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Physical geography: fundamentals of the physical environment

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Undergraduate study in
Economics, Management,
Finance and the Social Sciences

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THE LONDON SCHOOL OF ECONOMICS AND POLITICAL SCIENCE

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This is one of a series of subject guides published by the University. We regret that due to pressure of work the authors are unable to enter into any correspondence relating to, or arising from, the guide. If you have any comments on this subject guide, favourable or unfavourable, please use the form at the back of this guide.

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Introduction

Welcome to this 100 course, **147 Physical geography: fundamentals of the physical environment**, which most of you will be studying at the start of your BSc Geography and Environment.

Understanding the physical environment is fundamental to understanding the planet on which we live. Everything we do – from the energy resources we use to the weather we experience – is controlled by the Earth's physical environment. For the first time ever it seems that we are also influencing the global physical environment by adding carbon dioxide to the atmosphere causing global warming.

In this course we will investigate the structure of the Earth and how violent movements of the surface plates can cause volcanoes, earthquakes and tsunamis, sometimes resulting in the loss is hundreds of thousands of lives, such as the 2004 Boxing Day Southeast Asian tsunami. We will take a look at how weather is produced, which can result in massive hurricanes and the destruction of whole cities, such as New Orleans in 2005. We then put the two parts of the course together and see how changes in the position of the continents have affected global climate and even evolution.

The most important resource for life on the planet is water so we will also take a look at how the water cycle works. This leads us to how the landscape around us has been shaped over millennia by the action of water, ice and wind. We also investigate the biosphere, how and why plants and animals differ in different environments and how life has maintained a habitable environment on the Earth for the last 500 million years. Finally, we look at how the global environment has changed, first as a result of the coming and going of the great ice ages, when there were ice sheets 3 km thick over North America and Europe.

We investigate how we humans are currently changing the physical environment of the planet by warming it up and we look at what the consequences of global warming will be if we do nothing about it.

Aims and objectives

This course provides a wide-ranging introduction to the principles of physical geography. These are concerned with the form and functioning of the natural environment and how they change over various timescales.

This course is the foundation for further and more detailed study in the fields of geomorphology, climatology, biogeography, hydrology and past environmental change. It also provides valuable context for studying human geography in areas such as environmental management and sustainability.

Learning outcomes

After completing this course you should have:

- insight into the basic components of the natural environment and an understanding of how these are shaped by natural and some human processes
- knowledge of how these processes interact with one another and some perspective of both the time and spatial scales at which they operate.

These skills will be developed by using ideas and information acquired from reading to approach problems and answer questions about the natural environment.

Syllabus

There are no prerequisites for this course. Topics covered in this course are:

- Composition of the Earth: plate tectonics, earthquakes, volcanoes, rock types, geohazards.
- Tectonics and climate: setting the scene for our unique modern climate system.
- Atmosphere: composition and circulation.
- Hydrosphere and landscape evolution: precipitation, rivers, lakes, erosion, weathering patterns, hillslope dynamics.
- Oceans: surface and deep circulation, upwelling, productivity and climate.
- Biosphere: evolution, ecosystem concepts, ecological processes, soil dynamics, vegetation–geology–climate interactions.
- Global environmental change: glacial-interglacial cycles, sea-level changes, Heinrich events, El Niño Southern Oscillation, North Atlantic oscillation, global warming.

How to use this subject guide

For some courses that you study, you are directed to read your essential textbooks after you have worked through a chapter. For this course, the best thing to do is skim-read through the chapter to give you an idea of what the chapter is about, then familiarise yourself with the chapters in your textbooks. Then work slowly and carefully through the chapters in this guide, taking note of the learning outcomes.

We have provided you with activities throughout. We suggest that you do these, as they will bring together the topics and help you to understand them. You are strongly advised to have access to the internet as we will direct you to the internet to so dome research for some of these activities.

When you have finished the chapter make sure that you can 'tick off' all of the points you should have covered. If you can't, go back and read again carefully. You might find that visiting some of the websites that we recommend may well help bring your studies together as they can provide many more interactive features and illustrations than we can in this subject guide.

Reading

You will find advice on what books you need to buy or otherwise have access to at the beginning of each of the chapters of this guide. You should not continue to use an old edition of a textbook if a new edition has been published. Always buy the latest edition of recommended textbooks; if the latest edition is more recent than the edition to which the subject guide refers, use the index and tables of contents to identify the relevant parts of the new edition.

We have provided here for ease of reference a listing of all the reading and resources in this course.

Essential reading

Christopherson, R.W. *Geosystems: An Introduction to Physical Geography.* (Upper Saddle River, NJ: Pearson Education, 2011) eighth edition [ISBN 9780321770769].

Maslin, M. *Global Warming: A Very Short Introduction.* (Oxford: Oxford University Press, 2008) [ISBN 9780199548248].

Ruddiman, W. *Earth's Climate: Past and Future.* (New York: Freeman, 2007) second edition [ISBN 9780716784906].

Smithson, P., K. Addison and K. Atkinson *Fundamentals of the Physical Environment*. (London: Routledge, 2008) fourth edition [ISBN 9780415395168].

Waugh, D. *Geography: An Integrated Approach.* (Walton-on-Thames: Nelson Thornes, 2009) fourth edition [ISBN 9781408504079].

Detailed reading references in this subject guide refer to the editions of the set textbooks listed above. New editions of one or more of these textbooks may have been published by the time you study this course. You can use a more recent edition of any of the books; use the detailed chapter and section headings and the index to identify relevant readings. Also check the virtual learning environment (VLE) regularly for updated guidance on readings.

Further reading

Please note that as long as you read the Essential reading you are then free to read around the subject area in any text, paper or online resource. You will need to support your learning by reading as widely as possible and by thinking about how these principles apply in the real world. To help you read extensively, you have free access to the VLE and University of London Online Library (see below).

Other useful texts for this course include:

Barry, R. and R. Chorley *Atmosphere, Weather and Climate.* (London: Routledge, 2001) seventh edition [ISBN 0415077613].

Bell, M. and M.J.C. Walker *Late Quaternary Environmental Change: Physical and Human Perspectives.* (London: Longman, 1992) [ISBN 0582045142].

Benn, D.I. and D.J.A. Evans *Glaciers and Glaciation*. (London: Arnold, 1997) [ISBN 0340584319].

Bradley, R. *Quaternary Paleoclimatology*. (London: Academic, 1999) [ISBN 012124010X].

Bras, R.E. *Hydrology: An Introduction to Hydrologic Science.* (Reading, MA: Addison-Wesley, 1990) [ISBN 0201059223].

Briggs, D. and P. Smithson *The Fundamentals of Physical Geography*. (London: Routledge, 1993) [ISBN 0044458223].

Burroughs, W. *Climate Change: A Multidisciplinary Approach*. (Cambridge: Cambridge University Press, 2001) [ISBN 0521567718].

Collard, R. *The Physical Geography of Landscape*. (London: Collins Educational, 1992) [ISBN 0003222853].

Cox, J. *Weather for Dummies*. (New York: Hungry Minds, Inc., 2000) [ISBN 0764552430].

Davies, G.F. *Dynamic Earth*. (Cambridge: Cambridge University Press, 1999) [ISBN 0521590671].

Dickson, G. and K. Murphy *Ecosystems*. (London: Routledge, 1997) [ISBN 0415145139].

Hay, W.W. 'Tectonics and climate', *Geologische Rundschau: Zeitschrift für allgemein Geologie* 85 1996, pp.409–37.

Henderson-Sellers, A. and P.J. Robinson *Contemporary Climatology*. (Harlow: Longman, 1999) [ISBN 0582276314].

Imbrie, J. and K.P. Imbrie *Ice Ages: Solving the Mystery*. (Cambridge, MA: Harvard University Press, 1986) [ISBN 0674440757].

Keller, E. *Active Tectonics: Earthquakes, Uplift, and Landscape*. (Upper Saddle River, NJ: Prentice Hall, 1995) [ISBN 0023632615].

Knighton, D. *Fluvial Forms and Processes*. (London: Arnold, 1998) [ISBN 0340663138].

Lamb, S., and D. Sington *Earth Story*. (London: BBC Consumer Publishing, 1998) [ISBN 0563387998].

Lowe, J. and M. Walker *Reconstructing Quaternary Environments*. (Harlow: Longman Higher Education, 1997) second edition [ISBN: 0582101662].

Molnar, P. and P. England 'Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg?', *Nature* 346 1990, pp.29–34.

Morton, O. 'The storm in the machine', *New Scientist* 157 1998, pp.22–27.

Newson, M.D. *Hydrology and the River Environment*. (Oxford: Blackwell, 1994) [ISBN 019874157X].

O'Hare, G. *Soils, Vegetation and The Ecosystem*. (Harlow: Oliver & Boyd, 1988) [ISBN 0050042378].

Open University *Dynamic Earth*. (Milton Keynes: Open University, 1997) [ISBN 0749281839].

Open University *Ocean Circulation*. (Oxford: Open University/Pergamon Press, 1989) [ISBN 0080363695].

Robinson, D.A. and R.G.B. Williamson *Rock Weathering and Landform Evolution*. (Chichester: John Wiley and Sons, 1994) [ISBN 0471951196].

Rowell, D.L. *Soil Science: Methods and Applications*. (Upper Saddle River, NJ: Prentice Hall, 1994) [ISBN 0582087848].

Shaw, E.M. *Hydrology in Practice*. (London: Chapman and Hall, 1994) [ISBN 0412482908].

Skinner, B. and S. Porter *The Dynamic Earth: An Introduction to Physical Geology*. (Chichester: John Wiley and Sons, 2000) fourth edition [ISBN 0471161187].

Slaymaker, O. and T. Spencer *Physical Geography and Global Environmental Change*. (Harlow: Longman, 1998) [ISBN 0582298296].

Summerfield M.A. *Global Geomorphology*. (Harlow: Longman, 1991) [ISBN 0582301564].

Van Andel, T.H. *New Views on an Old Planet: A History of Geological Change*. (Cambridge: Cambridge University Press, 1994) [ISBN 0521447550].

Ward, R.C. and M. Robinson *Principles of Hydrology*. (London: McGraw-Hill, 1999) [ISBN 0077095022].

Watson, R. (ed.) *Climate Change 2001: Synthesis Report IPCC Intergovernmental Panel on Climate Change, The Intergovernmental Panel on Climate*. (Cambridge: Cambridge University Press, 2002) [ISBN 0521015073].

Williams, M., D. Dunkerley, P. de Deckker, P. Kershaw and J. Chappell (eds) *Quaternary Environments*. (London: Arnold, 1998) [ISBN 0340691514].

Wilson, R.C.L., S.A. Drury and J.L. Chapman (eds) *The Great Ice Age*. (London: Routledge, 1999) [ISBN 0415198429].

Online study resources

In addition to the subject guide and the Essential reading, it is crucial that you take advantage of the study resources that are available online for this course, including the VLE and the Online Library.

You can access the VLE, the Online Library and your University of London email account via the Student Portal at:

http://my.londoninternational.ac.uk

You should receive your login details in your study pack. If you have not, or you have forgotten your login details, please email uolia.support@london.ac.uk quoting your student number.

The VLE

The VLE, which complements this subject guide, has been designed to enhance your learning experience, providing additional support and a sense of community. It forms an important part of your study experience with the University of London and you should access it regularly.

The VLE provides a range of resources for EMFSS courses:

- Self-testing activities: Doing these allows you to test your own understanding of subject material.
- Electronic study materials: The printed materials that you receive from the University of London are available to download, including updated reading lists and references.
- Past examination papers and *Examiners' commentaries*: These provide advice on how each examination question might best be answered.
- A student discussion forum: This is an open space for you to discuss interests and experiences, seek support from your peers, work collaboratively to solve problems and discuss subject material.
- Videos: There are recorded academic introductions to the subject, interviews and debates and, for some courses, audio-visual tutorials and conclusions.
- Recorded lectures: For some courses, where appropriate, the sessions from previous years' Study Weekends have been recorded and made available.
- Study skills: Expert advice on preparing for examinations and developing your digital literacy skills.
- Feedback forms.

Some of these resources are available for certain courses only, but we are expanding our provision all the time and you should check the VLE regularly for updates.

Making use of the Online Library

The Online Library contains a huge array of journal articles and other resources to help you read widely and extensively.

To access the majority of resources via the Online Library you will either need to use your University of London Student Portal login details, or you will be required to register and use an Athens login:
http://tinyurl.com/ollathens

The easiest way to locate relevant content and journal articles in the Online Library is to use the Summon search engine.

If you are having trouble finding an article listed in a reading list, try removing any punctuation from the title, such as single quotation marks, question marks and colons.

For further advice, please see the online help pages:
www.external.shl.lon.ac.uk/summon/about.php

Examination advice

Important: the information and advice given here are based on the examination structure used at the time this guide was written. Please note that subject guides may be used for several years. Because of this we strongly advise you to always check both the current *Regulations* for relevant information about the examination, and the VLE where you should be advised of any forthcoming changes. You should also carefully check the rubric/instructions on the paper you actually sit and follow those instructions.

Remember, it is important to check the VLE for:

- up-to-date information on examination and assessment arrangements for this course
- where available, past examination papers and *Examiners' commentaries* for the course which give advice on how each question might best be answered.

This course is assessed by a three-hour unseen written examination. There is a Sample examination paper at the end of this subject guide on p.145. You will be required to answer three questions from a choice of 10. The Examiners may set questions on any part of the syllabus, or set questions which draw together parts of the syllabus.

Chapter 1: The structure of the Earth

Essential reading

Christopherson, R.W. *Geosystems: An Introduction to Physical Geography.* (Upper Saddle River, NJ: Pearson Education, 2011) eighth edition [ISBN 9780321770769] Chapters 11 and 12.

Smithson, P., K. Addison and K. Atkinson *Fundamentals of the Physical Environment*. (London: Routledge, 2008) fourth edition [ISBN 9780415395168] Chapter 10.

Waugh, D. *Geography: An Integrated Approach*. (Walton-on-Thames: Nelson Thornes, 2009) fourth edition [ISBN 9781408504079].

Further reading

Collard, R. *The Physical Geography of Landscape*. (London: Collins Educational, 1992) [ISBN 0003222853].

Keller, E. *Active Tectonics: Earthquakes, Uplift, and Landscape* (Upper Saddle River, NJ: Prentice Hall, 1995) [ISBN 0023632615].

Open University, *Dynamic Earth*. (Milton Keynes: Open University, 1997) [ISBN 0749281839].

Skinner, B. and S. Porter *The Dynamic Earth: An Introduction to Physical Geology*. (Chichester: John Wiley and Sons, 2000) fourth edition [ISBN 0471161187].

Summerfield, M.A. *Global Geomorphology*. (Harlow: Longman, 1991) [ISBN 0582301564].

Internet resources

http://earthobservatory.nasa.gov/

If you are going to visit just one website out of the ones listed, visit this one! An excellent site, containing information about practically everything there is to know about planet Earth. Highly recommended. Pay particular attention to http://earthobservatory.nasa.gov/Study/ which contains many excellent links to useful snippets of information.

http://earthobservatory.nasa.gov/Laboratory/

Interactive experiments where you can learn how and why the Earth changes through the use of interactive computer models. Although these experiments are aimed at younger members of the population, they contain useful background information. The 'Mission Biome' experiment is particularly informative: (http://earthobservatory.nasa.gov/Laboratory/Biome/).

www3.cerritos.edu/earth-science/tutor/landform_identification.htm

Online landform identification, with 'virtual visits' to field examples.

http://geothermal.marin.org/pwrheat.html

Information about geothermal energy from the Geothermal Education Office.

www.abag.ca.gov/bayarea/eqmaps/links.html

Maps of current earthquake activity.

www.abag.ca.gov/bayarea/eqmaps/eqmaps.html

A site full of information pertaining to earthquakes, from maps of earthquakes (principally California) to the effects of earthquakes.

Learning outcomes

When you have studied this chapter and the recommended reading, you should be able to:

- describe the nature and composition of the Earth's crust
- outline the history and explain the theory of plate tectonics
- discuss the types of landforms that occur at different plate boundaries
- describe the main features of an earthquake
- list the different landforms associated with vulcanicity, and describe the different types of volcano
- explain the three main rock types and discuss their differences.

Introduction

This chapter introduces the fundamental aspects of the structure of the Earth. We begin with the composition of the Earth and why there are different layers. For us the most important layer is the crust, which is constantly moving. The theory of this constant movement of the surface of the Earth is called plate tectonics and influences every aspect of the natural environment, for example where the continents have a huge impact on global climate (see Chapter 3). Plate tectonics also influence the composition of the atmosphere (see Chapters 2 and 3). However, what we discuss in this chapter is how plate tectonics cause geohazards such as earthquakes, volcanoes and tsunamis. In addition, we discuss the landforms that are the results of our dynamic and restless planet.

Structure of the Earth

We have found out about the Earth's structure through many subtle forms of investigation, particularly by studying the paths of earthquake waves as they travel through the Earth's interior, and by studying evidence of volcanic eruptions which bring material from deep within the Earth's interior to the surface.

You will see from Figure 1.1 that the Earth's structure is divided into three zones.

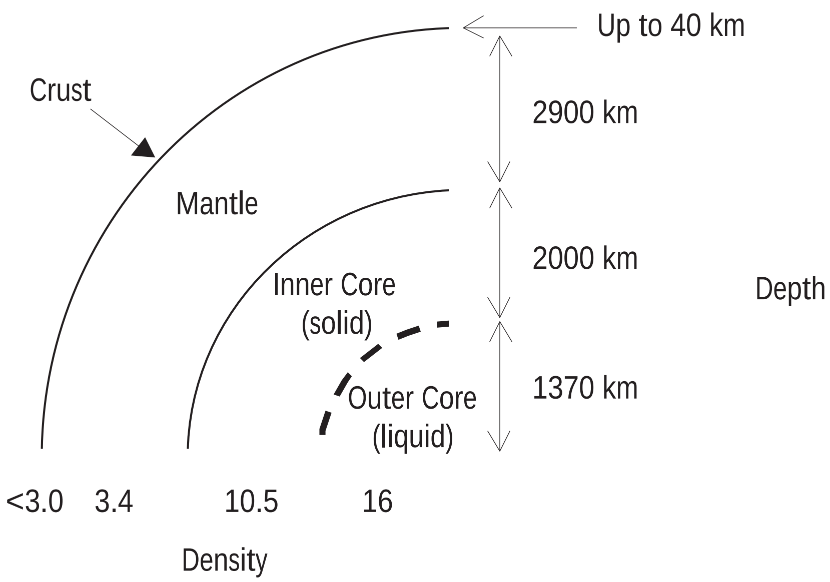

Figure 1.1: The structure of the Earth

Crust

This is the solid outer layer of the Earth, and in relative terms, this is equivalent to the skin of an apple. Its depth is usually never more than 1 per cent of the Earth's radius, or averaging 40–50 km, but this varies considerably around the globe. There are two different types: oceanic and continental and they are compared in Table 1.1.

