not take long to escape the garden. It grows best on disturbed ground but finds it difficult to establish in healthy undisturbed areas. Its spread has been assisted by humans due to land degradation, removal of **perennial** grasses through overgrazing by sheep and cattle and the introduction of the rabbit. It is toxic to many grazing animals.



Shutterstock.com/Geoff Sperring

FIGURE 13.16 Paterson's curse (*Echium plantagineum*)

INVESTIGATION 13.3

Favouring introduced species

Some human behaviours favour the survival of introduced species over native species. In this investigation you will analyse selected introduced species to determine whether human behaviour has contributed to their survival and success in Australian ecosystems.

METHOD

- 1 Choose one plant and one animal introduced species.
- 2 Use online and printed resources to answer the questions below for each species you have chosen.

QUESTIONS

- 1 Why was the species originally introduced?
- 2 What is its habitat?
- 3 Explain (including resource type) how it competes with named native species.
- 4 How does the introduced species meet the five criteria listed on page 338?
- 5 How have humans assisted the survival and spread of the introduced species?

ANALYSIS OF RESULTS

- 1 Give reasons for and against the introduction of exotic species into Australia.
- 2 What advice would you provide to the federal government on changing laws relating to introduced species?

CONCLUSION

Have humans assisted the survival of introduced species, thereby bringing about the decline of native species?



- Humans use natural ecosystems for a variety of purposes.
- The introduction of an exotic species can disrupt the fragile balance of an ecosystem.
- To become 'invasive', introduced species must meet stated criteria.
- Human behaviour sometimes favours introduced species over native species.

CHECK YOUR UNDERSTANDING

13.3

- 1 Describe a healthy ecosystem.
- 2 Distinguish between an introduced species and an invasive species.
- 3 List three ways that you have used a natural ecosystem.
- 4 **a** List the five criteria for a successful invasive species.
b How does Paterson's curse (Salvation Jane) meet those five criteria?
- 5 Provide two examples of human behaviour that have assisted an invasive species to outcompete a native species.

13.4 Declining Australian native species

Feral rabbits are listed as a Key Threatening Process in the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth). This is because of their negative impact on native species (both plant and animal) through competition for food, water and space resources, and damage to native vegetation and the land.

INVESTIGATION 13.4

Declining Australian native species



Work and enterprise



Sustainability



Critical and creative thinking

Work in pairs to complete this investigation. Divide the workload so that each person contributes equally.

Copy the table below and complete it to show the data for 20 native species. The first entry in the table has been completed. Review the content of this chapter and locate extra information using the Internet or other resources. Remember that just as one introduced species can affect more than one native species, one native species can be affected by a range of factors.

RESULTS

INTRODUCED SPECIES	NATIVE SPECIES AFFECTED	DECLINE (D) OR EXTINCTION (E) OF NATIVE SPECIES?	DESTRUCTION OF THEIR HABITAT	OUTCOMPETING FOR FOOD, WATER	PREDATION UPON NATIVE SPECIES	SPREAD DISEASE TO NATIVE SPECIES	TOXIC TO NATIVE SPECIES	OTHER
Feral cat	Paradise parrot	E			X			



» ANALYSIS OF RESULTS

- 1 Describe in detail three ways that introduced species can contribute to either the decline in numbers or extinction of native species. Provide examples to support your descriptions.
- 2 With your partner, discuss the following and write an agreed response:
 - Which one of the species that you included in this investigation had the most far-reaching impact on Australian native species? Provide at least three reasons for your choice.

CONCLUSION

Write a conclusion to summarise how introduced species affect Australian native species.

KEY CONCEPTS

- Introduced species can cause the decline or extinction of native species through:
 - destroying their habitat
 - outcompeting them for food and water
 - preying upon them
 - spreading disease to them
 - poisoning them.

