CHAPTER 10
Earth’s geological structure and processes

Introduction

Earth’s vast hidden bulk and relatively great age appear to make geological science an increasingly less attractive component of contemporary relevance in geography syllabuses and issue-driven environmental science courses. Yet, in their concern to understand and resolve problems of rapid environmental change, environmental degradation, resource depletion and hazard management, *inter alia*, students are frequently required to make piecemeal, ‘menu’-driven excursions into the geological world. As a result, they rarely develop a holistic appreciation of how Earth works, are often poor at making connections between topics and are left without a solid framework on which to build an understanding of Earth’s surface processes. In many ways, this not only fails to grasp the holistic nature of Earth Systems but also conflicts with the demands that climate and environmental change are now placing on us to appreciate Earth Science and Earth History as part of managing Earth’s future.

In order to address these problems, this Chapter links with chapters 11-13 and 24 in particular to explore the connections between Earth’s origins, its long-term geological evolution and its contemporary surface features and processes. An outline of Earth’s internal and surface structure, together with internal energy flows, is the prelude to the unifying theme of plate tectonics and the supercontinental cycle. This is developed by identifying first the principal components of crustal plates and processes of plate motion. Each component is described in turn, with an outline of its associated general geological processes. These are assembled into a global architecture of plates and global tectonic landforms. Attention is paid throughout to contemporary examples of components, processes and landforms.

The chapter provides a basis for understanding the modern distribution of oceans in Chapter 11; the location of key parts of the rock cycle developed in Chapters 12 and 13; the principal orogens in Chapter 24; and the major geomorphic processes and landsystems which shape the landsurface in Chapters 14–17; and the overall, pervasive influence of tectonics on so much more of Earth’s physical environments.

Chapter Summary

Origin and dynamics

- The planets of our solar system formed through the fractionation, condensation and coalescence of elements from a planetary nebula. Earth formed as a terrestrial planet in the hotter, inner zone of the system c. 4.6 Ga ago.

- Earth’s formative processes endowed it with thermal and gravitational energy, and the long-term release of thermal energy to space drives a continuous deformation and reorganization of the brittle crust.

- Plate tectonics, or the study of that reorganization, distinguishes between lighter and older continental crust floating on heavier but much younger oceanic crust and recognizes that nine-tenths of all crust is less than 600 Ma old.
• The crust evolves through the cyclical coalescence and fragmentation of supercontinents and corresponding changes in ocean size and distribution, over c. 500 Ma cycles.

• Earth is currently midway through such a supercontinental cycle, and the present global distribution of continents and oceans reflects the fragmentation of the former supercontinent Pangaea during the past 200 Ma.

Earth structure and internal energy

• Continuing vigorous fractionation segregated elements and minerals into Earth’s essential structure during the first c. 200 Ma of its history, with a dense nickel–iron core surrounded by less dense silicate-rich mantle and crust.

• The lightest fractionates were exhaled into space but outer films of aqueous and gaseous fractionates survive to form Earth’s oceans and atmosphere, where they are further synthesized in sunlight to form the biosphere.

• Earth’s internal or endogenetic energy is derived from the initial accretion and compression of planetary matter and its continuing fractionation, including the decay of radioactive isotopes.

• This process is augmented by the kinetic energy from initially more intensive meteorite bombardment and friction generated by the segregation of denser and less dense minerals. Internal thermogenesis generates a flow of geothermal heat to the crust.

• Displacement away from the core during fractionation and plate tectonic activity also invests earth materials with potential (gravitational) energy.

Crustal evolution: plate tectonics

• Earth’s brittle crust is divided into seven major and six minor mobile plates, which possess active margins where they diverge or converge and relatively stable interiors. Their motion is stimulated by slow convection currents in the outer mantle and aided by the partial melt of the asthenosphere.

• The crust bulges, stretches, thins and eventually rifts over the rising limb of a convection current, allowing a plume of molten basaltic magma to penetrate the crust and erupt at Earth’s surface.

• Formation of new oceanic crust by this effusion causes sea-floor spreading away from a developing mid-ocean ridge, with ocean enlargement on both sides of this constructive, divergent plate boundary.

• As continental plate is rolled away from the divergent boundary, convergence leading to crustal shortening and destruction must develop eventually elsewhere. This forces the subduction of denser oceanic crust back into the mantle beneath lighter continental crust, or collision and partial subduction at intercontinental plate margins.

• Subduction of oceanic crust leads to resorption at depth, where it undergoes metamorphosis or eventual remelting in the prevailing higher temperatures and pressures. The subduction zone is marked by an ocean trench, a volcanic island arc
system and volcanic eruption through the adjacent continental crust, with which the island arc system may fuse eventually.