Oceanic crust	Continental crust
Known as sima (rich in silica, and magnesium)	Known as sial (rich in silica and aluminium)
Composed mainly of basaltic lavas	Composed mainly of granitic rocks
Average 6–10 km in thickness	Average 35–40 km in thickness, but can be up to 70 km thick under mountain ranges
Relatively denser than continental crust (average density = 3; NB water = 1)	Relatively less dense than oceanic crust (average density 2.7–2.8; NB soil = 2.75)
Can be subducted beneath continental crust as it is denser. At its deepest (in subduction zones), has a temperature of 1200°C	Cannot be subducted, but instead 'floats' above the denser oceanic crust
Occurs under the oceans and forms 60–70 per cent of the total crust	Occurs only under large land masses or continental shelves, or beneath certain shallow seas, and forms 30–40 per cent of the total crust
Relatively younger than continental crust (is destroyed at subduction zones and is recycled)	Relatively older than oceanic crust – the world's oldest rocks are the great continental shields, e.g. North America, Australia.

Table 1.1: The differences between oceanic and continental crust

The boundary between the crust and the mantle is known as the **Mohovoriãiç discontinuity**, or 'Moho'. At this point, shockwaves (e.g. from earthquakes) begin to travel faster, indicating a change in structure.

Mantle

This is the zone within the Earth's interior ranging from 25 to 70 km below the surface, to a depth of ~2,900 km. It is composed mainly of silicate rocks, rich in iron and magnesium. Apart from the rigid top layer (the **lithosphere**, which also includes the crust), the lower mantle (the **asthenosphere**) remains in a semi-molten[1] state. At the base of the mantle, temperatures may reach up to 5,000°C. These high temperatures may help to generate convection currents which drive plate tectonics.

[1] Molten = melted, so it becomes like liquid

The boundary between the mantle and the core is known as the **Gutenberg discontinuity**.

Core

This is the very centre of the Earth and is composed of iron and nickel. It consists of an outer core (semi-molten) and inner core (solid). The temperature at the very centre of the Earth (~6,300 km below surface) may reach 5,500°C.

Activity

Study the above section carefully, and make sure that you understand the differences between the each of 'zones' of the Earth's structure. If it will make it clearer, redraw Figure 1.1, and make your own annotations from the text, and the information given in Table 1.1.

Plate tectonics

History

Francis Bacon (in 1620) was the first to formally draw attention to the fact that the continents could be fitted together like a jigsaw puzzle.

In the early twentieth century, both Alfred Wegener (Germany) and F.B. Taylor (USA) came independently to same idea, that continents were not static, but were drifting. However, the concept of **continental drift** usually attributed to Alfred Wegener.

Wegener suggested that there was once one large supercontinent, which he named **Pangea**. From the Carboniferous (250 million years ago) until some time in the Quaternary (from 2.5 million years ago), this broke up, first splitting into **Laurasia** in the north and **Gondwanaland** in the south, before forming the continental configurations that we know today. You can see his theory in Figure 1.2.

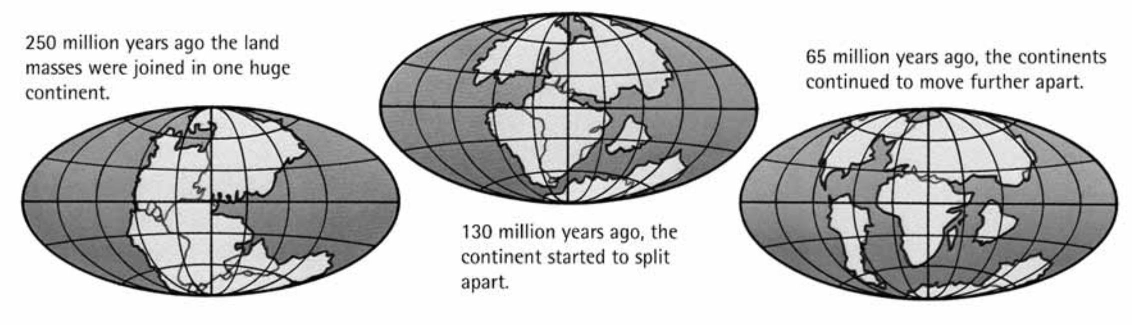

Figure 1.2: The supercontinent cycle

Wegener drew evidence from several sciences to support this theory.

Biology

- Certain identical rare fossils have been found in different continents, now separated by vast oceans.
- *Mesosaurus* (a small Permian reptile), for example, has only been found in South Africa and Brazil.
- A plant which existed only during coal-forming times has only been found in India and Antarctica.

Geology

- Rocks of similar type, formation and age have been found in South Africa and Brazil.
- Mountain ranges and fold belts all become consistent if the modern-day continents are fitted back into the Pangean landmass (e.g. the mountains of northwest Europe correspond geologically with the Appalachians of the USA). Look at Figure 1.2 and imagine where the modern-day mountain ranges are found – you will see that when the continents are fitted together, the mountain ranges line up.

Climatology

- Evidence of glaciation has been found in tropical Brazil and central India.
- Coal (which forms under warm, humid conditions) has been found under Antarctica.
- Limestone, sandstone and coal found in Britain could not have formed under its current climatic regime.

However, Wegener's theory was rejected at first, mainly because he was unable to explain a driving mechanism that would force the continents to drift apart.

Later evidence in support of sea floor spreading

In the 1950s, scientists began to study palaeomagnetism – as molten lava cools at the surface of the Earth's crust, the minerals contained within it (especially iron) align themselves with the magnetic pole. Although the Earth's magnetic pole was already known to vary on an annual basis, it was discovered that periodically, the magnetic pole actually reversed completely (during the past 76 million years, there are thought to have been 171 reversals). As new lava was being extruded from the submarine volcanoes, the minerals contained within it would therefore align themselves according to the direction of the **magnetic pole**, and would thus contain a record of the Earth's magnetic polarity. This magnetic striping was found to be virtually symmetrical either side of the Mid Atlantic Ridge.

In 1962, while investigating islands in the mid-Atlantic, American oceanographer Maurice Ewing discovered a continuous submarine mountain range extending the entire longitudinal length of the Atlantic sea floor. He also noted that the rocks were of volcanic origin, and geologically young (not ancient, as previously assumed). What he had actually discovered was in fact the Mid Atlantic Ridge.

Also in 1962, there was the discovery that the sea floor was spreading. While studying the age of rocks from the edge of the North American coast to the middle of the Atlantic Ocean, American geologist Harry Hess discovered that the rocks became progressively younger towards the Mid Atlantic Ridge. He confirmed that the newest rocks were still being formed in Iceland, and that the Atlantic could be widening by up to 5 cm per year.

However, if new crust was being formed at the Mid Atlantic Ridge, yet the Earth was not expanding in size, evidence was needed to suggest that the crust must be being destroyed elsewhere. This was found to be so around the margins of the Pacific, and thus the now virtually universally accepted theory of plate tectonics was born.

The theory of plate tectonics

The Earth's lithosphere (crust and upper mantle) is divided into seven large, and several smaller **plates** (see Figure 1.3). These plates are constantly moving, and are driven by convection currents in the mantle. Plate boundaries mark the sites of the world's major landforms, and they are also areas where mountain-building, volcanoes and earthquakes can be found.

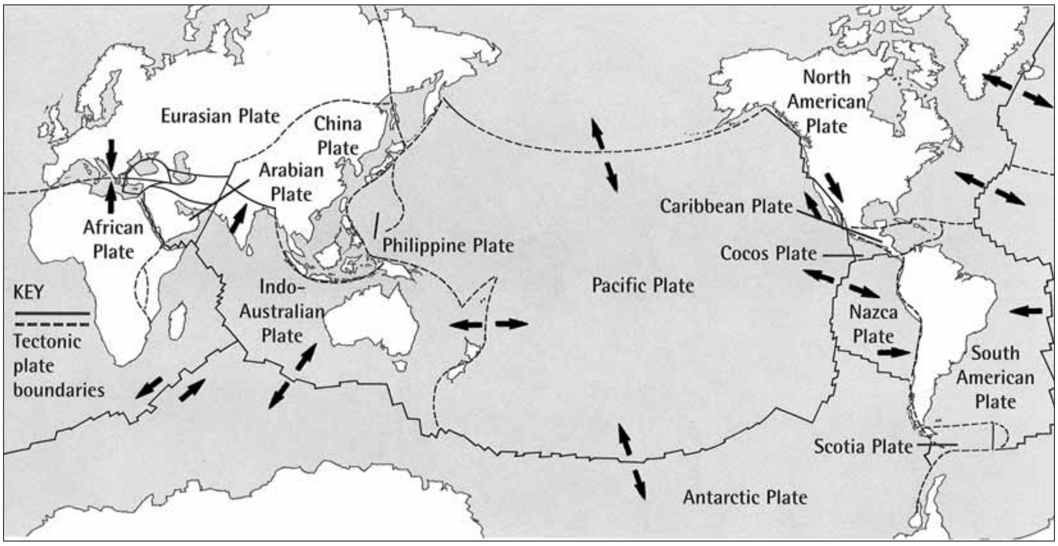

Figure 1.3: The world distribution of tectonic plate boundaries

However, in order to account for such activity at the plate boundaries, several points should be noted (modified from Waugh, 2000):

- Continental crust is less dense than oceanic crust so it does not sink. Whereas oceanic crust is continuously being created and destroyed, continental crust is permanent, and hosts the oldest rocks on the planet (the shieldlands).
- Continental plates may be composed of both continental and oceanic crust (e.g. Eurasia).
- Continental crust may extend further than the margins of the land masses (when continental crust is covered by an ocean, it is known as **continental shelf**).
- It is not possible for plates to overlap, so they may either crumple up to form mountain chains, or one plate must sink below the other.
- If two plates are moving apart, new crust is formed in the intervening space, as no 'gaps' may occur in the Earth's crust.
- The earth is not expanding, so if newer crust is being created in one area, older crust must be being destroyed elsewhere.
- Plate movements are geologically fast and continuous. Sudden movements manifest themselves as earthquakes.
- Very little structural change takes place in the centre of the plates (the shieldlands). Plate margins mark the sites of the most significant landforms, including volcanoes, batholith intrusions, fold mountains, island arcs and deep-sea trenches (see later sections throughout this chapter).

Plate boundaries

There are three types of plate boundary (or margin): constructive, destructive and passive.

Constructive margins

These arise where two plates move away from each other, and new crust is created at the boundary. They are mainly found between oceanic plates, and are consequently underwater features. Rift valleys may initially develop, but molten rock from the mantle (magma) rises to fill any possible gaps. Constructive margins are often marked by ocean ridges (e.g. the Mid Atlantic Ridge, the East Pacific Rise). The rising magma forms submarine volcanoes, which in time may grow above sea level (e.g. Iceland, Tristan da Cunha and Ascension Island on the Mid Atlantic Ridge, and Easter Island on the East Pacific Rise). Different rates of latitudinal movement along the boundary cause **transform faults** to develop as the magma cools – these lie perpendicular (at a right angle) to the plate boundary. Of the annual volume of lava[2] ejected onto the Earth's surface, 73 per cent is found on mid-ocean ridges, and approximately one-third of the lava ejected onto the Earth's surface during the past 500 years is found in Iceland. The Atlantic Ocean formed as the continent of Laurasia split in two, and the Atlantic is continuing to widen by approximately 2–5 cm per year.

[2] Once magma reaches the Earth's surface, it is known as lava.

Very rarely, constructive margins can occur on land, and it is thought that this is happening in East Africa at the Great African Rift Valley System. Extending for 4,000 km from the Red Sea to Mozambique, its width varies from 10 to 50 km, and at points its sides reach over 600 m in height. Where the land has dropped sufficiently, the sea has invaded – it has been suggested that the Red Sea is the beginnings of a newly forming ocean. Associated volcanoes include Mount Kilimanjaro and Mount Kenya to the east and Ruwenzori to the west.

Destructive margins

These occur where two plates move towards each other, and one is forced below the other into the mantle. The Pacific Ocean is virtually surrounded by destructive plate margins with their associated features, and its perimeter has become known as the Pacific Ring of Fire. The features present at destructive margins will depend upon what types of plates are converging.

When oceanic crust meets continental crust:

- The thinner, denser oceanic crust is forced to dip downwards at an angle and sink into the **subduction zone** beneath the thicker, lighter and more buoyant continental crust.
- A **deep-sea trench** forms at the plate margin as subduction takes place. These form the deepest areas on the planet.
- As the oceanic crust descends, the edge of the continental crust may crumple to form **fold mountains**, which run in chains parallel to the boundary (e.g. the Andes).
- Sediments collecting in the deep-sea trench may also be pushed up to form fold mountains.
- As the oceanic crust descends into the hot mantle, additional heat generated by friction helps the plate to melt, usually at a depth of 400–600 km below the surface.
- As it is less dense than the mantle, the newly formed magma will tend to rise to the Earth's surface, where it may form volcanoes.
- However, as the rising magma at destructive margins is very acidic, it may solidify before it reaches the surface and form a batholith at the base of the mountain chain (see below).
- As the oceanic plate descends, shallow earthquakes occur where the crust is stretched as it dips beneath the surface. Deeper earthquakes arise from increases in friction and pressure may be released as earthquakes.
- As the oceanic plate descends, increased stresses may trigger earthquakes: shallow earthquakes occur where the crust is stretched as it dips beneath the surface, and deeper earthquakes occur due to increases in friction and pressure as the plate subducts.

- The area in the subduction zone where most earthquakes take place is known as the **Benioff zone**.
- The depth of the deeper earthquakes may also provide an indication as to the angle of subduction, where gentler angles of subduction give rise to shallower earthquakes.
- If subduction occurs offshore, **island arcs** may form (e.g. Japan, the West Indies).

When oceanic crust meets oceanic crust:

- Where two oceanic plates collide, either one may be subducted.
- Similar features arise as those where an oceanic plate meets a continental plate.

When continental crust meets continental crust (note that this is very rare):

- Because continental crust cannot sink, the edges of the two plates and the intervening sediments are crumpled to form very deep-rooted fold mountains.
- The zone marking the boundary of the two colliding plates is known as the **suture line**.
- These boundaries mark the site at which the Earth's crust is at its thickest. For example, the Indo-Australian Plate is moving northeastwards and is crashing into the rigid Eurasian Plate, creating the Himalayas.
- Uplift is a continuous process (it is happening right now); however, weathering and erosion of the mountain tops means that the actual height of the mountains is not as great as the rate of uplift would suggest.
- Sediments which form part of the Himalayas were once underlying the Tethys Sea, which existed at the time of the Pangean supercontinent.

Passive margins

These occur where two plates slide past each other and crust is neither created nor destroyed. The boundary between the two plates is characterised by pronounced **transform faults**, which lie parallel to the plate boundary. As the plates slide past each other, friction builds up and causes the plates to stick, and release is in the form of earthquakes.

An excellent example of a passive margin is the San Andreas Fault (one of several hundred known faults) in California, which marks a junction between the North American and the Pacific Plates. Although both plates are moving in a northwesterly direction, the Pacific Plate moves at a faster rate than the North American late (6 cm per year, compared with just 1 cm per year), creating the illusion that the plates are moving in opposite directions.

Activity

Many good textbooks have figures illustrating the different plate margins – you should be able to find good examples in the recommended reading, for example. Using these figures as guides, sketch out your own diagram for each type of margin, being sure to annotate the main features. Features to note include, for example:

Constructive margins – in the ocean

- central rift valley
- fractures and transform faults on the sea bed
- rising magma from the asthenosphere
- arching oceanic crust creating a ridge along the sea floor.

Constructive margins – on land

- rift valley/rift valley system
- central plateau
- rising magma forming volcanoes

Destructive margins – oceanic meets continental crust

- descending oceanic crust
- oceanic trench at the subduction zone
- Benioff zone where earthquakes occur
- fold mountains at edge of continental plate
- melting oceanic crust, which rises to the surface to form volcanoes

Destructive margins – oceanic meets oceanic crust

- descending oceanic crust
- oceanic trench at the subduction zone
- Benioff zone where earthquakes occur
- melting oceanic crust, which rises to the surface to form volcanoes
- chain of volcanic islands (island arc)

Destructive margins – continental meets continental crust

- suture line (marking the point of collision)
- collision zone
- deep mountain roots

Passive margins

- tension faults that develop near to the margin

On each figure, also mark the direction in which the plates are moving – this may help you to understand why some of the features are occurring.

Earthquakes

General information

Earthquakes result from the sudden release of pressure which has slowly built up within the rocks of the Earth's crust. Energy is released in the form of shockwaves known as **seismic waves**, which lose energy as they radiate outwards from the centre of the earthquake (the **focus**). The point on the Earth's surface that suffers the greatest intensity of seismic waves is the **epicentre**, which lies directly above the focus.

Earthquake **intensity** is measured on the **modified Mercalli scale**, which ranges from one to 12, depending upon the intensity (see Table 1.2). This is a semi-quantitative linear scale.

Earthquake **magnitude** is measured on the **Richter scale** (named after the seismologist who devised it), which rates them on a scale of one to nine. It is a logarithmic scale where each step represents a tenfold increase in measured wave amplitude. Translated into energy, each whole number represents a 31.5-fold increase in energy release. Thus a magnitude 3.0 on the Richter scale is 31.5 more energy than a 2.0 and 992 times more energy than a 1.0. A value greater than 7.0 denotes a major earthquake. Since 1993 the Richter scale has been improved, as it was difficult to measure or differentiate between quakes at high intensity. The **moment magnitude scale** is more accurate than the original Richter amplitude magnitude scale. For example, the 1964 earthquake at Prince William

Sound in Alaska had an amplitude magnitude of 8.6 but on the moment magnitude scale it increased to a 9.2. The largest earthquake recorded occurred in Chile, in 1960, and reached 9.6 on the moment Richter scale (see Table 1.2). This earthquake is closely followed by the magnitude 9.0 which occurred in northern Sumatra on 26 December 2004, causing the most destructive tsunami ever. Most major earthquakes have magnitudes of ~6.5. The Richter scale is a quantitative logarithmic scale.