- ▶ The environment is the non-living component of the ecosystem.
- ▶ The ecosystem is the non-living and living components and their interactions.
- ▶ Abiotic factors are the non-living components of the ecosystem.
- ▶ Biotic factors are the living components of the ecosystem.
- ▶ Terrestrial ecosystems occur on land.
- ▶ Abiotic effects of introduced plant species include changing the soil and water chemistry.
- ▶ Abiotic effects of introduced animal species include disrupting the soil crust and soil compaction, leading to erosion and possibly siltation of waterways.
- ▶ Biotic effects of introduced plant species include outcompeting native plants for space, light, water and nutrients.
- ▶ Biotic effects of introduced animal species include outcompeting for space, water and food; predation upon and poisoning of native species and introduction of exotic diseases.
- ▶ Aquatic ecosystems are based on a body of fresh water.
- ▶ Introduced fish species affect aquatic ecosystems by:
 - increasing turbidity, which lowers the amount of light that reaches plants, limiting oxygen production
 - decreasing availability of food for native species.
- ▶ In aquatic ecosystems, introduced plant species block light reaching photosynthetic plants, limiting oxygen production.
- ▶ Marine ecosystems are based in a body of salt water.
- ▶ Introduced species affect marine ecosystems by outcompeting native species for food.
- ▶ Rabbits are the most invasive introduced animal pest species in Australia.
- ▶ Rabbits were released into the environment so they could be hunted for sport.
- ▶ Rabbits graze on native plants, seeds, roots and agricultural pastures.
- ▶ Rabbits out-compete native animals for food.
- ▶ Removal of grass and tree cover by rabbits leaves soil vulnerable to wind and water erosion.
- ▶ Due to their adaptability, rabbits quickly spread across rural and suburban Australia.
- ▶ Human behaviours have encouraged the spread and population increase of rabbits.
- ▶ Various control methods have been tried, including physical destruction of warrens, poison and biological controls.
- ▶ It has been estimated that the total annual cost of rabbits in terms of lost agricultural production is \$206 million.
- ▶ Humans use natural ecosystems for a variety of purposes.
- ▶ The introduction of an exotic species can disrupt the fragile balance of an ecosystem.
- ▶ To become 'invasive', introduced species must meet stated criteria.
- ▶ Human behaviour sometimes favours introduced species over native species.
- ▶ Introduced species can either cause the decline or extinction of native species through:
 - destroying their habitat
 - outcompeting them for food and water
 - preying upon them
 - spreading disease to them
 - poisoning them.

13 CHAPTER REVIEW QUESTIONS



1 Complete the table below to show the biotic and abiotic effects of introduced species on terrestrial and marine ecosystems.

TYPE OF ECOSYSTEM	INTRODUCED SPECIES IMPACTS IN THE ECOSYSTEM	
	BIOTIC	ABIOTIC
Terrestrial		
Marine		

- Describe three reasons for the deliberate introduction of either a plant or an animal into Australia.
- Describe three ways in which an exotic species could be accidentally introduced into Australia. Provide one example.
- Explain how abiotic constraints have placed a limit on the distribution of rabbits in Australia.
- Choose one introduced species, such as camel, fox, wheat, goat.
 - Describe three different human activities that have encouraged its spread across Australia.
 - Provide at least two different points of view about the value or harm caused by your chosen species.
 - List at least three native species that your chosen species competes with directly.

- Provide two examples of biological control of a named introduced species. Assess the success of one of these methods.
- Refer to Figure 13.17.
 - Identify the three introduced species.
 - Describe the density of the rabbit population from 1880 to 1910.
 - Provide three reasons for the shape of the eastern grey kangaroo graph from 1885 onwards.
- Sydney is unique among world cities in having national parks within its borders. Suggest how each of us might be able to assist the work of the National Parks and Wildlife Service in maintaining native animal and plant populations within these national parks.
- Justify the continued contribution of money to research organisations, both government and non-government, in finding ways to combat invasive pest species.
- Cats are recognised as one of the greatest threats to native animals and birds. Suppose a virus was developed that, if released, could sterilise any cat that it infected. Present and analyse arguments both for and against the release of this virus.

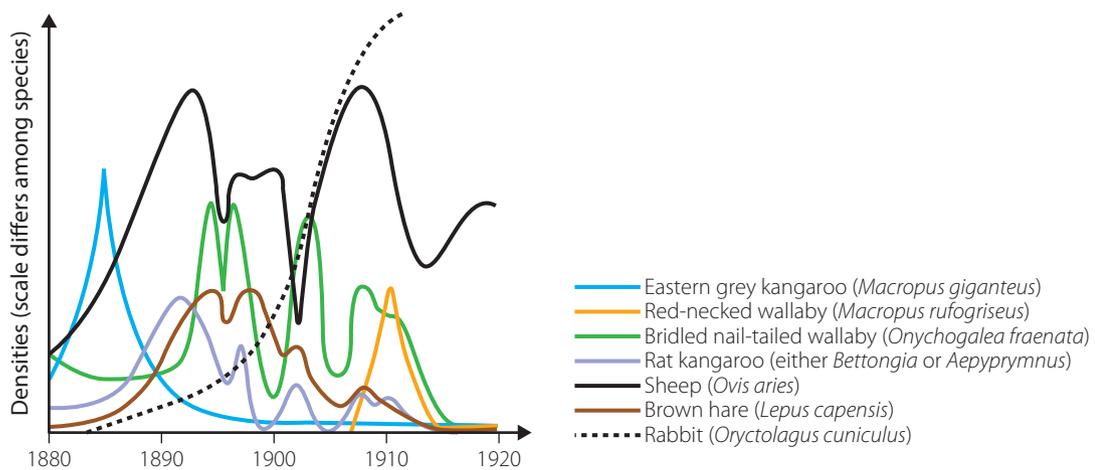


FIGURE 13.17

Recher, H. F. et al. (eds) (1992) *A Natural Legacy: Ecology in Australia*, Pergamon Press, Sydney, p. 260.