Modified Mercalli scale (intensity)	Description of effects on land	Richter scale (magnitude)
I	Vibrations show up on instruments; however, movement is not felt by humans.	0.0–4.3
II	Movement felt by those resting and/or on the upper floors of tall buildings.	
III	Shaking felt inside buildings. Hanging objects swing. People outside may not realise earthquake is taking place.	
IV	Most people indoors feel movement. Hanging objects may swing. Windows, doors and dishes rattle. Parked cars may rock. Some people outside may feel movement.	4.3–4.8
V	Movement noticed by all. Doors swing open and closed, liquids spill, dishes break, etc. Pictures and wall hangings swing. Small objects may move/fall over. Those sleeping may wake up. Trees may shake.	
VI	People have difficulty walking. Movement felt by all. Windows break, pictures fall off walls, furniture moves, objects fall from shelves. Plaster in walls may begin to crack. Trees and bushes shake. No major structural damage, although it may be slight in poorly constructed buildings.	4.8–6.2
VII	People have difficulty standing. Drivers feel their cars shaking. Some furniture breaks. Large bells ring. Plaster, loose bricks and tiles fall from buildings. Slight-to-moderate damage in well-constructed buildings, considerable damage in poorly constructed buildings.	
VIII	Car steering may be affected. Tree branches break. Well-constructed buildings may suffer slight damage. Houses that are not secured down may begin to move off their foundations. Poorly constructed buildings may experience severe damage. Tall structures (including towers and chimneys) may fall. Cracks appear in wet ground, hillslides may take place in wet ground. Water levels in wells may change.	6.2–7.3
IX	General panic among populations. Sand and mud may bubble from the ground. Well-constructed buildings may be severely damaged. Houses that are not secured down may move off their foundations. Reservoirs experience damage. Some underground pipes are broken. Cracks appear on the ground.	
X	Most buildings collapse, some bridges may be affected. Railway tracks begin to bend. Dams seriously damaged. Large landslides may occur, and water may be thrown onto the banks of rivers, canals, lakes, etc. Large cracks appear on the ground.	
XI	Large cracks appear on the ground. Rocks fall. Railway tracks bend and roads break up. Most buildings destroyed (some earthquake-proof buildings may withstand tremors up to 8.5 on the Richter scale). Some bridges may collapse. Underground pipelines destroyed.	7.3–8.9
XII	Total destruction. Ground moves in a wave-like motion. Large amounts of rock may be moved. Rivers change their course. Objects are thrown into the air. Vision is blurred.	

Table 1.2: The Mercalli and Richter scales

Often severe earthquakes are so deep in the Earth that no surface displacements are seen. However, as the shockwaves reach the surface, landwaves may roll across the terrain, which may trigger events such as mass movements and avalanches.

By their nature, earthquakes are often quite difficult to predict, and so they are capable of causing much damage should they strike without warning. Earthquakes take place all the time, but it is the size and location of the earthquake which will determine the scale of destruction. Often, the extent to which an earthquake is termed 'damaging' depends upon its location in relation to human populations.

Note that much of the damage associated with earthquakes may not be due to the tremors themselves, but to the after-effects, such as fires from broken gas pipes, disruption of transport and other services, poor sanitation, disease (e.g. from broken sewers and contaminated water supplies), exposure caused by lack of shelter, food shortages, lack of medical equipment, etc.

Earthquake features

There are three main stages to an earthquake:

- **Foreshocks** relate to the initial shattering of obstructions or bonds along the failure plane.
- **Principal shock** is the most severe shock. It may last from just a few seconds to a couple of minutes.
- **Aftershocks** recur as the shockwaves travel around the Earth. They generally decrease in frequency and intensity over time, but may occur over a period of several days to several months. They have great potential to cause damage, as structures have already been weakened by the principal shock.

Types of shockwave

Earthquakes produce three different types of shockwave, which become progressively weaker with distance from the Earthquake focus, like ripples on a pond. The nature of the wave also determines how it travels through the Earth's interior (see Figure 1.4).

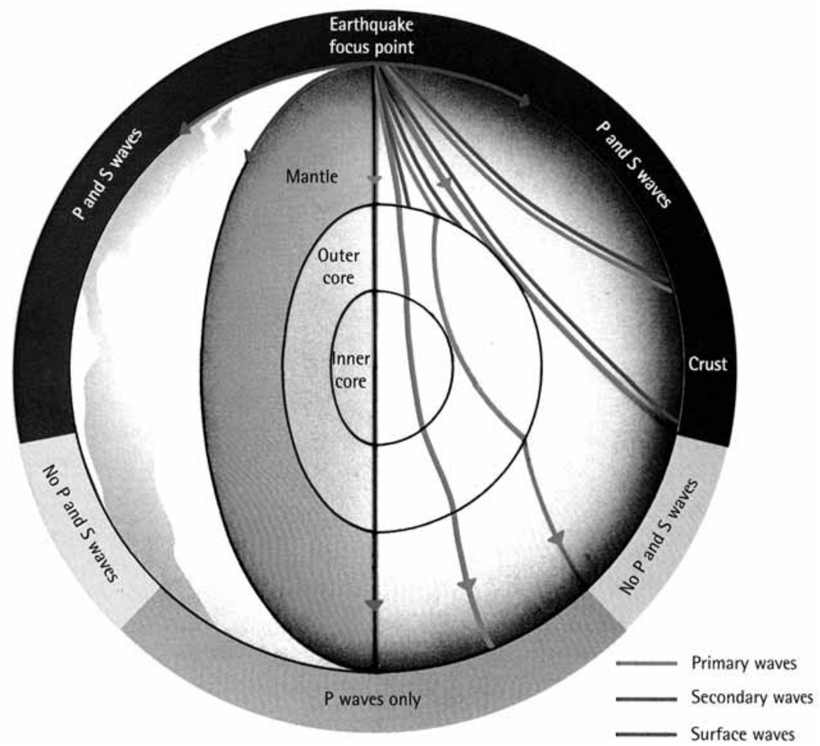

Figure 1.4: The movement of the different earthquake waves through the structure of the Earth

The three main types of wave and their differences are outlined in Table 1.3:

Wave type	Wave character	Speed	How it passes through the Earth's interior	Figure
Primary (*P*)	Longitudinal[3]	Fastest waves, travelling at an average speed of 5 km per second.	Are able to pass through solids and liquids, so can travel through the core.	Figure 1.5a
Secondary (*S*)	Transverse[4]	Slower, travelling at an average speed of 3 km per second (i.e. 60 per cent of the speed of P waves).	Are not able to travel through liquids, so cannot pass through the outer core.	Figure 1.5b
Surface/long (*L*) waves	Transverse	Slowest waves, with greatest wavelength[5], but they carry most of earthquake's energy.	Travel around the surface of the Earth – the surface waves of the Chilean earthquake of 1960 travelled 20 times around the Earth, and were still registering on seismometers 60 hours after the main shock.	Figure 1.5c

Table 1.3: The main types of earthquake wave

[3] Longitudinal waves have a 'push-pull' motion where particles travel in the same direction as the wave.

[4] In transverse waves particles oscillate on a vertical plane about the direction of travel (i.e. undulating like rolling ocean waves).

[5] The wavelength is the distance between two peaks within a wave (or two troughs).

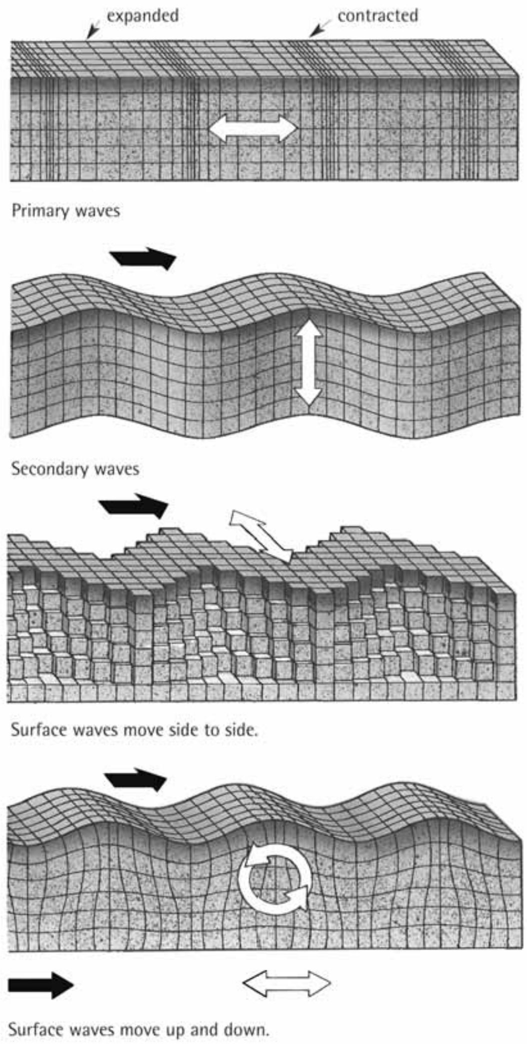

Figure 1.5: The different types of earthquake wave

Tsunamis

These are huge 'tidal waves' caused by the displacement of the sea bed. Displacement may be caused by an earthquake, but may also be caused by the slumping of sediments around the coast, or especially near to deep-sea trenches. Whole series of waves may be set up, which have wavelengths of several hundred kilometres. Because they posses so much energy, they may race across the ocean for thousands of kilometres at speeds of up to 900 km per hour – a large tsunami can cross the Pacific in about 24 hours.

The height of a tsunami is directly proportional to the depth of the water across which it is travelling. In the middle of the deep ocean, a tsunami wave may be relatively unnoticeable. Therefore its effects are at their most intense in shallow waters, so shelving coastlines are particularly vulnerable to damage should a tsunami hit.

Most dangerous tsunamis occur in the Pacific Ocean, as it is surrounded by tectonic plate margins. The Pacific Tsunami Warning System has been set up, which triggers warning alarms if an earthquake greater than 6.5 on the Richter scale is detected by one of its 69 seismic stations across the area. Tsunami warnings can then be issued, and appropriate action taken in areas at risk.

However, as was discovered on 26 December 2004, a tsunami originating from a magnitude 9.0 earthquake in northern Sumatra killed over 100,000 people in countries surrounding the Indian Ocean. There are now moves to set up tsunami warning systems in the Indian and Atlantic Oceans.

Activity

Earthquakes take place all the time, but the ones we hear about in the news tend to be those occurring near to major population centres. Search the internet or read through old newspapers for articles about earthquakes that have taken place. When you read them, pay attention to the sequence of events that have taken place and try to distinguish the three different types of earthquake shock. Also consider the location of the earthquake, and compare it with Figure 1.3 – is there a connection with tectonic plate boundaries? If so, what sort of boundary is it related to (constructive/destructive/ passive)?

Vulcanicity

Lava

There are two types of lava, and these are compared in Table 1.4.

Basaltic, or basic lava	Andesitic, or acidic lava
Hot (1,200°C)	Less hot (800°C)
Lower silica content	Higher silica content
Low viscosity, so flows quickly and far	Viscous, so flows slowly, and less far
Takes longer to cool and solidify, so flows considerable distances as lava rivers.	Cools and solidifies quickly, so flows over shorter distances
Retains gas, giving it mobility	Loses gas quickly, so becomes even more viscous
Produces large-scale landforms of gentle slope angles	Produces more localised features, with steeper slope angles
Eruptions are frequent, but relatively gentle	Eruptions less frequent, but violent due to viscous lava and build up of gases.
Ejecta: lava and steam	Ejecta: ash (tephra), rocks (pyroclasts), lava and steam
Found at constructive plate boundaries where magma rises from the mantle, e.g. Heimaey, Iceland (a fissure along the Mid Atlantic Ridge); and over hotspots, e.g. Mauna Loa, Hawaii	Found at destructive plate boundaries where oceanic crust subducts, melts and rises, e.g. Mt St Helens, USA (subduction zone), Mt Fuji, Japan (island arc)

Table 1.4: A comparison of the different types of lava

Note that there are two different types of basic lava:

- **aa** – cools into extremely irregular 'clinker-like' surface of sharp edges
- **pahoehoe** – 'rope lava' buckles up into series of cord-like pleats.

Although the two lavas are chemically the same, these differences are thought to arise from differing flow mechanisms, speed of cooling and the shape of the enclosed gas bubbles.

Intrusive landforms

These form within the Earth's crust; however, they may become visible at the Earth's surface due to erosion and weathering (see Chapter 5). When molten rock is forced up through the crust, it may solidify in a number of forms (see Figure 1.6).

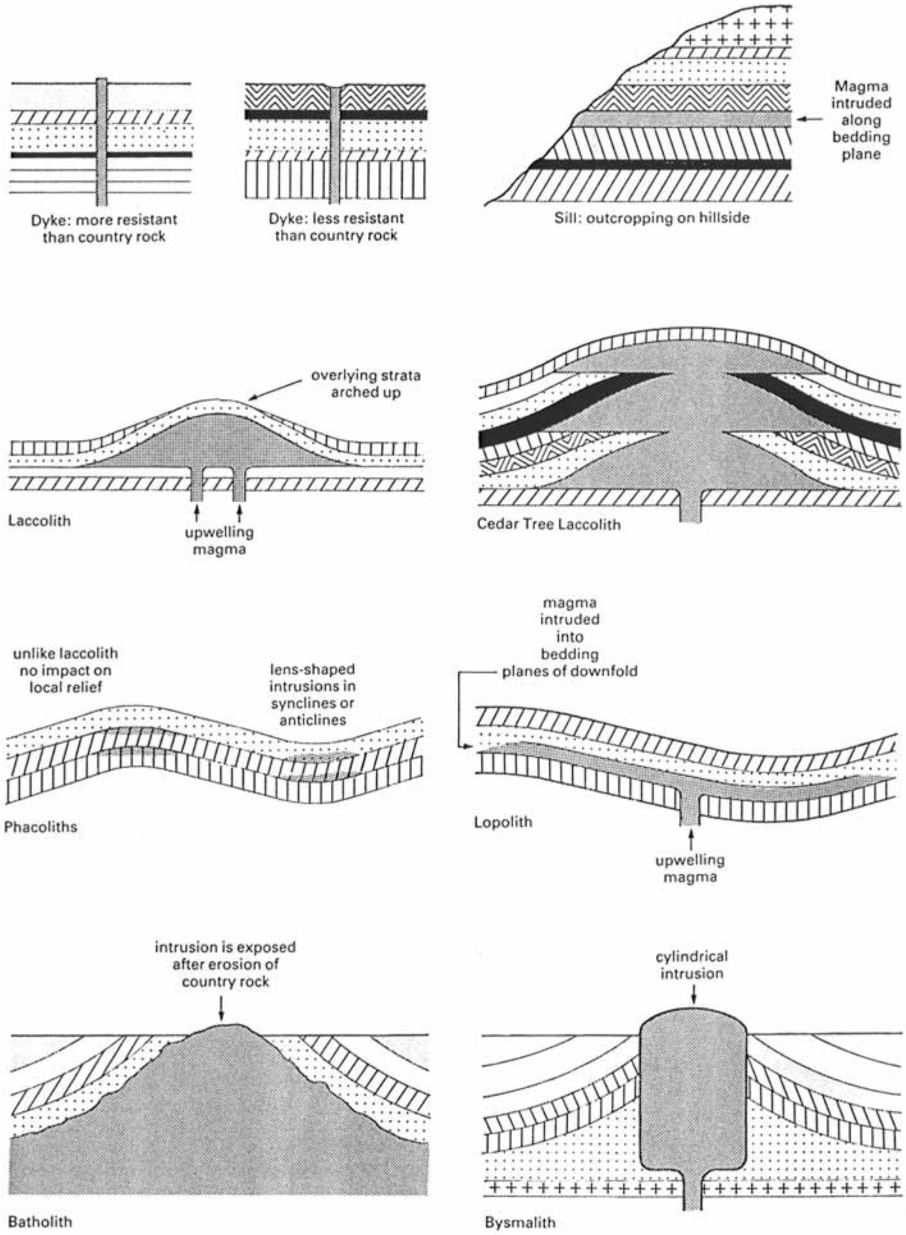

Figure 1.6: The different types of intrusive landforms and their effect on relief

- Laccoliths, e.g. Eildon Hills, Scottish Borders (200 m above surrounding area)
- Loppoliths
- Batholiths (e.g. underlying Britain's southwest peninsula and Brittany)
- Phacoliths
- Bysmaliths
- Dykes (e.g. Cleveland Dyke, stretching 40 km across North Yorkshire Moors)
- Sills (e.g. Great Whin Sill, northeast England)
- Phacoliths.

Note that due to the high heat which may have been released as the magma intruded, it may have altered the surrounding country rock. Therefore such features listed above may be surrounded by halos of metamorphic rock. For example, the great batholith underlying southwest England is surrounded by kaolin (otherwise known as china clay, and hence the china-clay pits commonly found in Cornwall).

Extrusive landforms: volcanoes

Extrusive landforms are those which are formed above the Earth's surface as a result of the lava being extruded. Volcanoes are mostly associated with tectonic plate boundaries, and it is thought that 80 per cent of the world's presently active volcanoes are found above subduction zones.

Because the ash ejected from volcanoes is often very rich in minerals, it is usually extremely fertile. For this reason, humans will quite often risk the chance of eruption for the opportunity to farm the fertile soils of volcanic areas. In other cases, it is the volcanic activity itself which provides the land upon which people can live (for example volcanic islands such as Iceland on the Mid Atlantic Ridge). In Iceland, geothermal energy is harnessed from the volcanic activity, and is used to provide heating for the nation.

Activity

Visit the website http://geothermal.marin.org/pwrheat.html of the Geothermal Education Office. Make notes on how geothermal energy can be exploited by human society.

The basic structure of a volcano is shown in Figure 1.7, and the different types of volcano are listed below.

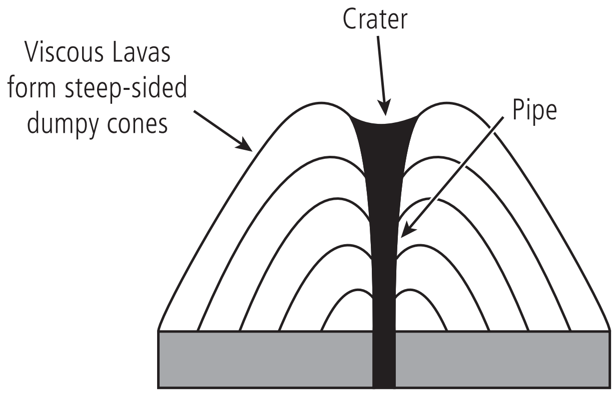

Figure 1.7 The basic structure of a volcano

Hotspots

Not all volcanoes are found above plate margins. Hotspots are areas of the Earth's crust where there is an unusually high flow of heat, marked by volcanic activity. They are usually found on oceanic crust, although they may also occur on continental crust. For example, it is thought that there is a 'superplume' (extremely large hotspot) underlying Yellowstone Park, Wyoming, USA. Of the 125 hotspots that are thought to have been active over the past ten million years, most are located away from the boundaries of tectonic plates, and it is generally thought that they result from hot plumes of molten rock in the mantle that rise to the surface. Should the hotspot be stationary, chains of volcanoes may develop on the overlying crust as it is moved by tectonic activity. Therefore these chains of islands can be used to monitor long-term movements of tectonic plates. Good examples include the Hawaiian Islands, Pacific Ocean; and Réunion, near Madagascar in the Indian Ocean.

Fissure eruptions

At constructive margins, lava may erupt through fissures, rather than through a central vent. Heimaey, Iceland (1973), began as fissure eruption, 2 km in length, but Laki, Iceland (1783), was 30 km in length. As the lava is basic, it flows great distances, and may form large plateaux, for example those that can be seen as basaltic columns in Iceland, Greenland, and most famously in Northern Ireland (the Giant's Causeway) and northwest Scotland (Fingal's Cave on the Isle of Staffa).

Lava cones

These are shown in Figure 1.8. The slope of the cone depends on whether the molten lava was fluid or viscous (basic or acidic), and cones are built up from repeated lava flows. Fluid, basic lavas give rise to more gently sloping cones (e.g. Mauna Loa, Hawaii, ~400 km in diameter at the sea floor and 112 km at sea level). Viscous acidic lavas give rise to more steeply sloping cones, which may be convex ('dumpy') in appearance as the lava tends to solidify close to the equator. In the case of Mont Pelée, Martinique, the lava was so viscous and solidified so quickly as it was coming up the vent that it was extruded as a **spine** or **plug**. However, it broke up rapidly on cooling.

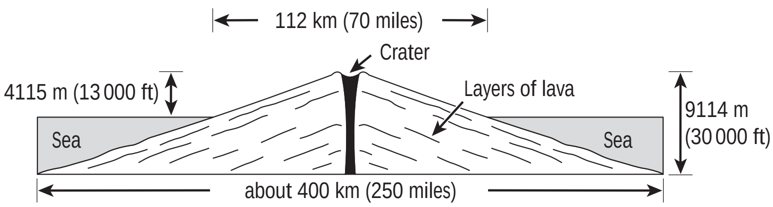

Figure 1.8: Lava cone formed from basic lava

Ash and cinder volcanoes

These are shown in Figure 1.9. In violent eruptions, lava is ejected to great heights, where it breaks into small fragments. These then fall back to Earth and build up a symmetrical cone with slightly concave sides, composed of layers of fine ash and larger cinders. Good examples include Paracutín, Mexico; and Volcano del Fuego, Guatemala.

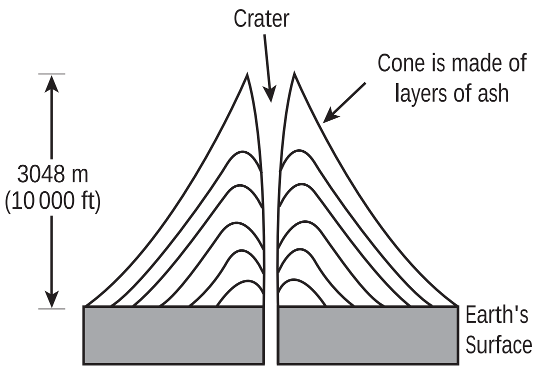

Figure 1.9: Ash and cinder volcano

Composite volcanoes

These are shown in Figure 1.10. Composite volcanoes are composed of alternating layers of ash and lava usually resulting from alternating types of eruption, where first ash (from initial violent eruption) and then lava (usually acidic) are ejected. Dykes may extend out from the central pipe, allowing lava to escape from the sides of the cone, where it may build up small conelets (parasitic cones). A good example is Mount Etna, Sicily.

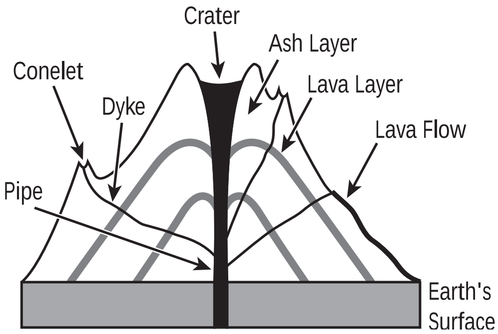

Figure 1.10: Composite volcano

Calderas

Occasionally, volcanic eruptions are so violent that they clear the magma chamber beneath the volcano. The summit of the cone may then sink into the empty magma chamber beneath the vent, creating a huge crater that may be several kilometres in diameter (see Figure 1.11). These calderas may later become flooded (e.g. Lake Toba, northern Sumatra), and later eruptions may create conelets in these lagoons (e.g. Wizard Island in Crater Lake, USA; Anak Krakatoa within Krakatoa, Sunda Strait, Indonesia).

Underwater volcanoes

If volcanoes erupt under the sea (e.g. at plate margins), the lava cools very quickly due to the cool temperatures of the surrounding water. This may give rise to interesting forms, such as **pillow lava**, so called as it appears to billow outwards.

Types of volcanic eruption

In ascending order of magnitude (gentlest to most explosive):

- Icelandic
- Hawaiian
- Strombolian
- Vulcanian
- Vesuvian
- Krakatoan
- Peléan
- Plinian.

Pyroclasts

Volcanoes also eject fragmented (or **pyroclastic**, meaning ‘fire broken’) material of various sizes including:

- tephra (volcanic glass shards)
- ash

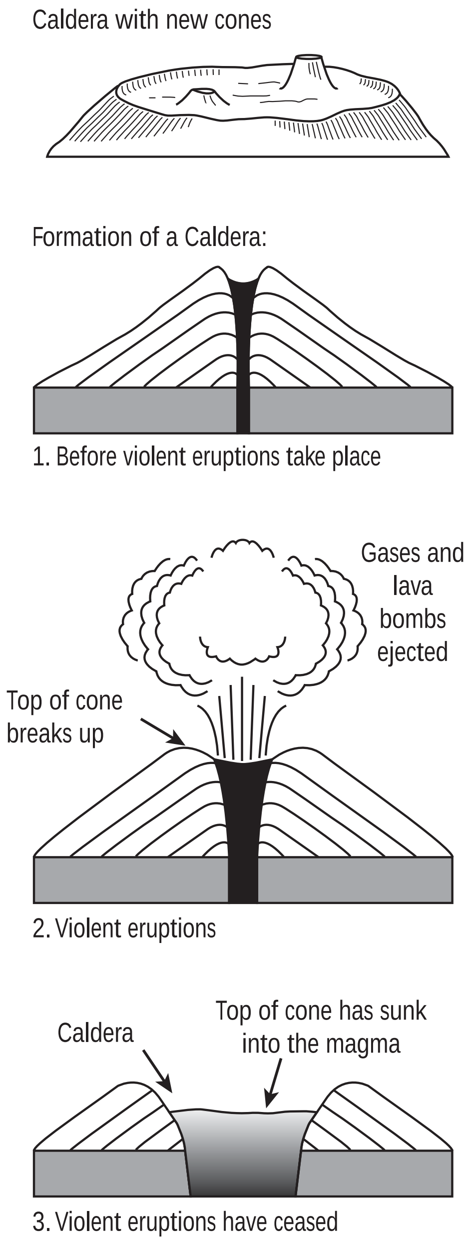

Figure 1.11: The formation of a caldera

- lapilli (small stones)
- bombs (larger material)
- pumice (solidified foam/scum on the top of the lava flow).

These may then form pyroclastic flows, which may take the form of either a fast-moving cloud of very hot toxic gas, known as a **nuée ardente** (e.g. Mont Pelée, Martinique, 8 May 1902), which then deposits a material known as **ignimbrite**, or it may fall to Earth and be transported down the side of a volcano as a **lahar**, or mud slide (e.g. Mt Pinatubo, Philippines, 1991).

Other features

Geysers

These develop when water in an underground cavern with a restricted opening becomes superheated by the surrounding rock and pressure builds up. Once a pressure threshold is crossed, the water is ejected violently as steam, and the process starts again. Water may be ejected straight out of the cavern, or it may be ejected from a sump in a pipe. A good example is 'Old Faithful' at Yellowstone National Park, USA, which releases every 30 minutes.

Fumaroles

These are small volcanic vents through which hot gases and steam are continuously emitted at low pressure. If the gas is rich in sulphur, yellow sulphurous deposits may form around the vent, which becomes known as a solfatara.

Hot springs

These are formed when superheated water flows gently out of the rocks. The water often contains minerals dissolved from the rocks, and these are believed to be good for ailments such as rheumatism. Because of this, many hot springs have spas (health resorts) nearby.

Mud volcanoes

These form when hot water mixes with mud and surface deposits.

Activity

Look in an atlas and locate the examples of the volcanoes given above. Can you see a relationship with the boundaries of plate tectonics given in Figure 1.3?

Search the internet for accounts of volcanic eruptions that have taken place. Compile case studies of how volcanic activity has impacted human life. Volcanoes are a natural hazard, yet why do people still choose to live near to them?

Rock types

The volume of the Earth's crust is composed of 95 per cent igneous rocks and only 5 per cent sedimentary and metamorphic rocks, combined. However, at least 74 per cent of the rocks exposed at the surface are sedimentary shales, sandstones and limestones. We will examine these different rock types below.

Igneous

See Figure 1.12. This is the original rock type from which all others are derived. Igneous rocks are of volcanic origin, and are usually crystalline. There are various methods of classification, including the degree of acidity and location of cooling, both of which are relevant to rocks' structure and resistance. The most common are granite, basalt and gabbro. Rocks may contain parallel horizontal planes (known as pseudo-bedding planes or sheet joints) due to the expansion of the rock after the overlying layers have been removed by denudation. Jointing (fractures in any direction) is also common, formed by contraction of rock as it cools, e.g. hexagonal jointing in basalt (e.g. Giant's Causeway, Northern Ireland). Such joints/fractures may provide potential zones of weakness for weathering, and so are important for the development of the rock outcrop.

				>10% free quartz		quartz-free	
				Ferromagnesian minerals increase (e.g. olivine, pyroxene) →			
Rate of cooling	Location of cooling	Size of crystals		Acid (>66% silica)	Intermediate (52-66% silica)	Basic (45-52% silica)	
slow	underground	large	Plutonic	GRANITE	Diorite	GABBRO	
slow in centre	partially underground	medium	Hypabyssal	Micro-granite	Quartz-porphyry	DOLERITE	
Fast	surface	small	Volcanic	RHYOLITE	ANDESITE	BASALT	
				viscous		runny	Viscosity when molten
				light		dark	Colour
				light		heavy	Density

Figure 1.12: The classification of igneous rocks

Sedimentary

See Figure 1.13. Sedimentary rocks are composed of:

- particles of other rocks derived from denudation, e.g. sand, clay or gravel, which may be held together by a natural cement, chemically precipitated in the gaps between the particles (e.g. **sandstone**, **conglomerate**, **breccia)**.
- organic matter, e.g. microscopic marine organisms, such as foraminifera, coccoliths and sponge spicules (e.g. **limestone**, **flint**, **chert**); ancient plants (e.g. **coal**, **peat**); **diatoms** –minute aquatic algae (e.g. **diatomite**, **diatomaceous earth**).

MECHANICALLY FORMED or CLASTIC SEDIMENTS	INCREASING SEDIMENT SIZE → ARGILLACEOUS <0.002mm e.g. clays 0.002-0.062mm e.g. marl, shale		ARENACEOUS 0.062-2mm e.g. sandstones, gritstones		RUDACEOUS>2mm e.g. breccia, conglomerates
CHEMICALLY FORMED	CARBONATES e.g. dolomite	CHLORIDES e.g. rock salt	IRONSTONES e.g. haemetite	SILICATES e.g. flint	SULPHATES e.g. gypsum
ORGANICALLY FORMED	CALCAREOUS e.g. most limestones	CARBONACEOUS e.g. coal	FERRUGINOUS e.g. ironstone	PHOSPHATIC e.g. guano	SILICEOUS e.g. diatomite

Figure 1.13: The classification of sedimentary rocks

Such particles agglomerate to form rocks mainly as a result of long-term compressional forces, but chemical forces may also be important. Some sedimentary rocks are entirely chemically formed from the evaporation and precipitation of salts from solution (e.g. **magnesian limestone,** composed of the chemical compound magnesium carbonate).

Sedimentary rocks are commonly laid down in parallel layers known as **bedding planes**. Vertical jointing may also be present and may develop as the sedimentary rock contracts as it dries out (e.g. in limestone). Joints and bedding planes may provide potential zones of weakness for weathering and so are important for the development of the rock outcrop/ feature, e.g. cave formation due to jointing, limestone pavements (e.g. Malham, Yorkshire; the Burran, western Ireland).

Metamorphic

'Metamorphic' means 'changed in shape or form' and can apply to any igneous or sedimentary rock whose physical or chemical structure has been altered by heat or pressure (see Figure 1.14). Metamorphic rocks are common in zones of tectonic activity (e.g. plate margins), where folding, faulting and vulcanicity provide the necessary forces involved, and are usually crystalline. However, they are less easy to classify, as the parent rock may be changed into a variety of daughter forms depending upon the degree of stress involved. In some cases, the parent rock type may be indiscernible. Although joints may survive metamorphosis, often the fresh melting and fracturing will destroy them. However, metamorphic rocks may contain their own lines of weakness (e.g. cleavage lines in slate).

Note that in all rock types, tectonic activity may produce joints of varying orientations, e.g. tension during folding and creation of faults.

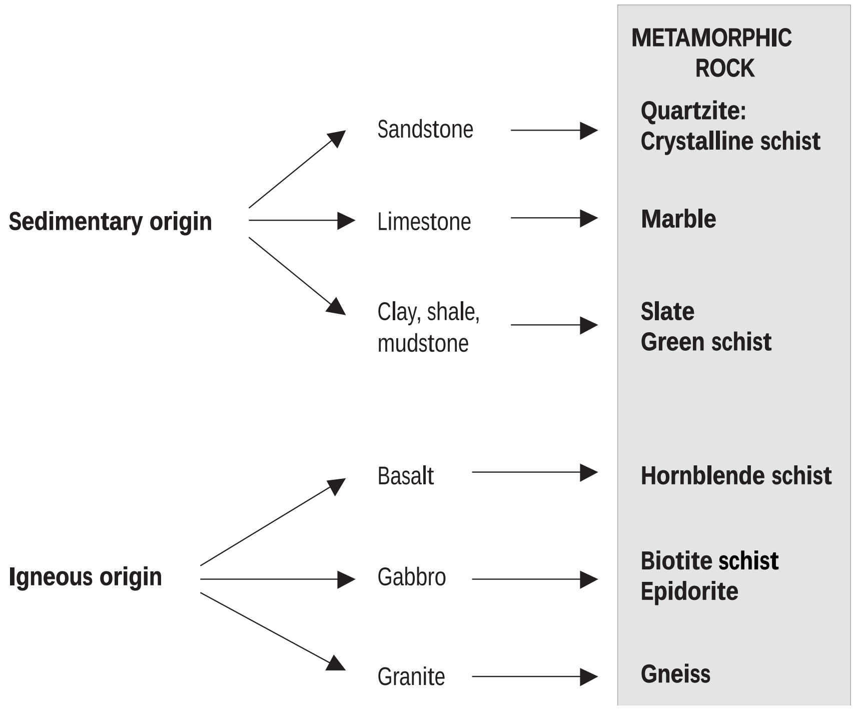

Figure 1.14: The classification of metamorphic rocks

A reminder of your learning outcomes

Having studied this chapter and the recommended reading, you should be able to:

- describe the nature and composition of the Earth's crust
- outline the history and explain the theory of plate tectonics
- discuss the types of landforms that occur at different plate boundaries
- describe the main features of an earthquake
- list the different landforms associated with vulcanicity, and describe the different types of volcano
- explain the three main rock types and discuss their differences.

Sample examination questions

1. Discuss how the initial ideas of continental drift evolved into the comprehensive theory of plate tectonics.
2. Illustrate and explain the different plate boundaries and provide examples of where each occurs in the world.
3. What causes earthquakes and how are they measured?
4. Volcanoes: good or bad? Discuss.

To answer Question 4 we suggest you include the following.

- Introduce your answer by explaining the global distribution of the world's active volcanoes.
- Although they are a natural hazard, many humans choose to settle in areas of volcanic activity, and so whether volcanoes are seen as being good or bad can be viewed through their impact on society.
- Explain the hazards associated with living near to a volcanic area. Remember that volcanoes also frequently have earthquakes associated with them, and so their impacts must also be considered. Try to include examples wherever you can.
- Explain the ways in which volcanoes may be exploited by humans through their potential influence on land use, and the way that their energy can be exploited. Again, try to cite examples where possible.
- Weigh up the these aspects, and justify whether or not you think volcanoes are 'good' or 'bad'.
- Always remember to conclude by bringing together the most important parts of your answer.

Notes

Chapter 2: The atmosphere

Essential reading

Christopherson, R.W. *Geosystems: An Introduction to Physical Geography.* (Upper Saddle River, NJ: Pearson Education, 2011) eighth edition [ISBN 9780321770769] Chapters 2–8.

Smithson, P., K. Addison and K. Atkinson *Fundamentals of the Physical Environment*. (London: Routledge, 2008) fourth edition [ISBN 9780415395168] Chapters 3–8.

Further reading

Barry, R. and R. Chorley *Atmosphere, Weather and Climate.* (London: Routledge, 2001) seventh edition [ISBN 0415077613].

Cox, J. *Weather for Dummies*. (New York: Hungry Minds, Inc., 2000) [ISBN 0764552430].

Davies, G.F. *Dynamic Earth*. (Cambridge: Cambridge University Press, 1999) [ISBN 0521590671].

Henderson-Sellers, A. and P.J. Robinson *Contemporary Climatology*. (Harlow: Longman, 1999) [ISBN 0582276314].