Answer the following questions.

- 1 *Native vegetation is crucial for the health of the NSW environment, supporting agricultural productivity as well as the biodiversity that is central to Australia's cultural identity.* (NSW Office of Environment and Heritage, 2018)
Justify this statement using examples from at least two of the sections in Module 4.
- 2 Using examples from your studies, evaluate the impact of changing knowledge of Earth and Environmental Science on soil management in Australia.
- 3 Discuss ways in which introduced species may benefit the Australian environment.
- 4 Analyse ways in which Australia can make more effective use of its scarce fresh water resources to deliver high-quality drinking water to people, adequate irrigation to farms and environmental flows to ecosystems.
- 5 Discuss the effect of land clearing on water, soil and introduced species.
- 6 Using examples, analyse the links between soil and water pollution.
- 7 Describe the effect of introduced plants and animals on Australian soil and water.
- 8 Australian farmers quickly adopt new technologies to conserve water and topsoil. Using examples, justify their interest in these technologies.
- 9 Outline the impact of the introduction of the European rabbit on the biotic environment.
- 10 Explain how human activities have assisted in the spread of a named introduced plant or animal.
- 11 Several species of dung beetle existed in Australia before European settlement. These animals evolved to deal with the dung from marsupials. Dung beetles from South Africa were introduced between 1967 and 1982. These beetles were evolved to deal with cow dung. Discuss the impact of South African dung beetles on the Australian ecosystem.
- 12 Outline two examples of how Aboriginal and Torres Strait Islander peoples' attitudes to introduced species may differ from that of non-Indigenous Australians.
- 13 Justify the continued research expenditure by organisations such as CSIRO into control methods for the European rabbit.

DEPTH STUDY SUGGESTIONS

- Investigate the relationship between pedestrian traffic and soil compaction in different areas of your school campus or a local park.
- Measure water quality in a local creek before and after a heavy rain. How does stormwater input affect the volume and quality of the water?
- Compare soil features, including nutrient and pH levels, in an area of native vegetation and an area with heavy weed infestation.
- Quantify the amount of soil erosion in similar areas with and without erosion control measures. What methods are most effective in preventing erosion?
- Extract data from a large data set such as the Aussie Backyard Bird Count to document changes over time in your local area. Investigate possible reasons for these changes.
- Design and test a scale model of an artificial wetland. Test the water to determine its effectiveness at removing sediment and then see if this can be improved.
- Determine whether inputs and extractions from groundwater are being managed sustainably in your local area.
- Model dryland salinity and native vegetation in large containers with a deep salt layer.
- Investigate and document the process of salinisation over time and its effects on vegetation and soil-surface salt content.
- Investigate the different types of biological control (viral, bacterial, parasitic and predatory controls) that have been used to reduce the numbers of introduced species in Australia.
- Investigate the reduction in numbers or complete extinction of a native plant or animal due to the introduction of a species from overseas. What could be done to counteract the effects of the introduced species?

GLOSSARY

A

abiotic relating to the non-living components of an ecosystem, such as sunlight or water

abiotic factors non-living part of the ecosystem

ablation loss of ice from a glacier or ice sheet

absolute (age) dating determining the age in years of geological or fossilised materials using isotopic clocks

abyssal plain large flat area on the ocean floor (3000–6000 m); lies between a continental rise and a mid-ocean ridge

accretion increase due to the gradual accumulation of additional layers

accretionary wedge accumulation of sediment that is scraped off the oceanic crust during subduction with a continental crust. It forms a pile at the edge of the continental crust

accumulation addition of ice to a glacier or ice sheet

accuracy closeness of a measured value to what is known to be correct

adhesion attraction between water molecules and the surface the water is in contact with

advection transfer of heat or material by the flow of a fluid

aeolian wind-blown, as in aeolian salt

A horizon uppermost soil horizon; contains organic material

albedo proportion of light falling on a surface that is reflected from the surface

aquatic ecosystem based on a body of water

aquifer geological formation of soil, sand and rock able to store and transmit water in pore spaces and cracks.

Archaea domain of single-celled organisms distinct from bacteria

assimilation process in which the rock surrounding a body of magma dissolves into the magma

asthenosphere layer of solid rock that lies directly beneath the lithosphere

atmosphere layer of gases that surrounds a planet. On Earth, the atmosphere is mainly nitrogen and oxygen

autotrophs organisms that make their own food

B

back-arc basin geological feature associated with an island arc, formed on the ocean floor along the subduction zone of a convergent plate boundary

banded iron formation (BIF) sedimentary rock composed of alternating layers of coloured chert or jasper and iron oxides

bathymetric map accurate visual representation of the floor of submerged terrain

bathymetry study of the depth of water in oceans, rivers or lakes and the mapping of the submerged terrain

Benioff-Wadati zone zone of increased earthquake activity associated with the subducting plate along a subduction zone

biomagnification increasing concentration of a chemical or toxin in living things as it passes up each level of the food chain

biosphere sum of all the living things on Earth

biotic relating to living components of an ecosystem, such as animals, soil bacteria, fungi and plants

biotic factors living or once-living part of an ecosystem

B horizon soil horizon where clay and oxides accumulate

bolide large body from space that strikes the surface at high velocity, creating a crater

bolus ball-shaped piece of material

brittle describes a material that will deform and suddenly break when it reaches its elastic limit

buoyancy upward force exerted by a fluid on an object

C

caldera circular crater formed when the top of the conduit of a volcano is exploded outwards or the area collapses

capillary action movement of water through a narrow space against the force of gravity

carbon dating technique used to determine the absolute age of a once-living material by measuring the ratio of carbon-14 that remains in the material to the amount of carbon-12

carbonate mineral containing the carbonate group, CO_3^{2-} ; calcite is an example

chemical (rocks) rocks formed by chemical precipitation of minerals

chemical weathering process that changes the chemical nature of a rock or mineral

chemosynthesis process by which some living things use energy from inorganic chemicals to synthesise energy-rich compounds for food

chloroplast structure within cells where photosynthesis occurs

C horizon zone of weathered material from which soil is forming

clastic (rock) rocks formed from fragments of rock or minerals

cleavage parting or separation of a mineral along smooth surfaces

coalification chemical and physical (heating and pressure) process of transforming vegetation into coal

cohesion attractive forces that draw molecules inward

column or bar graph type of graph used when items have been counted into unrelated categories. Columns do not touch

conduction process in which heat is directly transferred between two places with no movement of material

conduit space or passage through which magma rises from a magma chamber to the surface

confined aquifer lower layers of groundwater separated by impermeable sediment or rock

connate fossil salt found in sedimentary rocks

continental lithosphere part of the lithosphere that makes up continents; consists of continental crust and residual mantle and is usually thicker than oceanic lithosphere

continental shelf sloping extension of a continent, usually covered by ocean

contractionism early theory on the formation of Earth that proposed that Earth started as a molten ball and contracted as it cooled. This caused heavy metals to sink to the core and lighter metals to stay near the surface. Buckling of the crust formed mountains

controlled kept constant

controlled variable variable that is kept constant so that it does not interfere with the outcome of an experiment

convection process in which energy is transferred from one place to another by the movement of fluids

convection cell system in which a temperature gradient causes a fluid to circulate as a result of changing density

convection currents transfer of heat from one place to another by movements within a fluid

convergent plate boundary area where two or more tectonic plates are moving towards each other

core tool tool made by striking a rock (core) with a hammer stone to chip and shape it

Coriolis force force acting on fluids due to the rotation of Earth

cross-cut one geological material cutting across another

crustal extension thinning of the lithosphere due to tension forces

crustal shortening reduction in size of Earth's crust due to deep-seated faulting elevating sections of crust

cryosphere solid part of the hydrosphere, comprising ice and snow

crystal form geometric shape of a well-formed mineral crystal

crystal fractionation change in magma composition caused by crystallisation removing some elements from the liquid magma

crystal lattice arrangement of atoms in a highly ordered three-dimensional structure

cumulonimbus tall cloud with a flat base that often produces thunderstorms

cut-and-fill method method of mining used for steeply dipping ore bodies where the rock and ore are removed and the hole backfilled to expose the next level for mining

D

daughter nucleus nucleus produced when a parent nucleus undergoes radioactive decay

deep layer ocean layer that extends from 1 km below the surface to the sea floor

deep-ocean trench long, steep and deep depression in the ocean floor

density amount of matter in an object compared to the volume of that object

density current current caused by the sinking of cold, saline water more dense than the water surrounding it

dependent variable variable being measured in an experiment

depth study investigation or activity completed by a student or students to explore more deeply a topic of interest from the Year 11 Earth and Environmental Science course

derived data data deduced from raw data by mathematical manipulation, such as graphs, algebraic equations and geometric constructions

diatreme type of volcanic structure created by by phreatic eruptions

direct sampling removing a small representative portion of Earth's material for analysis of its composition

divergent (plate boundary) area where two or more tectonic plates are moving away from each other

downwelling sinking of warm water due to Ekman flow towards a coast

ductile a material that shows plastic deformation

E

echo sounder sonar equipment used to measure the depth of the ocean

Ekman flow movement of water at an angle to wind direction, caused by the Coriolis force

ecosystem system formed by the interactions between members of a biological community and their environment

effusive type of quiet volcanic eruption in which lava flows out of fissures

El Niño phase of ENSO in which low-pressure Walker cells move into the central Pacific, causing dry conditions in Australia