Internet resources

http://earthobservatory.nasa.gov/

If you are going to visit just one website out of the ones listed, visit this one! An excellent site, containing information about practically everything there is to know about planet Earth. Pay particular attention to http://earthobservatory.nasa.gov/Study/ which contains many excellent links to useful snippets of information.

http://earthobservatory.nasa.gov/Observatory/

An extremely exciting interactive site, where you can make your own global simulation models, and make comparisons with other data sets and time periods. Data sets available include those for ‘atmosphere, oceans, land, life on Earth, and heat and energy’. Highly recommended. Note that you will need the Quicktime plug-in to view this, but a link is provided should you not already have it.

http://earthobservatory.nasa.gov/Laboratory/

Interactive experiments where you can learn how and why the Earth changes, through the use of interactive computer models. Although these experiments are aimed at younger members of the population, they contain useful background information. The ‘Mission Biome’ experiment is particularly informative (http://earthobservatory.nasa.gov/Laboratory/Biome/).

www.noaa.gov

The main page for the USA’s National Oceanic and Atmospheric Administration (NOAA). A very useful scientific site for the natural environment, which details not only scientific data and information, but also links to relevant recent events in the media.

www.noaa.gov./wx.html

A comprehensive site detailing information about weather, including weather warnings. NOAA's National Weather Service is the primary source of weather data, forecasts and warnings for the USA, from which television weathercasters and private meteorology companies prepare their forecasts.

www.ncdc.noaa.gov/ol/climate/research/cag3/cag3.html

106 years of weather data for the USA, at a glance.

www.ncar.ucar.edu/ncar/

The official site for the USA's National Center for Atmospheric Research, NCAR.

Learning outcomes

When you have studied this chapter and the recommended reading, you should be able to:

- list the greenhouse gases and understand the basic physics of the atmosphere
- describe the factors affecting the energy balance of the atmosphere
- explain the vertical structure of the atmosphere
- discuss the factors controlling atmospheric motion
- explain the different weather systems operating in temperate and tropical latitudes
- define hurricanes and tornadoes and compare/contrast their similarities/differences.

Introduction

This chapter introduces the basic characteristics of the atmosphere, its structure and composition. It also introduces the processes that cause the atmosphere to move, which leads to our weather. At the end of the chapter, we discuss how different types of storms are formed.

Atmospheric composition

Air is a mechanical mixture of gases, not a chemical compound. What is significant is that these gases are mixed in remarkably constant proportions up to about 80 km above the Earth's surface. Four gases – nitrogen, oxygen, argon and carbon dioxide – account for 99.98 per cent of air by volume (see Table 2.1). Of special interest are the greenhouse gases, which despite their relative scarcity have a large effect on the thermal properties of the atmosphere. The greenhouse effect and global warming are discussed at greater length in Chapter 7.

Component	*Symbol*	*Volume % (dry air)*	*Molecular weight*
Nitrogen	N_2	78.084	28.02
Oxygen	O_2	20.943	32.00
*‡Argon	Ar	0.932	39.88
Carbon dioxide	CO_2	0.0357	44.00
‡Neon	Ne	0.0018	20.18
*‡Helium	He	0.0005	4.00
†Ozone	O_3	0.00006	48.00
Hydrogen	H	0.00005	2.02
‡Krypton	Kr	0.0011	
‡Xenon	Xe	0.00009	
§Methane	CH_4	0.0017	

Notes: *Decay products of potassium and uranium.
†Recombination of oxygen.
‡Inert gases.
§At surface.

Table 2.1: Average composition of the dry atmosphere below 25 km

Greenhouse gases

These gases act like a blanket to trap heat being emitted by the Earth. As this heat cannot escape out into space, the atmosphere warms up, i.e. there is a **greenhouse effect**. The major greenhouse gases and their sources are listed below.

Carbon dioxide (CO_2)

This is part of the complex global carbon cycle (see Figure 2.1). It is released from the Earth's interior, respiration, soil processes and oceanic evaporation. Conversely, it is dissolved in the ocean and consumed by plant photosynthesis in both the surface ocean, and on land.

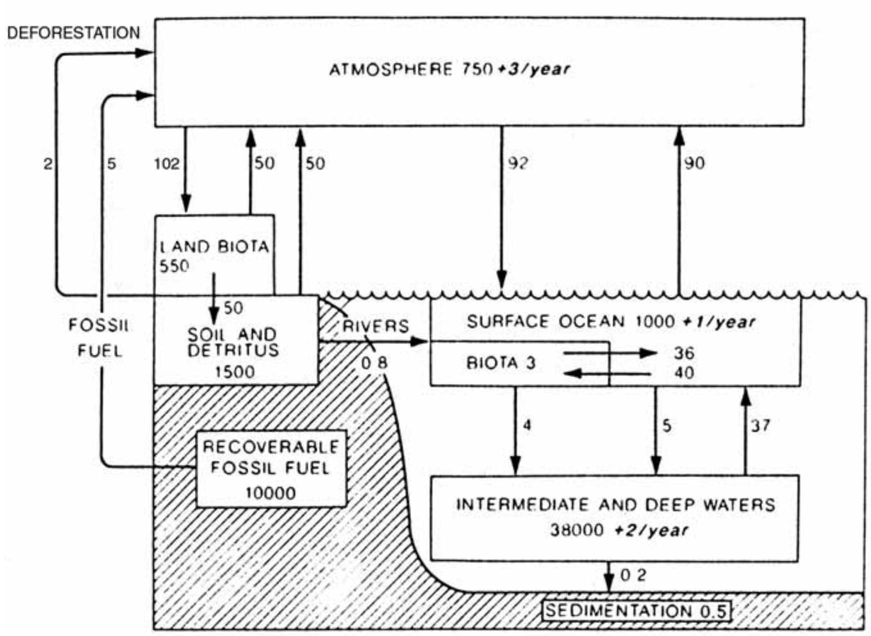

Figure 2.1: Global carbon reservoirs in gigatons of carbon (GtC) and annual fluxes in GtC per year. Italics show estimates by Sundquist et al. (1990) of net accumulation of human generated carbon flux.

Methane (CH_4)

This is produced primarily by anaerobic (oxygen-deficient) processes in natural wetlands, rice paddies, and by animal digestive processes and biomass burning. It is destroyed in the troposphere by the reaction with hydroxyl (OH).

Nitrogen oxides

These are produced biologically in the oceans and soils as well as by industrial processes, cars, biomass burning and chemical fertilisers.

Ozone (O_3)

Ozone is produced by the break-up of oxygen (O_2) molecules by solar ultraviolet radiation high up in the atmosphere, mainly in the tropics, and is destroyed by nitrogen oxides and chlorofluorocarbons.

Chlorofluorocarbons (CFCs)

CFCs are human-made and are used for aerosol propellants, refrigerator coolants and air conditioners. They were not seen in the atmosphere before 1930 and are considered responsible for the ozone holes over both the Arctic and Antarctic.

Water vapour

This is the forgotten (but most important greenhouse) gas which makes up about 1 per cent by volume of the atmosphere. However, it is highly variable in time and space and tied to the complex global hydrological cycle (see Chapters 4 and 6).

Aerosols

Aerosols are suspended particles of sea salt, dust (particularly silicates), organic matter and smoke. The height at which these aerosols are introduced will determine whether they cause regional warming or regional cooling.

Mass of the atmosphere

The atmosphere is a body of gas, so in order to understand the variations in mass, temperature and pressure we need to understand the mechanical laws of gases. Two simple laws govern changes in pressure:

- **Boyle's Law** states that at a constant temperature, the volume of a mass of gas varies inversely as its pressure.

  $P = (k_1 / V)$

- **Charles's Law** states that at constant pressure volume varies directly with absolute temperature measured in degrees Kelvin.

  $V = (k_2\ V)$

  where:

  P = pressure

  V = volume

  T = absolute temperature (in Kelvin)

  k_1, k_2 = mathematical constants

These laws imply that the three quantities of pressure, temperature and volume are interdependent, such that any change in one will produce a corresponding change in the others. These two gas laws can be combined, to give:

$PV = RmT$

where:

R = a gas constant for dry air

m = mass of air

T = absolute temperature (in Kelvin)

We can also rewrite this equation to account for the density of air (where the density ρ is mass/volume):

$P = R\rho T$

Air is highly compressible, i.e. its lower levels are much denser than those above. One-half of the total mass of air is found below 5 km (see Figure 2.2) and the average density decreases from about 1.2 kgm^{-3} at the surface to 0.7 kgm^{-3} at 5,000 m, close to the extreme limit of human habitation.

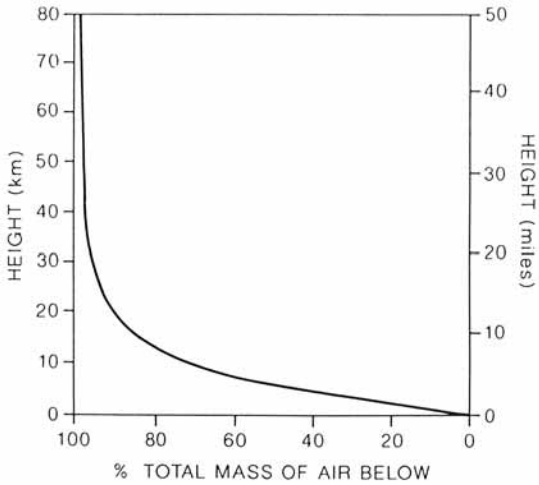

Figure 2.2: Percentage of the total mass of the atmosphere lying below elevations of up to 80 km (50 miles)

Activity

One of the major components of the atmosphere is moisture. From the recommended texts, find out how clouds are formed and why they are important in regulating the temperature of the Earth.

Atmospheric energy

The prime source of energy injected into our atmosphere is from the Sun. The Sun continually sheds part of its mass by radiating waves of electromagnetic energy and high-energy particles into space. In the long term, this constant emission represents almost all of the energy available to the Earth. The amount of energy received by the Earth prior to the entrance to the atmosphere is controlled by solar output, the Sun–Earth distance, the altitude of the Sun, and day length.

Solar output

The Sun can be viewed as a black body, i.e. it both absorbs and radiates energy at the maximum rate possible. The energy received at the top of the atmosphere has been measured by satellites, and has been found to be about 1368 Wm^{-2} or 1.96 cal cm^{-2} min^{-1}. This is called the solar constant. This radiation is made up of:

- 8 per cent ultraviolet and shorter-wave radiation
- 39 per cent visible light
- 53 per cent near-infrared.

It has been suggested that the solar constant can change by up to 0.1 per cent due to **sunspots**. These are darker, or cooler, areas on the surface of the Sun, and their number and position (and hence the radiation received by Earth) have an 11-year cycle.

Distance from the Sun

The **eccentricity** (shape) of the Earth's orbit changes from near circular to an ellipse over a period of about 100,000 years (see Chapter 7 for further details). Described another way, the long axis of the ellipse varies in length over time.

Today, the Earth is at its closest (146 million km) to the Sun on 3 January – this position is known as **perihelion**. On 4 July it is at its greatest distance from the Sun (156 million km), known as **aphelion**.

Changes in eccentricity cause only very minor variations, approximately 0.03 per cent of the total annual **insolation**[1] budget, but it can have significant seasonal effects: if the orbit of the Earth were perfectly circular, there would be no seasonal variation in solar insolation. Today, the average amount of radiation received by the Earth at perihelion is ~351 Wm^2, reducing to 329 Wm^2 at aphelion, a difference of more than 6 per cent. At times of maximum eccentricity over the last five million years, this difference could have been as large as 30 per cent.

[1] Insolation = the amount of solar radiation reaching the Earth

As the intensity of solar radiation reaching the Earth diminishes in proportion to the square of the planet's distance, global insolation falls at the present time by nearly 7 per cent between January and July.

Altitude of the Sun

The altitude of the Sun (i.e. the angle between its rays and a tangent to the Earth's surface at a particular point) affects the amount of solar radiation received at the surface of the Earth. The more directly overhead the Sun is, the more energy is received per unit area. Latitude (see Figure 2.3), time of day and season all effect the Sun's altitude.

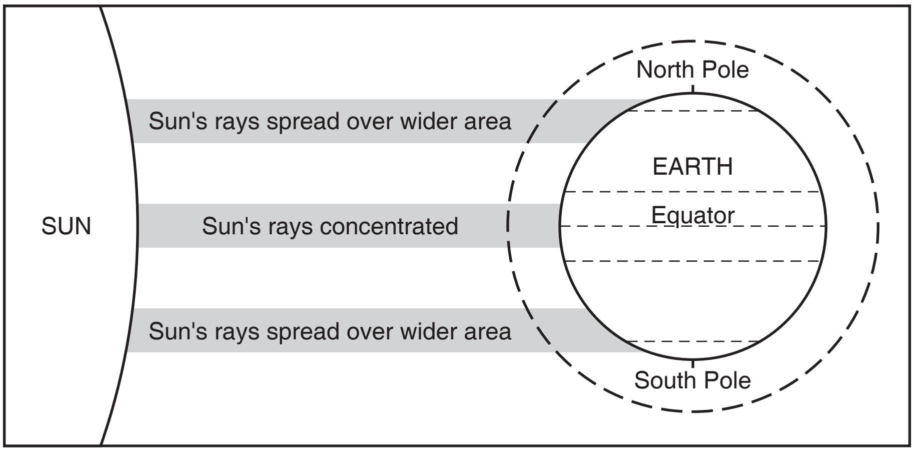

Figure 2.3: Angle of the sun's rays hitting the Earth, demonstrating why different parts of the globe receive different amounts of solar energy

Day length

The tilt of the Earth's axis of rotation with respect to the plane of its orbit (the plane of the ecliptic) produces seasonality, as it varies the day length in both hemispheres. For example, daylight hours at the poles vary from 0 to 24 hours, depending upon the season. In summer, the hemisphere is tilted towards the Sun, which consequently appears higher in the sky. This makes it warmer because it receives more than 12 hours of sunlight. At the same time, the opposite hemisphere is in winter: it is tilted away from the Sun, which appears lower in the sky, and it is colder as it receives less than 12 hours of sunlight. Tilt has been shown to vary between 21.8° and 24.4° over a period of 41,000 years (see Chapter 7).

Activity

Find out from the recommended texts which parts of the Sun's energy are blocked by the atmosphere. Make notes on the reasons why this energy is blocked. Find out how much of the Sun's energy hitting the Earth is reflected back before it has the chance to enter the atmosphere.

Vertical structure

The atmosphere can be divided conveniently into a number of well-marked horizons, based mainly on temperature (see Figure 2.4). These are as follows:

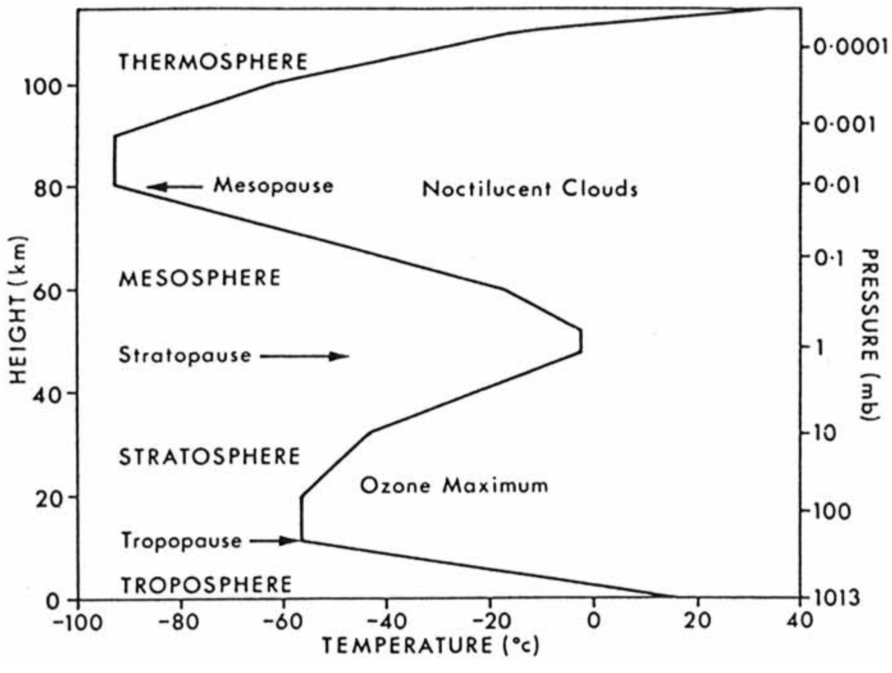

Figure 2.4: Variations in the temperature of the atmosphere with height

Troposphere

This is the lowest layer of the atmosphere, and is the zone where atmospheric turbulence and weather are most marked. It contains 75 per cent of the total molecular mass of the atmosphere, and virtually all of the water vapour. Throughout this layer there is a general decrease in temperature at a mean rate of 6.5°C/km. This whole zone is capped by a temperature inversion layer, the **tropopause**, which acts as a lid on the troposphere and on weather.

Stratosphere

This second major atmospheric layer extends upwards from the tropopause to about 50 km. Although the stratosphere contains much of the ozone (a greenhouse gas), the maximum temperature (caused by the its absorption of ultraviolet radiation) occurs at the **stratopause**, where temperatures may exceed 0°C. This large temperature increase is due to the relative low density of the air at this height.

Mesosphere

Above the stratopause, average temperatures decrease to a minimum of –90°C. Above 80 km, temperatures begin to rise again because ozone and oxygen molecules absorb radiation. This temperature inversion is called the **mesopause**. Pressure is extremely low in the mesosphere, decreasing from 1 mb at 50 km to 0.01 mb at 90 km (surface pressure is about 1,000 mb).

Thermosphere

Above the mesopause, atmospheric densities are very low. Molecular and atomic oxygen in this zone absorb solar radiation,

Atmospheric motion

The large-scale motion of the atmosphere is controlled by two key factors:

- more solar energy is received at the equator than at the poles
- Coriolis force – the influence of the rotation of the Earth.

Latitudinal energy budget

The atmosphere and the oceans move because they are trying to redistribute the energy received from the Sun – as shown in Figure 2.5, much more energy is received at the equator than at the poles. This is exacerbated by the fact that ice at the poles has a higher **albedo** (reflectivity) and hence more energy is also lost to space than received in these areas.