El Niño–Southern Oscillation (ENSO) interaction between the atmosphere and ocean in the tropical Pacific causing periodic variation between below-normal and above-normal sea surface temperatures and rainfall

elastic capable of resuming an original shape when a deforming force is removed

elastic rebound theory model of earthquake formation in which elastic potential energy stored in rock is suddenly released as heat and seismic waves

empirical able to be verified through observation and experimentation

energy capacity to cause change or effect

environment physical parameters and biotic attributes of an ecosystem

equilibrium state in which opposing forces are balanced

erosion gradual removal of weathered material from its site of formation

eutrophication process caused by excess nutrients in water that act as fertiliser, leading to overgrowth of algae

evaporation conversion of a liquid to a gas

evapotranspiration transfer of water from land to the atmosphere by evaporation from surfaces and plants

exotic species another name for an introduced species

explosive describes volcanic eruptions that violently expel ash and volcanic bombs

extant still in existence

extinct no longer in existence

F

falsifiable able to be disproved

fault structure formed when rock strata fracture and movement occurs on the sides of the fracture

fault block block created when faults break a large rock unit into smaller units

fault gouge rock crushed when two plates move against each other, resulting in a rock with very small grain size

fault plane surface between two blocks of rock where it fractures during an earthquake

feedback loop change in one part of a system that either causes changes that reinforce the original change (positive feedback) or make the change smaller (negative feedback)

felsic silicate mineral, or rock rich in silica and aluminium; quartz and feldspar are examples

fission splitting of the nucleus of an atom into two or more smaller nuclei

fissure linear channel or gap through which magma can reach the surface to form lava

flake tool sharp piece of rock used as a tool, made from a piece flaked off a core rock by striking it with a hammer stone

fold structure formed when compression causes rock layers to buckle and bend. A product of plastic deformation

fold and thrust belt highly deformed mountain range inland from a magmatic arc

fold belt linear region of Earth's crust where rocks of around the same age have been pushed together and have bent or folded

folding bending or curving of flat rock due to pressure and /or temperature caused by tectonic activity

foliation layered texture in rocks formed by mica recrystallisation

fore-arc basin geological feature formed at a convergent plate boundary between an ocean trench and a volcanic arc

fossil fuel fuel that is the product of anaerobic decomposition over millions of years of buried plant and animal material

fossil preserved evidence, for example in the form of bones, shells or impressions, of a once-living thing

fracture break along an irregular surface

G

gangue mineral that does not have economic value found in an ore

geosphere solid part of planet Earth, such as the mantle and crust

geosynclinal historical theory based on permanentism to explain mountain building and interpret geological features

geothermal gradient rate at which temperature increases with depth

glacier slow-moving mass of ice created by the accumulation and compaction of snow

graben depressed, elongated block of crust with faults on each side

gravity universal force of attraction between masses

gyre a giant circular surface current

H

Hadley cell convection cell acting to move heat away from the equator

half-life ($t_{1/2}$) amount of time it takes for the amount of a substance to reduce by half

hammer stone stone used to strike and fracture another rock, either to shape it or to flake off pieces with a sharp edge

hardness resistance of a mineral to scratching or abrasion

heat energy form of energy comprising the jostling and vibration of particles in a substance

heat of fusion heat required to transform the state of a substance from solid to liquid

heat of vaporisation heat required to transform the state of a substance from liquid to gas

herbaceous describes green, non-woody plants

herbivore animal whose diet consists solely of plant material

heterotroph organism that feeds on other living things

histogram type of column graph where columns touch each other because the data categories have a natural order

horizon layer of soil with distinctive characteristics

horst raised block of crust with normal faults on each side

hotspot section of Earth's crust, not at a plate boundary, that undergoes volcanism

hotspot volcano section of the upper mantle, not at a plate boundary, where rocks melt to form magma that rises through cracks to form a volcano

hybrid vigour improvement of offspring characteristics due to breeding two different strains or species

hydraulic fracturing form of onshore drilling where water, sand and chemicals are injected into rock under high pressure. This creates fractures in the rock, allowing natural gas and oil to flow out. Also known as 'fracking'.

hydrogen bonding attraction of positively charged hydrogens to negatively charged atoms

hydrosphere water on a planet, including oceans, rivers, lakes, glaciers, ice sheets and water vapour

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 sheet large area of ice covering more than 50 000 km²

ice shelf floating masses of ice attached to a land mass

igneous rock rock or mineral formed from the crystallisation of magma or lava

inclusion fragment of rock found inside another rock

independent variable variable that is controlled or manipulated by the experimenter