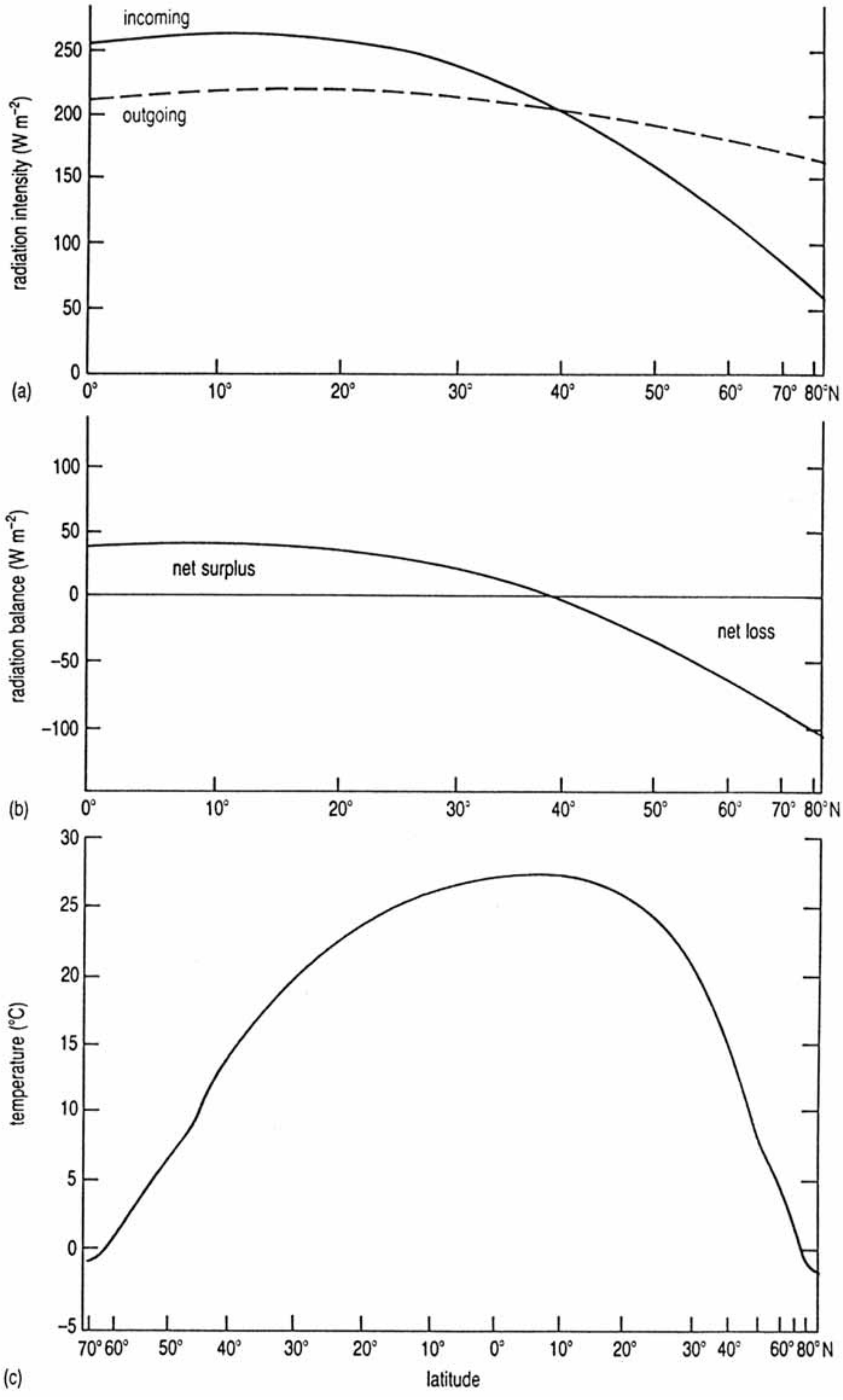

Figure 2.5: (a) Incoming and outgoing radiation for the northern hemisphere
(b) Net gain or loss depending on latitude
(c) Mean temperature of the surface ocean waters in both the northern and southern hemisphere

The intense heating of the equator causes air to rise, resulting in an area of low pressure that sucks new air in, producing surface winds. This produces a major problem, as within the tropics, the surface winds oppose the poleward movement of energy; so the warm, wet air that rises in the tropics moves towards the poles and gradually sinks in the subtropics.

In contrast, at the poles, intense cooling causes air to sink, producing an area of high pressure and hence strong cold out-blowing surface winds. The subtropical air mass, formed from sinking tropical air, moves northwards to encounter the polar winds, and forms the **polar front**.

These major winds form three major vertical circulation cells called the **Hadley cells**, as shown in Figure 2.6.

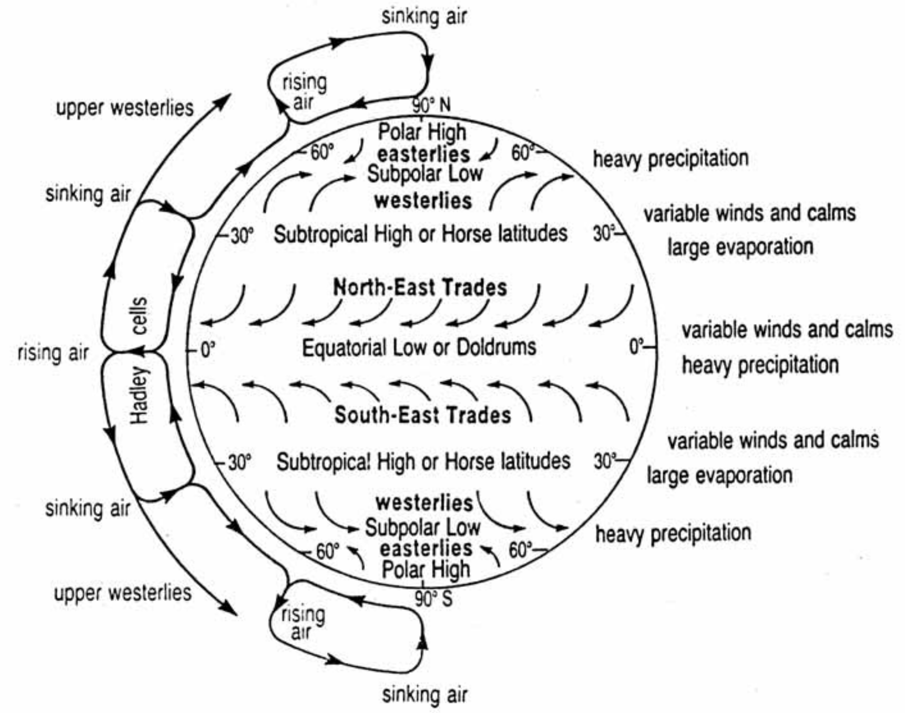

Figure 2.6: Wind system and Hadley cells for an idealised Earth covered only by oceans

Coriolis force

The horizontal direction of the surface and high-altitude winds within the Hadley cells are controlled by the Coriolis force (Figure 2.7). Because the Earth is rotating, everything (in both hemispheres) has an easterly velocity. However, because the Earth is roughly spherical, the distance round the equator is larger than the distance, say, round the Tropic of Cancer. So, during each full rotation of the Earth (i.e. one whole day, ~24 hours), a person standing at the equator must move much further through space than a person in the subtropics; thus the person at the equator has a much greater easterly velocity than the person at the subtropics. In other words, Coriolis force is the relative effect of moving from one line of latitude to another.

Another way to explain the Coriolis force is that if you fire a rocket northwards from the equator it will appear to turn to the right. This is because it has a high easterly velocity from its starting point at the equator, and is moving into a slower area; so it moves faster and hence moves east. The reverse is true if you fire a rocket south from the North Pole towards the equator: at the Pole, it has a very low eastward relative velocity so it is slower relative to the area it is moving into. It thus falls behind, and again turns to the right. Of course, the opposite is true in the southern hemisphere, where the rocket would always turn towards the left.

- Northern hemisphere winds (or rockets) always turn to the right.
- Southern hemisphere winds (or rockets) always turn to the left.

When this is applied to the surface winds it is clear to see (see Figure 2.7).

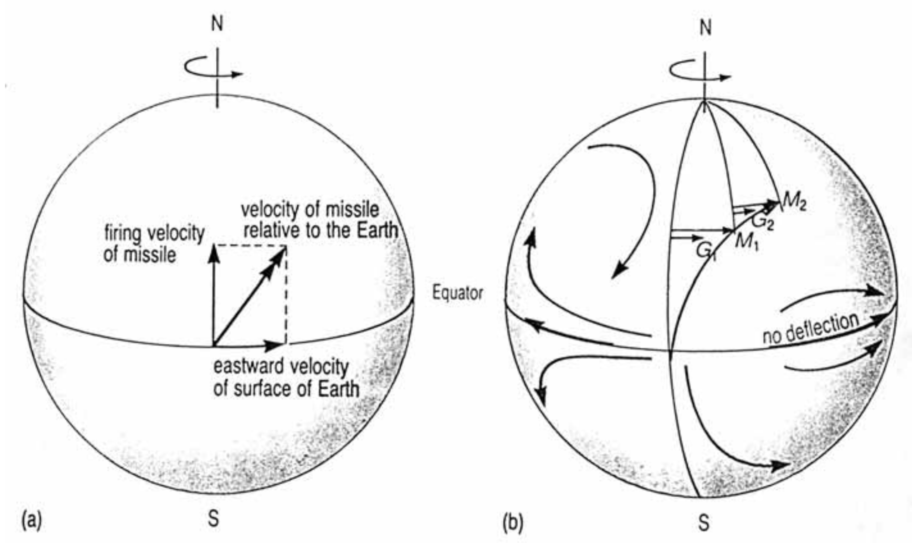

Figure 2.7: Deflection of a missile fired northward due to the Coriolis force

It is the Coriolis force that causes your bathwater to drain clockwise in the northern hemisphere, and anticlockwise in the southern hemisphere (at the equator, it drains with no rotation at all).

Weather

Temperate weather

Depressions (low-pressure frontal systems)

Temperate weather is dominated by the clash between the cold polar air and the warm subtropical air masses. Where these two air masses meet is called a **front**. In the northern hemisphere this occurs at approximately 40°N (see Figure 2.8).

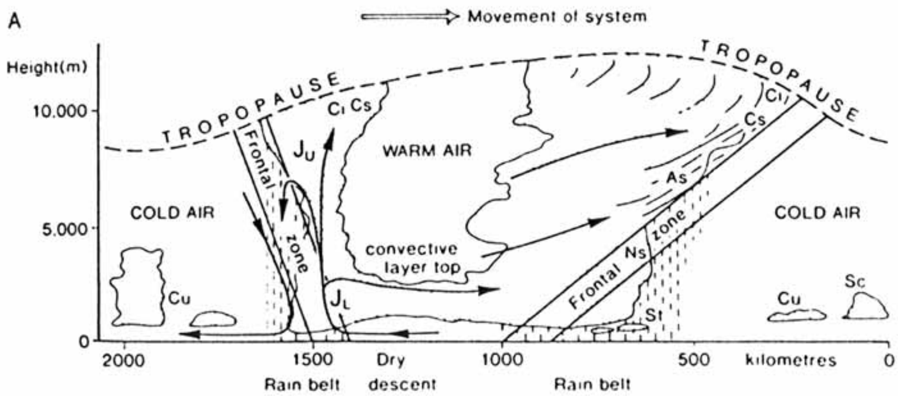

Figure 2.8: Cross-section of a typical depression passing over northern Europe (Note that there is rain where the cold and warm air meet up)

Along this front are waves, with a leading edge or warm front, and a following cold front. Because of Coriolis force, the winds blow clockwise in the northern hemisphere (and anticlockwise in the southern hemisphere). These waves can develop into a **depression**.

A depression (also termed a **low** or **cyclone**) is an area of relatively low pressure, covering an area of 1,500–3,000 km in diameter, and usually has a life span of 4–7 days (Figure 2.8). The key feature of a depression is that both the warm and cold front can bring rain. This is because warm air can contain more moisture than cold air, so when a warm air mass meets a cold air mass the air is chilled and water condenses, forming clouds and rain (see Figure 2.8).

High-pressure systems

Not everything is gloomy and rainy in the temperate latitudes! If an area is covered by a warm subtropical high-pressure system, it brings clear skies and sunny weather. Note that the Coriolis force means that the light winds associated with these high-pressure systems are clockwise in the northern hemisphere and hence are opposite to the general easterly movement of the frontal system. Hence high-pressure systems can become blocking systems and remain in place for many days.

Tropical weather

Inter-Tropical Convergence Zone (ITCZ)

Tropical weather is dominated by the Inter-Tropical Convergence Zone (ITCZ). This is where the trade wind systems of both hemispheres converge due to the Coriolis force (see Figure 2.7). The ITCZ forms because of the intense solar heating of the tropics, causing both massive evaporation and heating of the air, and hence the air rises. As this moisture-rich air rises, the reduction in pressure cools it, and this lessens its ability to hold water – this extra water then condenses to form clouds. This is why in the tropics there are huge towering columns of clouds which produce extremely intense convectional rainfall.

Monsoons

The name 'monsoon' is derived from the Arabic word *mausim*, which means 'season' (most of the rain that falls in Southeast Asia occurs during the summer).

One can tell where the monsoons originate, as winds are always defined by the direction from which they are coming; so the southwest monsoons start in the southwest and move towards the northeast, etc.

In summer the intense heating of the Asian continent causes air to rise, which lowers the air pressure and consequently sucks in air from the southern hemisphere, causing winds from the south to cross over the equator. This creates the opposite effect of the Coriolis force in the northern hemisphere, causing it to change direction by over 90°, resulting in the southwest monsoons. These winds are not only warm, but they have also travelled a long distance over the Indian and Pacific Oceans, and as a result are full of moisture. When these winds pass over the land, they are forced to rise, which causes them to cool and give up their moisture in the form of torrential rain – the monsoons.

Activity

Write down as many differences that you can find between the climate of the tropic and the temperate zones. Then think about temperature and rainfall patterns around the Earth to explain these differences.

Storms

Hurricanes (tropical cyclones and typhoons)

What are hurricanes?

Severe cyclonic tropical storms that start in the North Atlantic Ocean, Caribbean Sea, Gulf of Mexico, west coast of Mexico and northeast Pacific are all called hurricanes. They are called typhoons in the western Pacific and simply tropical cyclones in the Indian Ocean and Australasia. They are, however, all the exactly the same type of storm and in this course we will call all of them hurricanes.

Hurricanes occur in the tropics between 30°N and 30°S, but not near the equator as there is not enough atmospheric variation to generate them.

For a storm to be classified as a hurricane, the sustained wind speed must exceed 120 km/hr. Of course, in a fully developed hurricane, wind speeds can exceed 200 km/hr.

What causes a hurricane?

Hurricanes develop over the oceans where the trade winds are sucked towards the equator, as a result of the hot air that is rising there; but they tend to lose their force once they move over land.

To generate a hurricane, the sea temperature must be above 26°C for at least 60 m below the surface, and the air humidity must be about 75–80 per cent. This combination provides the correct amount of heat and water vapour to sustain the storm once it has started. A hurricane will then form in the following way:

- The warm ocean heats the air above it and causes it to rise, producing a low-pressure zone which sucks in air from the surrounding area.
- This rising air contains a lot of water vapour because of strong evaporation from the hot surface of the ocean. As the air rises, it cools and becomes less able to hold as much water vapour, so some of it condenses as water droplets and forms clouds.
- This transformation from water vapour to water droplets releases energy called latent heat, which in turn warms the air even more, causing it to rise even higher.[2]
- This feedback can make the air within a hurricane rise to over 10,000 m above the ocean. This is the eye of the storm and the spiralling rising air it produces creates a huge column of **cumulonimbus** clouds.
- When the air inside the hurricane reaches its highest level, it flows outwards from the eye, producing a broad canopy of **cirrus** cloud.
- The air cools and falls back to sea level, where it is sucked back into the centre of the storm.
- The Coriolis force causes the air that is sucked into the bottom of the hurricane to spin into the storm in a clockwise direction, while the air escaping at the top spins out in an anticlockwise direction (note that this is the opposite in the southern hemisphere).

The size of a hurricane can vary from 100 km to over 1,500 km. A hurricane can form gradually over a few days or in the space of 6 to 12 hours and, typically, the hurricane stage will last two to three days and take about four to five days to die out.

[2]You can see a mini-version of this with steam coming out of a kettle – as the hot air rises from the kettle, it hits the colder air and it forms steam, a 'mini-cloud'. If you have ever put you hand near the steam you can feel it is very hot and this is because of all the energy being released as the water vapour changes from a gas back to a liquid.

Hurricanes are rare

Yet the formation of hurricanes is much rarer than the opportunities for them to occur. Only 10 per cent of falling pressure centres over the tropical oceans give rise to fully fledged hurricanes. In a year of high incidence, perhaps a maximum of 50 tropical storms will develop globally to hurricane levels (although not all of these will cause disasters). However, 2005 was a significant year for hurricanes in the North Atlantic, with 20 hurricanes forming, five of them achieving category 4 or 5. This included Hurricane Katrina, which destroyed New Orleans in the USA. This makes another interesting point, which is that hurricanes are destructive for two reasons: high winds and lots of intense rainfall.

Tornadoes

What are tornadoes?

A tornado is a violent rotating column of air, which can be observed at a distance as an ice cream cone-shaped cloud formation. Other storms similar to tornadoes in nature are whirlwinds, dust-devils (weaker cousins of tornadoes occurring in dry lands) and waterspouts (a tornado occurring over water).

Tornadoes are most numerous and devastating in central, eastern and northeastern USA, where an average of five per day are reported every May (Figure 2.9). They are also common in Australia (15 per year), Great Britain, Italy, Japan and Central Asia. Most fatalities, however, occur in the USA, where between 1950 and 1978, 689 tornadoes were classified as 'killers'.

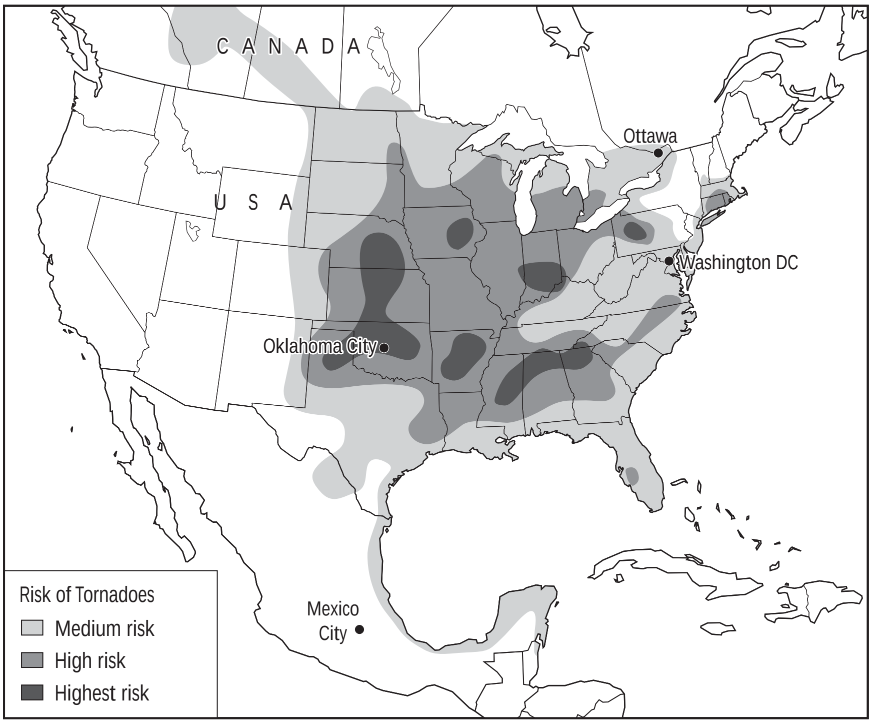

Figure 2.9: Map of the areas most at risk from tornadoes in North America

What causes tornadoes?