Indian Ocean Dipole interaction between the atmosphere and ocean in the Indian Ocean that causes periodic variation between below-normal and above-normal sea surface temperatures and rainfall

inorganic describes something that does not contain the elements carbon and hydrogen

intertropical convergence zone area of low pressure at the equator

introduced species species that is not native to a specific location

invasive species introduced species that spreads rapidly and causes damage to the environment

ion atom with a positive or negative charge due to losing or gaining electron(s)

island arc curved chain of volcanic islands formed when one ocean plate subducts under another ocean plate

isostasy process in which the forces of weight and buoyancy adjust to create an equilibrium

isotopic clock radioactive isotope with a known rate of decay that can be used to date geological materials

K

knapping technique of striking two stones together, causing one of the stones to fracture and create sharp edges

L

La Niña phase of ENSO in which low-pressure Walker cells move westward, causing wetter conditions than normal in Australia

large igneous province (LIP) extremely large accumulation of igneous rocks formed when hot magma extrudes onto Earth's surface

latent heat heat lost or gained during a change of state

laterite soil or rock type rich in iron and aluminium

lava magma that has lost much of its volatiles and erupts at the surface of Earth

law of cross-cutting relationships law of stratigraphy, which states that an intrusion is always younger than the rock it cuts across

law of faunal succession law used for relative dating of rock layers, which states that groups of fossilised plants and animals succeed each other vertically in a specific order and this pattern can be seen over wide distances

law of inclusions law of stratigraphy, which states that included fragments are older than the rock in which they occur

law of lateral continuity law of stratigraphy, which states that layers of sediment are deposited as continuous layers that extend sideways until they peter out or something interrupts the spread

law of original horizontality law of stratigraphy, which states that sediments are originally deposited in horizontal layers

law of superposition law of stratigraphy, which states that the oldest stratum occurs at the bottom and the youngest stratum occurs at the top

lid upper solid mantle, which is the lower part of the lithosphere

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 a straight line that is fitted to a graph of data points

liquid immiscibility inability of two liquids to mix with each other

literature review report and evaluation of information from secondary sources

lithosphere Earth's spherical, outermost layer, composed of rigid crustal and mantle rocks

logbook record of an experiment or investigation kept by the scientist performing the experiments; it is a legal record of the experiments and their results

longwall method method of underground coal mining where coal is removed in thick slices along a longwall of up to several hundred metres

lustre appearance of light reflected off a mineral surface

M

Madden-Julian Oscillation weather pattern generated at the equator that has a period of several months

mafic silicate mineral rich in iron and magnesium; olivine and pyroxene are examples

magma fluid consisting of liquid rock, dissolved gases, solid minerals and rock fragments

magma differentiation changes in magma composition that occur due to material being removed or added

magmatic arc volcanic mountain chain and intrusions created at subduction zones

magnitude measure of the energy released in an earthquake

mantle layer of hot, solid rock that lies between Earth's crust and the molten iron core

mantle plume localised mass of hot mantle rising by convection

marine ecosystem that occurs in oceanic waters

mass balance difference between annual accumulation and annual ablation of a glacier or ice sheet

mass spectrometer instrument used to determine the masses of different chemical elements within a sample

matrix fine-grained material in a rock surrounding larger particles such as crystals, rock fragments or fossils

measurand quantity being measured

melt liquid part of a magma; the product of melting

mesosphere lowest layer of Earth's mantle, located between the core and the asthenosphere; layer of the atmosphere between the stratosphere and ionosphere

metamorphic rocks rocks formed from other rocks when crystals grow in a changed environment

meteorite large piece of solid rocky or metallic material that has landed on the surface of Earth after travelling through space

microplastic piece of plastic less than 5 millimetres long

Mid-Atlantic Ridge divergent tectonic plate boundary located on the floor of the Atlantic Ocean

mid-ocean ridge mountain range formed on the floor of the ocean by molten magma in the mantle rising up through a divergent plate boundary

mineral naturally occurring inorganic substance with a definite structure and composition

mineral deposit area where there is an accumulation of a certain mineral or minerals

mining boom period when there is increased demand and prices for mined commodities, leading to increased investment in mining

mixed layer another name for the surface layer of the oceans

model representation of a system or phenomenon that explains the system or phenomenon. A model may be mathematical equations, a computer

simulation, a physical object or words, or take another form

mountain geological feature that rises steeply above neighbouring terrain with a restricted summit area and a height greater than 610 m above its surroundings

N

nappe large sheet of rock that has been moved sideways by several kilometres due to faulting or folding

natural gas hydrocarbon gas consisting mainly of methane

natural selection survival of the organisms most suited to their environment so that they reproduce and pass their characteristics onto their offspring

normal fault type of fault in which land is pulled apart at a divergent plate boundary and the hanging wall drops down the footwall