We can see tornadoes as miniature hurricanes, but although tornadoes can form over tropical oceans, they are more common over land. The formation of a tornado is encouraged when there is warm, moist air near the ground and cold, dry air above. This occurs frequently in late spring and early summer over the Great Plains of the USA. Intense heating of the ground by the Sun makes warm, moist air rise. As it does so, it cools and forms large **cumulonimbus** clouds. The strength of the updraft (the rising air) determines how much of the surrounding air is sucked into the bottom of the tornado.

Two things help the tornado to rotate violently:

- the Coriolis force
- the high-level jet stream passing over the top of the storm, which adds an extra twist to the tornado.

Because of the conditions under which tornadoes are formed, they can easily occur beneath thunderstorms and hurricanes.

Measuring tornado strength

The strength of a tornado is defined using two different measures, the Fujita scale and the Pearson scale.

- **The Fujita scale (F).** This classifies the strength of a tornado based on the speed that it rotates. This is important as it measures how destructive the storm will be. The 'F' classification is described in Table 2.2.

Fujia scale	Description
F1	Usually (but not always) harmless
F2	Capable of pushing vehicles off roads and tearing the roofs of houses
F3	Capable of damaging wooden houses and lifting vehicles off the ground
F4	Both F4 and F5 intensities can knock down wooden and brick buildings and can pick up vehicles and carry them for over a mile.
F5	However, intensity F5 is usually only reached for a few seconds and on average the USA only experiences two F5 tornadoes per year.
F6	Possible, although has never been observed.

Table 2.2: The Fujita scale

- **The Pearson scale.** This is the length and width of the tornado path.

Using these two scales, the potential damage and the area that is likely to be affected can be classified and predicted.

Ice, wind, hail and snow storms

Ice, wind, hail and snow storms are associated with either the polar front or high mountain regions, and are worse in the winter time than during the rest of the year. In the northern hemisphere, these types of storms are common over North America, Europe, Asia and Japan. Storms are usually associated with depressions and the violent mixing of warm and cold air masses.

Snow

For snow to reach the ground, the temperature of the air between the base of the cloud and the ground must be below 4°C, otherwise the snowflakes melt as they travel through the air.

Hail

For hailstones to form, the top of the storm must be very cold. In the reduced pressure high up in the atmosphere, water droplets can become supercooled to less than 0°C, and they collide in the atmosphere to form ice balls or hailstones. If you cut open a hailstone you can see the layers of ice that have built up like an onion. The stones can vary between 2 mm and 20 cm. Their size depends on how strong the updraft of air is as this determines how long they stay in the atmosphere before dropping out.

Blizzards

The worst storm conditions are called blizzards. These combine strong winds, driving snow, ice and hail, with air temperatures as low as –12°C and visibility less than 150 m.

Activity

1. Using the National Oceanic and Atmospheric Administration website (www.noaa.gov), find out the latest information about hurricanes and tornadoes. Note down the details of the last big hurricanes (also called cyclones and typhoons) and tornadoes, as this will be useful information which you can include in exam questions.
2. Still using the NOAA website, find out and write down the key ways they use to track and predict the occurrence of hurricanes and tornadoes in the USA.

Conclusion

Weather and climate influence all our lives, from what clothes we wear, to where we go on holiday, to what crops farmers grow and when. Understanding the atmosphere and its dynamic nature provides us with insights into how to predict weather patterns. Already we have made great advances. Today three- to four-day forecasts are as accurate as the two-day forecasts 15 years ago. The lead times of the advance warnings of tornadoes (i.e. the time that residents have to react) has increased from five minutes in 1986 to 12 minutes in 1998. Now, 70 per cent of all hurricane paths can be predicted up to 24 hours in advance. But we still have a long way to go to prevent our turbulent atmosphere from causing massive loss of life, especially as our climate is likely to change in the future due to global warming. However, it is only by studying the atmosphere that we will improve our understanding of weather and future climate change.

A reminder of your learning outcomes

Having studied this chapter and the recommended reading, you should be able to:

- list the greenhouse gases and understand the basic physics of the atmosphere
- describe the factors affecting the energy balance of the atmosphere
- explain the vertical structure of the atmosphere
- discuss the factors controlling atmospheric motion
- explain the different weather systems operating in temperate and tropical latitudes
- define hurricanes and tornadoes and compare/contrast their similarities/differences.

Sample examination questions

1. Discuss the different controls on the amount of solar energy received by different parts of the Earth.
2. Describe and explain the vertical pressure and temperature profile of the atmosphere.
3. Describe the different components of the atmosphere and discuss which are the most significant greenhouse gases.
4. Illustrate and describe Hadley cells and discuss the effects of the seasonal movement of the Inter-Tropical Convergence Zone.

To answer Question 4 we suggest you include the following.

- Introduce your answer by explaining what a Hadley cell is.
- Draw a picture of the cross-section of the Earth with the three Hadley cells, similar to Figure 2.6. Clearly label all the different zones, particularly the ITCZ.
- Explain what produces these Hadley cells, including the effects of rising and sinking of warm and cold air respectively, and also the Coriolis effect.
- Discuss in detail how the ITCZ is formed. Remember to mention that it is where in-blowing winds are generated at ground level due to the strong rising hot air at the ITCZ.
- Draw the location of the ITCZ during July and December.
- Discuss what causes the ITCZ to move throughout the year, remembering that the angle of the Sun relative to the equator changes through the year.
- Discuss the implications of the seasonal movement of the ITCZ; for example, remember to mention the monsoons and when they occur in Amazonia, west Africa and Southeast Asia.
- Always remember to conclude by bringing together the most important parts of your answer.

Notes

Chapter 3: Climate and tectonics

Essential reading

Ruddiman, W. *Earth's Climate: Past and Future.* (New York: Freeman, 2007) second edition [ISBN 9780716784906] Chapter 4.

Further reading

Hay, W.W. 'Tectonics and climate', *Geologische Rundschau: Zeitschrift für allgemein Geologie* 85 1996, pp.409–37.

Molnar, P. and P. England 'Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg?', *Nature* 346 1990, pp.29–34.

Open University *Dynamic Earth*. (Milton Keynes: Open University, 1997) [ISBN 0749281839].

Open University *Ocean Circulation*. (Oxford: Open University/Pergamon Press, 1989) [ISBN 0080363695].

Van Andel, T.H. *New Views on an Old Planet: A History of Geological Change*. (Cambridge: Cambridge University Press, 1994) [ISBN 0521447550].

Learning outcomes

When you have studied this chapter and the recommended reading, you should be able to:

- outline the direct effects of climate and tectonic activity and discuss the different influences of horizontal and vertical movement of the continents
- explain the importance of tectonic activity in controlling regional precipitation and the monsoon system
- describe how tectonic activity can affect climate indirectly
- explain how the relationship between climate and tectonics has influenced evolution through geological time.

Introduction

This chapter demonstrates that our modern climate system is a product of long-term tectonic changes and that in many ways it is unique in geological history. Tectonics have two major effects on our climate:

- **direct** effects include uplift, which changes atmospheric circulation and the hydrological cycle, and continental movement, which affects ocean circulation
- **indirect** effects include subduction, volcanism, introduction of gases into the atmosphere, erosion and consumption of gases by chemical weathering.

Direct effects

Horizontal tectonics

Over millions of years, continents move around due to the process of plate tectonics (see Chapter 1). This changes the shape of the ocean basins and controls where mountain ranges and plateaux occur. To simplify these effects we can look at north–south changes in the position of the continents or 'latitudinal land and ice distribution', and then we can look at west–east changes or 'longitudinal land distribution'.

Latitudinal land and ice distribution

The best way to illustrate the huge effect of the latitudinal position of the continents is through the use of computer models (see Figure 3.1). What these have demonstrated is that if all the continents are at the poles, then the equator–pole temperature gradient is extremely large, ranging from +28°C to –10°C (Figure 3.1.1). If ice builds up on these polar continents, the temperature gradient becomes even larger, ranging from +28°C to –30°C. This is in complete contrast to a world where the continents are centred on the tropics, as there the temperature range would much less, ranging from +30°C to +2°C. This arises as the ocean is a very good transporter of heat, so when the poles are continent-free, the ocean can mix the heat from the tropics and subtropics, and the polar regions maintain a very low thermal gradient.

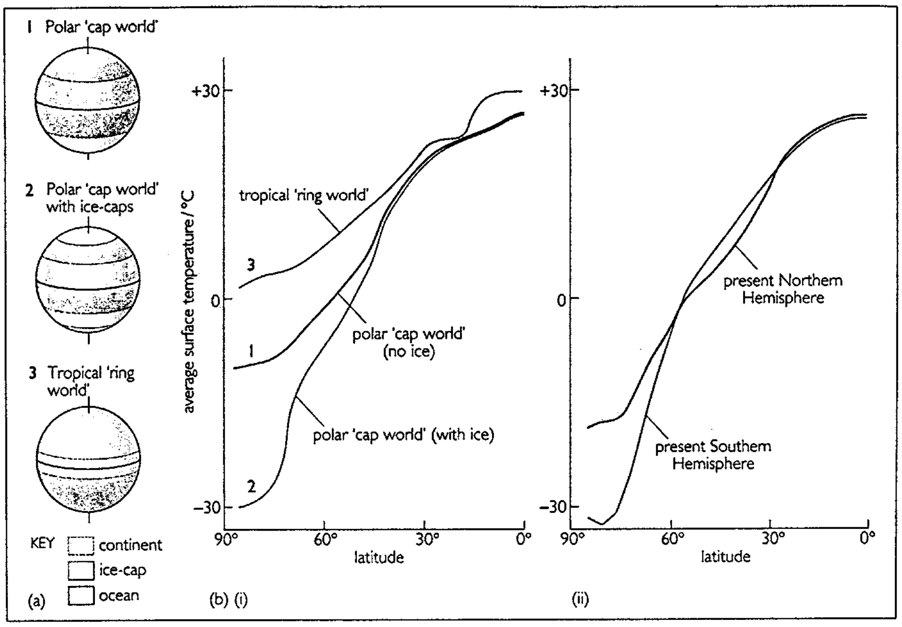

Figure 3.1: Simplified model of the position of the continental plates and the effect they have on the equator-pole temperature gradient

If we consider the present-day configuration of the continents, there is one polar continent with an ice cap (Antarctica) and one polar region which is surrounded by continents so that the ocean is highly restricted in its movement (the Arctic). If we compare the modern-day temperature gradients, they are very similar to the polar 'cap world' with ice caps. It should be noted that the modern equator–pole temperature gradient is one of the largest in the geological record, as only very rarely have both poles been glaciated. This produces an extremely energetic modern climate, as this energy must be redistributed.

Longitudinal land distribution

Surface ocean. Again, the best way to illustrate the theoretical effects of the longitudinal position of the continents is through the use of computer models (see Figure 3.2).

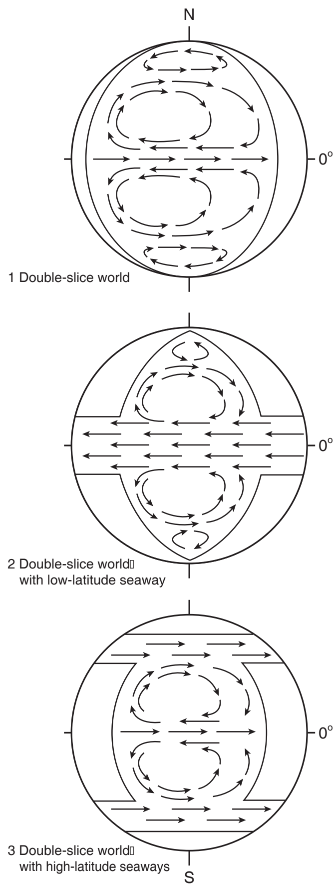

Figure 3.2 Three simplified models of the oceanic circulation with different configurations of the continents (Note: today the northern hemisphere resembles number 1 and the southern hemisphere resembles number 3)

The most important elements of longitudinal continents are the gaps, or **gateways**, that they contain, as these allow the oceans to circulate around the globe.

- Remember that ocean circulation is driven by the surface winds, and hence they follow a very similar pattern.
- Because of the spin of the Earth, the oceans will always try to go around the planet.

Computer models clearly show what happens if we change the position of the continents. For example:

- If the world was split into two halves, a 'double-slice world', then the ocean forms two **gyres**[1] in each of the hemispheres (see Figure 3.2.1).
- If a passageway is opened in the tropics (a so-called **low-latitude seaway**), then the world's ocean circulation is dominated by the westward flow around the equator (Figure 3.2.2).
- If instead the passageways are nearer to the poles (so-called **high-latitude seaways**), then there is strong eastward flow (Figure 3.2.3).

[1] A gyre is the circulation of the ocean in a loop. This loop is not closed and ocean currents can join and leave it. However, the majority of the sea water circles around within the given ocean basin.

The direction of flow in the ocean is controlled by the surface winds, so the direction corresponds to the direction seen in Figure 2.7. Each of the theoretical examples shown in Figure 3.2 has occurred in some way during the geological past. They do in fact have a huge effect on the energy distribution around the world – at present the northern hemisphere looks like the double-slice world and the southern hemisphere looks like the double-slice world with a high-latitude seaway.

One of the main reasons why Antarctica has a massive ice sheet on it is because of the **Southern Circumpolar Current**. This current goes right the way around the continent and acts like a giant refrigerator, as the current steals heat from Antarctica and releases it into the South Atlantic, Indian and South Pacific Oceans.

Deep ocean circulation. In the North Atlantic, the surface northeast-tending **Gulf Stream** (also known as the North Atlantic Drift) carries warm and relatively salty surface water from the Gulf of Mexico up to the Nordic seas. Upon reaching this region, the surface water has cooled sufficiently to become dense enough to sink into the deep ocean, forming **North Atlantic Deep Water** (NADW) (Figure 3.3). The 'pull' exerted by this sinking maintains the strength of the warm Gulf Stream, ensuring a current of warm tropical water into the North Atlantic, which sends mild air masses across to the European continent. The NADW then flows back down the Atlantic Ocean and into the Southern Ocean, where it is met by a second source of deep water: in the Southern Ocean the **Antarctic Bottom Water** (AABW) is formed in coastal polynias,[2] where out-blowing Antarctic winds push sea ice away from the continent edge, and act to supercool the exposed surface waters. This leads to more sea-ice formation and brine rejection,[3] producing the coldest and saltiest water in the world. AABW flows around the Antarctic and penetrates the North Atlantic (flowing under the warmer, less dense NADW) and also the Indian and Pacific Oceans.

[2] A polynia is a hole which opens in the sea ice, usually due to the strong winds blowing across the ice.

[3] Salty water cannot freeze, so when sea ice forms, the water freezes, leaving the salt in the ocean – which becomes more saline as a result. The increased salinity increases the density of the sea water and also enables it to cool further. This is known as brine rejection.

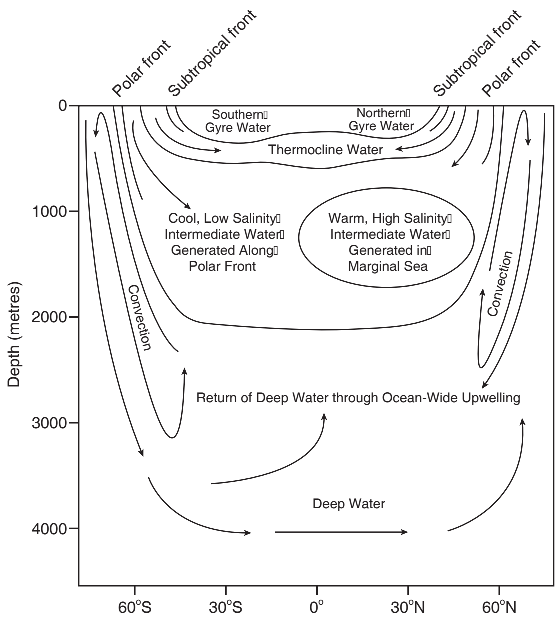

Figure 3.3: Deep ocean circulation of the Atlantic Ocean

This balance between the sources of NADW and AABW is extremely important in maintaining our present climate system; particularly as the formation of the NADW maintains the mild European climate, and the relatively ice-free northern hemisphere (see Chapter 7). However, in geological terms, this system is relatively new as it was caused by the opening of Drake Passage, a gateway between the Antarctic and South America (~35 million years ago), and the closure of the Central American Passage (sometimes called the Panama Gateway) between North and South America (~4 million years ago).

Again, simple computer models can show the effects of the closing and opening of these gateways. Figure 3.4A shows the normal conditions with 17 Sv ($10^6 m^3/s$) of NADW and 38 Sv of AADW. However, if we open the

Central American Passage, the NADW disappears and only the AADW remains (Figure 3.4B). The same is true if both passages are closed (Figure 3.4C), or if the Central American Passage is deep and open and the Drake Passage is closed (Figure 3.4D). This demonstrates that our current climate is unique and has really only existed for the last two to four million years.

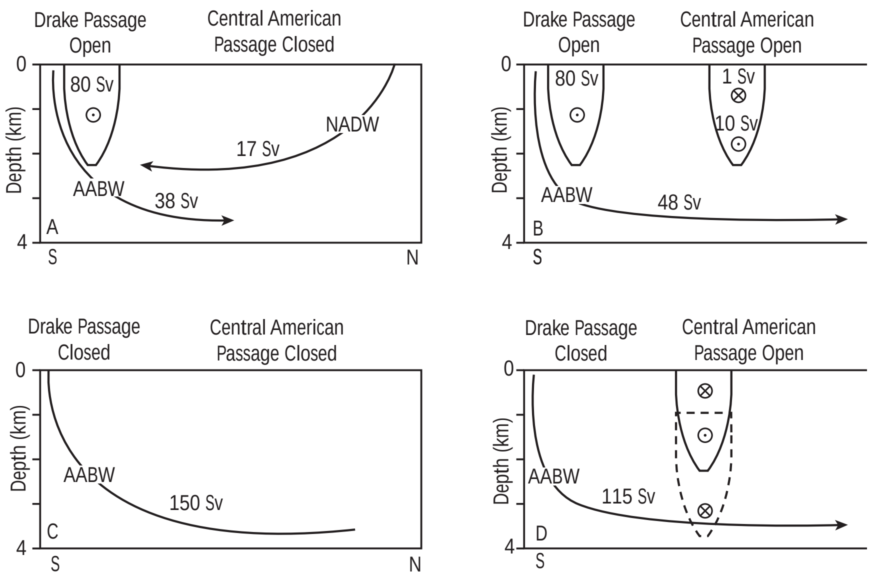

Figure 3.4: Model results of what happens to the formation of North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) with different gateways open or shut. Note ocean circulation is given in Sv = 106 m3/s

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Activity

Ocean gateways have been very important throughout geological history. Using the recommended texts, find as many examples as you can of oceanic passageways that have either opened or closed in the past, and the approximate time that they occurred.

Vertical tectonics

During the process of plate tectonics, mountain ranges and extensive plateaux are formed. These can either be destroyed by plate tectonics or slowly eroded over a longer time period. There are three main effects: rain shadow, circulation, and influence on monsoons.

Rain shadow effect

This is the effect brought about by the topography of the land, where mountain ranges can interfere with atmospheric circulation and bring about changes in the local climate between the windward and lee sides of a mountain.

As air is forced over a mountain range, the reduction in pressure reduces the air temperature. This means that the air can hold less moisture and thus there is rain on one side of the mountain. When the air passes over the top and drops down the other side of the mountain, the reverse occurs and the air heats up. However, the air on this side has much less moisture and as it heats up, this moisture level falls relative to what the air can potentially hold. Hence the air is extremely dry and deserts are very common on the other side of mountains (Figure 3.5). A good example of a rain shadow desert is the Atacama in South America, brought about by the influence of the Andes.

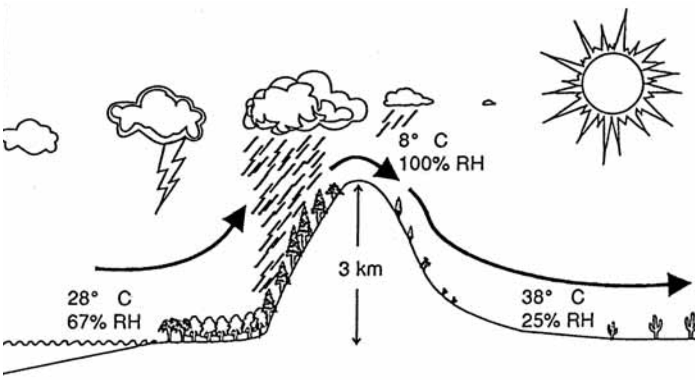

Figure 3.5: Precipitation effects of moisture-laden air passing over a mountain range (RH = relative humidity)

Again, computer models can show what a major effect this can have on the hydrology of continents. Because of the direction of the near-surface winds (see Chapter 2), the rain shadow is on the eastern side of mountains in the tropics (as the winds come from the east), whereas in the temperate latitudes, the rain shadow is on the western side (as the winds primarily come from the west).

If the mountain range is built on the western side of a continent, then the rain shadow is mainly over the land (Figure 3.6A). However, if the mountain range is built on the eastern side of the continent, then most of the rain is lost over the ocean, leading to a very dry continent (Figure 3.6B). Today we are very lucky as the Rockies (North America) and Andes (South America) – which are part of the same mountain range – are on the west side of the continents, keeping them wet.

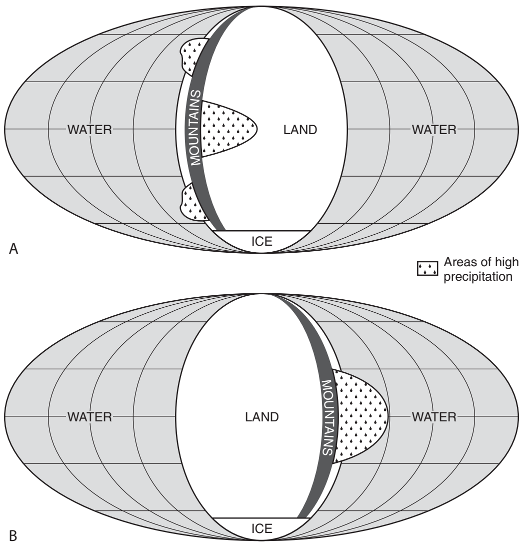

Figure 3.6: Theoretical effects of having a mountain range on either the west or east coast of a single supercontinent. Heavy dots indicate regions of high precipitation

The other constraint on rain shadows is whether the raised continent is a mountain range or a whole plateau. In the case of a plateau, the computer models show that again, rainfall is restricted to the edges of the plateau (Figure 3.7). This is very important when we discuss the climate of supercontinents.

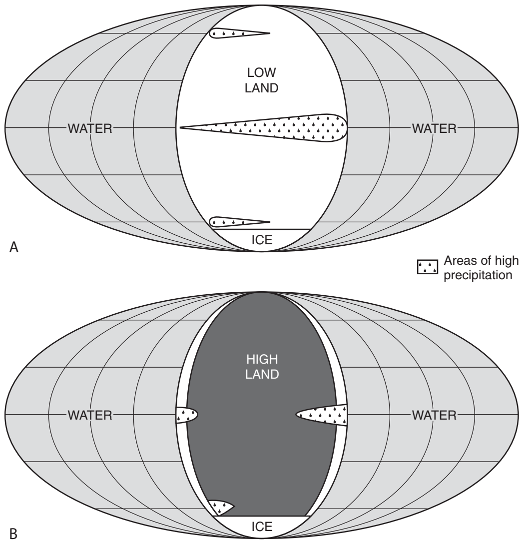

Figure 3.7: Theoretical effects of having a continent elevated by either (A) 200 m or (B) 1500 m. Heavy dots indicate regions of high precipitation

Atmospheric circulation

A mountain range or plateau has a major effect on atmospheric circulation, and hence where warm and cold air masses go to and where precipitation falls. In the modern day, the Tibetan plateau and the North American plateau have large effects on both summer (Figure 3.8A) and winter (Figure 3.8B) circulation; especially when you compare this circulation with a northern hemisphere without any plateaux (Figure 3.8C). If you add the major ice sheets of the last glacial period over Greenland, North America and northern Europe (see Chapter 7), then the circulation becomes even more complicated.

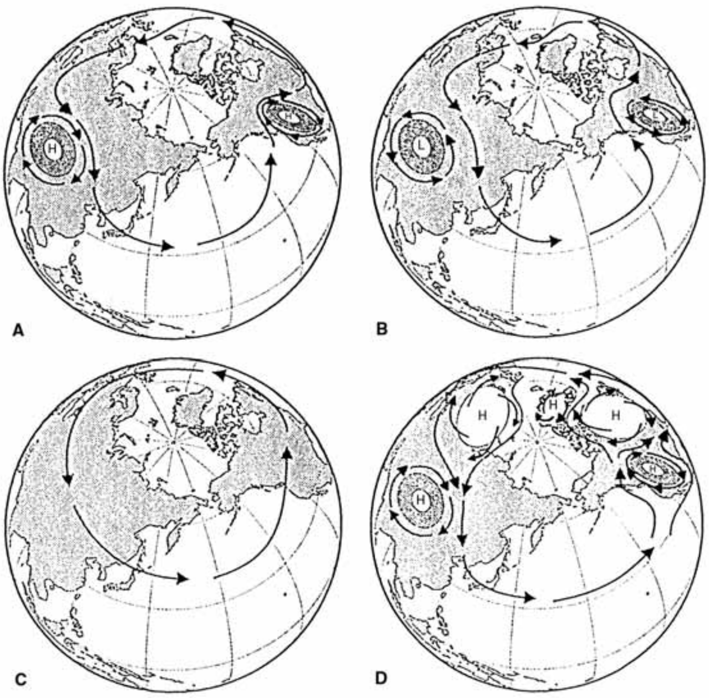

Figure 3.8 Circulation patterns of the northern westerly jet stream at different times and different uplift patterns: (A) Northern hemisphere winter; (B) Northern hemisphere summer; (C) No uplift, so the continents are a constant 200 m high; (D) Last glacial maximum (~21,000 years ago) with significant 3 km high ice sheets on North America and Europe

Uplift and resultant monsoonal circulation

Southeast Asian monsoon. One of the most important features in the modern-day tectonically controlled climate is the monsoon system. In summer, the Tibetan plateau heats up more quickly than the surrounding lower land. This produces rising air and a low-pressure system that sucks in air from the surrounding area, which includes the Indian Ocean. However, the majority of the air is in the southern hemisphere and as it is pulled across the equator, the direction of the Coriolis force shifts, helping it towards the Tibetan plateau. In addition, the raised mountain ranges on either side of the East African Rift also help to bounce this air into the northern hemisphere (Figure 3.9). As this moister air comes over the land, it cools and drops its moisture in the form of extremely heavy rain – the monsoons.

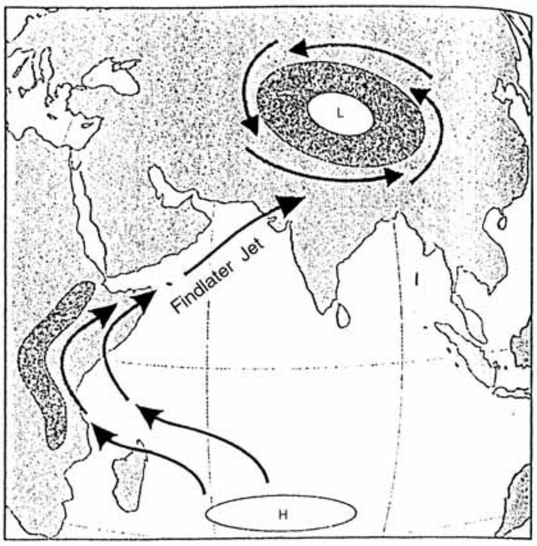

Figure 3.9 The effects of the uplift of the East African Rift and the Tibetan plateau on the Findlater jet and the movement of the Southeast Asian monsoon over the Indian sub-continent.

Amazon monsoon. Monsoons also occur in South America over the Amazon Basin. Again, this is due to tectonic processes placing the South American continent on the equator. Hence, during the southern hemisphere summer, the Amazon Basin heats up, producing a very large low-pressure zone that sucks in moist air from the North Atlantic Ocean.

Activity

Draw an outline of the world's continents and mark the current location of the Andes and Rocky mountain ranges and the Tibetan plateau (these can be found in any good atlas of the world). From Chapter 2, you can work out the general direction of the winds at different latitudes. Using this information, shade in the areas which should be part of these mountains' rain shadows and where the deserts will be. Remember that the Tibetan plateau is a more complicated example as the winds change direction through the year. Now compare your map with the location map of vegetation found on page 80 of Open University, Dynamic Earth (1997). Why are the maps slightly different?

Indirect effects

The major indirect effect of tectonics on climate is through the introduction of gases and dust into the atmosphere. The key to how long the effect will last is the height at which the gases and dust are injected. If a ‘normal’-sized volcano erupts, it will pump the gases and dust it releases into the troposphere (see Chapter 2). This produces a short-term cooling effect, as the dust and other aerosols block out the Sun (Figure 3.10). For example, during the summer after the 1980 Mount St Helens eruption, it was much colder than usual. This effect, however, is only short term, as rain ‘cleans’ the air of both the aerosols and dust. In the geological past, however, eruptions have been much larger, and much more prolonged. In these cases they are so violent that the gases and dust are injected into the stratosphere (Figure 3.10). As this zone is above the clouds, there is no rain to clean the atmosphere so they are not removed.

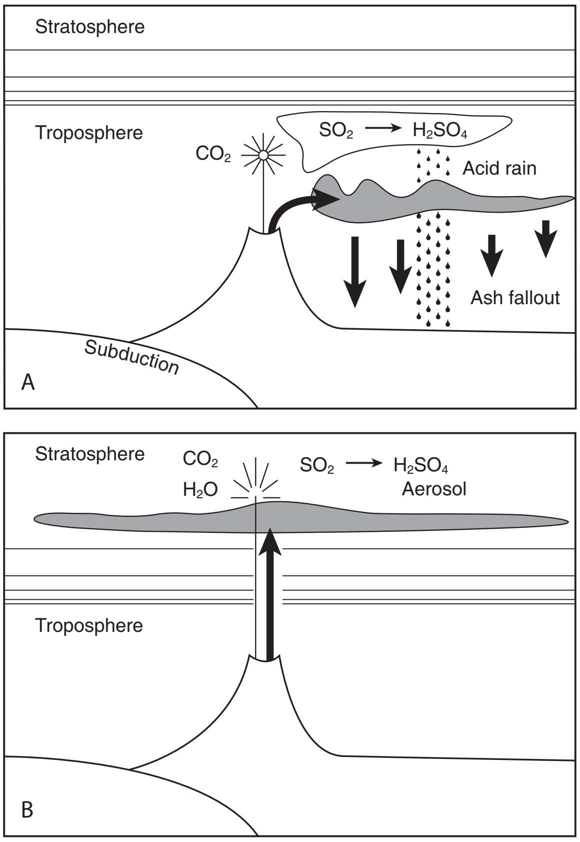

Figure 3.10 The effects of volcanism on the atmosphere: (A) normal volcanic eruption with material injected into the troposphere, which can be rained out over a few years; (B) super-volcanic eruption where material is injected into the stratosphere, where it can remain for thousands of years.

Over a long period of time, dust and gases in the low-pressure stratosphere (such as CO_2 and SO_2) have the opposite outcome, which is to enhance the greenhouse effect, warming the planet.

Global climate and evolution

Over Earth’s history, the continents have come together in a supercontinent at least twice. Each time, this has had a dramatic effect on the story of life on Earth. This can be seen from a climatic point of view: when a supercontinent is first formed, there is a huge amount of tectonic activity: lots of clashes between continents and lots of volcanic eruptions. As a result, huge volumes of gases and dust are injected high up into the atmosphere, producing a massive greenhouse effect. Also, as the continents come together they reduce the extent of shallow seas where life thrives. In addition, the supercontinent is very high up with many plateaux, so the precipitation on land is greatly reduced. So in summary, supercontinents are extremely bad for life. As shown in Figure 3.11, a mass extinction and a reduction in diversity coincides with each supercontinent.

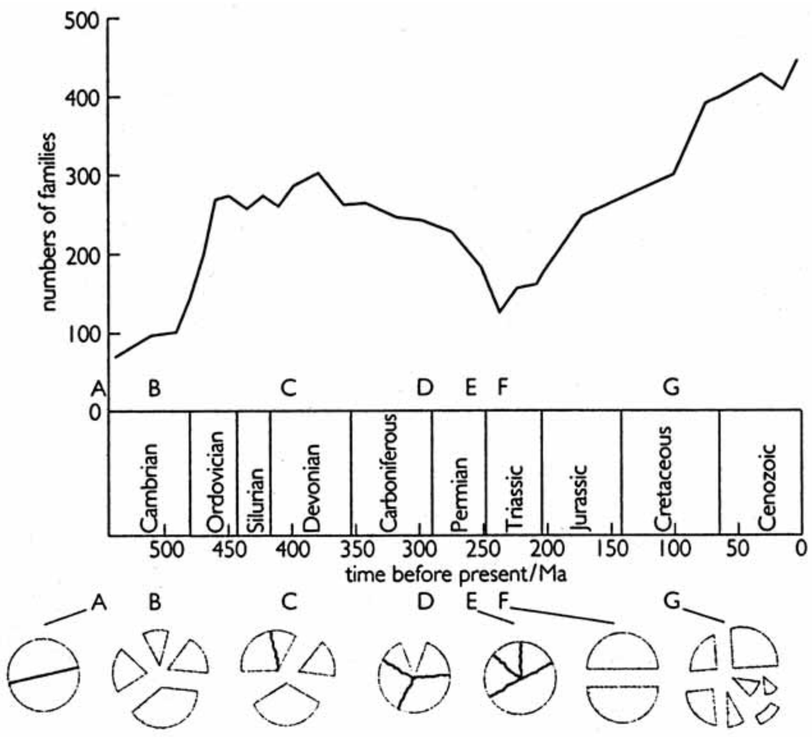

Figure 3.11 Comparison of the diversity of life on Earth and relative positions of the continental plates. Note that mass extinctions correspond to periods of supercontinents such as Pangea about 250 to 200 million years ago

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Activity

Page 137 of Open University, Dynamic Earth (1997) shows the global distribution of large igneous provinces. Summarise in note form how these provinces occur and the general consequences for global climate.

Conclusion

Tectonic activity defines our present climate system, and has produced the following characteristics:

- An extremely high equator-to-pole temperature gradient, which makes our climate system very dynamic and violent.
- A unique ocean circulation system, particularly the deep water circulation system, which includes the NADW maintenance of a warm and mild climate over Europe.
- Monsoonal systems, which produce extremely fertile land on which half the population of the world live.

A reminder of your learning outcomes

Having studied this chapter and the recommended reading, you should be able to:

- outline the direct effects of climate and tectonic activity and discuss the different influences of horizontal and vertical movement of the continents
- explain the importance of tectonic activity in controlling regional precipitation and the monsoon system
- describe how tectonic activity can affect climate indirectly
- explain how the relationship between climate and tectonics has influenced evolution through geological time.

Sample examination questions

1. Explain the ways in which our current climate system has been modified by tectonics.
2. Illustrate and explain the ways in which ocean circulation can be altered by the position of the continents.
3. Discuss the reasons why there is currently ice at both poles.
4. Illustrate and explain the causes of the monsoonal systems in Southeast Asia and South America.

To answer Question 3 we suggest you include the following.

- Introduce the essay by explaining the relative uniqueness of our current climate system.
- Explain that three things are required to produce significant ice sheets at the poles: relatively cold global temperatures; land over or adjacent to the poles; and an adequate supply of moisture to maintain the ice.
- List each of the major steps over the last 100 million years which have lead to our current situation with ice at both poles and explain their effects on global climate, e.g. separation of Australia from the Antarctic; separation of South America from the Antarctic; uplift of Tibet; closure of Panama gateway.
- Make sure you discuss the effect of changing ocean circulation, place continental land masses close to or on the poles and also the effect of lowering global carbon dioxide levels.
- Explain that during the Quaternary period for the majority of the time there have been huge ice sheets over both North America and Europe up to 3 km thick.
- Discuss the effects of having ice at both poles, for example the very large equator–pole temperature gradient and the dynamic nature of global climate.

Always conclude your essay with the key points you have mentioned above.

Notes