O

ocean basin depression in the seabed where oceans occur

oceanic lithosphere part of the lithosphere that lies under the ocean, generally thinner and denser than continental lithosphere

ochre range of clays and oxides with colours ranging from pale yellow to orange to red; used as pigments

offshore drilling process that creates deep holes beneath the sea floor to explore for, or to extract, natural resources

onshore drilling process that creates deep holes on land to explore for, or to extract, natural resources

open-stoping method method of underground mining where large excavations occur, with the surrounding rock being strong enough to support the roof

ore rock or sediment that contains minerals of economic importance in a quantity that warrants mining

organic rocks rocks composed of material formed by biological processes

orogeny process that creates mountains

orographic relating to mountains

osmosis movement of water through a semi-permeable membrane to an area of higher ion concentration

outlier a data point that is distant from the other data points in the sample

P

parent nucleus starting nucleus before nuclear decay occurs

partial melting occurs when some, but not all, of the minerals in a rock melt

paterae broad, shallow bowl-shaped features

peds clumps in a soil formed of mineral particles bound together

peer review evaluation of scientific research by others working in the same field

percolation seepage of water through the soil

perennial plant that lives for several years

permafrost ground that has remained continually frozen for 2 or more years

permanentism discarded theory that the size and state of Earth has remained unchanged for most of its history

Permian–Triassic mass extinction event that occurred about 250 million years ago in which 90% of all marine species and 70% of all terrestrial species became extinct

petroleum mix of liquid hydrocarbons formed naturally by the action of heat on buried organic matter in marine sedimentary basins

pH measure of the acidity of a substance; lower values are more acid than higher values

photosynthesis chemical process that occurs when green plants combine carbon dioxide and water in the presence of light energy to produce simple sugars and oxygen

phreatic describes an explosive eruption caused when magma turns groundwater into steam

phreatomagmatic describes an explosive eruption caused when water comes into direct contact with magma

physical weathering process causing a rock or mineral to break into smaller pieces

phytoremediation use of living plants to clean up pollution in soil, air or water

planetesimal small planet that has formed from dust and rock

plastic deformation permanent change of shape, without breaking, due to stress in a material

plates slabs of Earth's crust and mantle that make up the lithosphere

plume body of hot material rising from deep in the mantle

pluton large body of igneous rock that solidifies deep beneath the surface

pore space space between mineral grains in a soil

porosity amount of pore space in a soil

precipitation deposition of water, ice or snow from the atmosphere to Earth's surface

precise (relating to scientific measurements) the degree to which individual measurements cluster around the mean

precision in science, a measure of the variability of the measurements; how close two or more measurements are to each other

primary data data that you have measured or collected yourself

product element *see* daughter nucleus

pyroclastic describes volcanic rock composed of fragments created by explosive eruptions

pyroclastic flow eruption of clouds of ash and heated gases that flows down the sides of a volcano

Q

quantitative describes something that can be measured, such as length, height, mass

R

radiation transfer of energy as electromagnetic waves or subatomic particles

radioactive isotopes types of atoms with unstable nuclei that emit excess energy in the form of radiation

radiogenic produced by radioactivity

radiometric dating use of the known rate of decay of radioactive isotopes to date material such as rock

range geographical area where a species lives

raw data original data taken directly from a measurement

recharge infiltration of surface water into an underground aquifer

reflect to bounce back off a boundary between layers

refract to bend when travelling across the boundary between layers

regional metamorphism formation of metamorphic rocks by heat and pressure

regolith broken crustal material that forms a layer between unaltered rock and the atmosphere

relative dating determining the order of past geological events

reliable relating to experiments, which when repeated, give the same results and random error is eliminated or minimised

remote sensing gathering information about a rock or soil from far away using equipment usually on a satellite or a plane

reproducibility giving the same result, within uncertainty, when repeated measurements are made

research question specific question that a particular experiment or investigation is designed to answer

reverse faulting type of fault that occurs when land is compressed at a convergent plate boundary and the hanging wall rises above the footwall

reverse osmosis water treatment using pressure to force water molecules through a semipermeable membrane that only allows the passage of small water molecules and excludes salts and other pollutants

ridge push force associated with the uplift of heated mantle material that creates the potential for plates to move away from a mid-ocean ridge

rift valley continuous trench formed on a divergent plate boundary where land is pulled apart

rock cycle model describing the interrelated processes forming and modifying rocks

room-and-pillar method method of underground mining where rooms are excavated and pillars of rock left to support the roof

run-off movement of water across the ground surface

rupture the breaking of a material when it reaches its elastic limit

S

salinisation increase in the salt concentration

satellite imagery images taken from satellites as they pass over Earth with the purpose of providing a view of the geology of the area below

scatter graph graphical representation of 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

secondary data data or information that has been collected by someone else

sector or pie graph circular graph that displays data as fractions or percentages of a whole

sedimentary rocks rocks formed from sediments and the products of weathering

seismic tomography imaging technique using S- and P-waves to explore inside Earth

seismic waves vibrational energy that can travel through Earth

seismic wave shadow zone part of Earth where seismographs cannot detect waves from a particular earthquake

seismometer instrument that detects seismic waves

shield area large tectonically stable area in Earth's crust composed of Precambrian crystalline igneous or high-grade metamorphic rocks

shield volcano volcano with shallow dipping sides formed when lava flows erupt from an eruptive centre, or crater, and flow outwards

silica another name for silicon dioxide

silicate mineral containing silicon–oxygen tetrahedra; the most common group of minerals in the lithosphere

siliceous ooze sediment made up of the silica skeletons of microscopic sea creatures that are deposited on the ocean floor

sill sheet of igneous rock that has been intruded between sedimentary rock layers

SI units standard units of measurement in science, based on multiples of the metre, second, kilogram, kelvin and ampere

slab pull force caused by the weight of cold, dense lithosphere sinking into the asthenosphere in a subduction zone

snowmelt water generated by the melting of snow and ice

soil complex system of fine-grained surface crustal material consisting of abiotic (non-living) and biotic (living) components

soil profile vertical section through a soil showing the soil horizons and possibly parent material

soil sampling collection of a representative amount of soil from a specific area to carry out analysis of the soil

solidus line indicating when melting begins on a pressure–temperature graph

solvent substance that can dissolve other substances

specific gravity ratio of a mineral's density to that of water

specific heat amount of heat needed to raise the temperature of 1 g of a substance by 1°C

spectrograph instrument that maps and measures electromagnetic radiation

strain change in shape, volume or length caused by a stress

strata layers

stratification formation of layers

stratigraphic column sequence of sedimentary rock with the oldest rock usually at the bottom and the youngest rock usually at the top

stratigraphic section *see* stratigraphic column

streak colour of powder produced when a mineral is crushed

stream sediment sampling collecting a representative amount of the fine material found in a stream bed for analysis to determine the composition of material further upstream

stress force acting per unit area on the surface of a body

subducted of a plate, to be moved under another plate at a plate boundary

subduction movement of one tectonic plate under another that occurs at a convergent plate boundary

subtropical high belt of high pressure at latitudes of 30°

sulfide mineral composed of metals combined with sulfur

surface layer upper, thin and well-mixed layer of the ocean

surface tension resistance of a fluid to change in its surface area

sustainable relating to maintaining the environment without causing harm

suture line joining together of plates along a fault line, usually characterised by mountain ranges

systematic error error that results in a consistent, predictable offset from the 'true' value; for example, a zero error

T

tectonics structural arrangement of rocks in Earth's crust

temperature measure of the vibrational energy of a substance

terrestrial ecosystems that occur on land

terrigenous sediment produced by erosion of rocks on the land

tetrahedron (plural: tetrahedra) molecular structure of the group SiO_4 in which four oxygens surround a silicon atom so that their centres form a four-sided pyramid

texture size, shape and arrangement of particles or mineral grains in a rock

thermocline layer in the ocean where the temperature steadily declines

thermohaline refers to the temperature and salinity factors that affect water density

thermohaline circulation global circulation of cold, salt water that redistributes heat in the ocean

thrust fault low-angle reverse fault created by compression

thrust sheet block of rock bounded above and below by thrust faults

trade winds surface winds of Hadley cells moving towards the equator and curving westward

transfer move from one place to another

transform change from one form to another

transform fault plate boundary where two tectonic plates slide horizontally past each other

transpiration process by which water moves from the soil through a plant until it escapes into the atmosphere

trench deep and narrow depression in the ocean formed when one tectonic plate subducts under another

trophic level position that an organism occupies in a food chain

tropopause upper boundary of the troposphere

troposphere layer of the atmosphere closest to Earth's surface

turbidity measure of the amount of suspended particles in water

U

uncertainties estimates of the range of values within which the 'true' value of a measurement or derived quantity lies

unconfined aquifer aquifer that is near the surface and easily recharged by surface waters

unconformities gaps in the geological rock record

underplating addition of material to the underside of a tectonic plate

upwelling replacement of water moved by Ekman flow by cold deeper water

V

valid describes results that are affected by a single independent variable and hence are reproducible

velocity speed of an object in a specified direction

viscosity resistance to flow

volatiles dissolved gases in a magma

W

Walker circulation convection cells that operate along the equator

waste rock material displaced when valuable ore has been removed from a mining site

water cycle model describing the circulation of water on Earth

water table saturated layer of an aquifer closest to the surface

weathering physical and chemical alteration and breakdown of rocks and minerals

X

xenolith older, pre-existing rock fragment incorporated into younger rock

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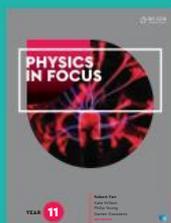
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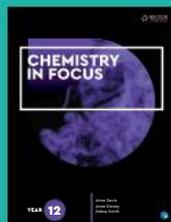
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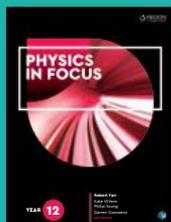
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