- Subduction of lighter continental crust at intercontinental margins is less dramatic and accompanied by partial melt and underground emplacement of granitic batholiths, rather than volcanic eruption.
- Crustal shortening and subduction are accompanied by crustal thickening, with lighter rocks elevated by isostatic uplift to form cordilleran mountain systems or orogens.
- The relatively rapid formation and resorption of denser oceanic crust and slower recycling of lighter continental crust maintain a mosaic of younger oceanic plates over some 61 per cent of Earth’s surface and older continental plates.
- Plate surfaces and boundaries possess their own distinctive global architecture and morphotectonic landforms, characterized by distinct suites of rocks and related geological and geomorphological processes.

The geological evolution of Britain

- Rocks representative of half of Earth’s age and of structures formed during all three Phanerozoic orogenic periods of the past 0.6 Ga are found in the British Isles, despite their small land area.
- Geological terranes and formations assembled as far away as 60° S reflect a slow northward drift during the past 0.5 Ga across the equator through tropical, subtropical and temperate ocean and terrestrial environments.

CASE STUDY    Tectonics and Landforms in the western USA

**Aims and objectives**  Chapters 10-13 focus on terrestrial geological, geomorphic and oceanic environments and their processes of rock formation, deformation and denudation. This Case Study provides a sub-continental outline of the general tectonic history and mega-landform character of the western USA. It is intended as an overview, linking named regions with illustrations provided in the main text of these chapters.

Studying the geological and structural (tectonic) history and character of a whole continent is a huge and complex challenge, yet an outline overview can be rewarding ~ emphasising the scale, tectonic provinces and sequencing of continental architecture and morphotectonic “mega-landforms” and linking processes with real examples. We illustrate this here for just *part* of the North American continent ~ the tectonically-active western USA, part of the North American Cordillera ~ where predominantly desert and mountain climates and relative lack of vegetation make geology on the ground easy to see.

At a glance, an atlas map of North America reveals 4 major topographic regions which reflect, in the most generalized sense, four principal morphotectonic provinces. They consist of the stable craton which underlies northern and eastern Canada, Hudson Bay, islands of the Canadian Arctic and Greenland; the older, Palaeozoic Appalachian cordillera in the east; and an interior, sediment-trapping basin stretching from the Arctic
(where it is drained by the Mackenzie river system) to the Gulf of Mexico, widening to incorporate the Mississippi-Missouri and Ohio river systems. The fourth province ~ the western Cordillera ~ is the subject of this case study.

Although the Cordillera are a complex assemblage of exotic terranes, many of them containing rocks well over 2 Ga old, their modern form reflects the interaction of the North American and Pacific plates during the Mesozoic and Cenozoic era ~ just the past c. 200 Ma. Once Atlantic rifting commenced and North America began to move westwards, active subduction created volcanic island arc and arc-continent activity along its entire west coast. Crustal shortening between 180-150 Ma emplaced large batholiths beneath then-coastal orogens, in much the same way as in the Andes of south America (see Chapter 24). They migrated inland as shortening also triggered eastwards-thrusting, and accretion continued on the western continental margin. The Sierra Nevada batholith was emplaced in this way during the later Mesozoic. Further east, crustal shortening thrust up the Rocky Mountains in two phases between 70-40 Ma. This Laramide Orogeny created not one but a series of ranges, from eastern New Mexico in the south to the Canadian border with western Montana in the north (and onwards through Alberta and northern British Columbia towards the Arctic Coast). Despite intense erosion, including Quaternary alpine glaciation, which stripped off their Palaeozoic sedimentary cover to expose a Precambrian granite basement, they rise abruptly over 4km OD today above the High Plains to the east.

The advancing continent began to override parts of the Pacific mid-ocean ridge and its Farallon microplate, leading in due course to a mixture of subducting crust (melting at depth) and rising asthenosphere several hundred kilometres inland. Substantial thermal diapirism raised the Colorado plateau during the early Neogene, < 20 Ma ago, thus triggering a unique and most spectacular series of morphotectonic consequences to north and west ~ the Basin & Range system and the Sierra Nevada eastern fault scarp. The Basin-Range system represents asymmetric extension and is, in effect, a massive continental landslide towards the Pacific broken up into several hundred parallel, half-graben valleys and alternating mountain blocks, mostly with west-facing scarps. They cover the entire state of Nevada and extend as far as eastern California in the west, Oregon in the northwest, across northern Utah into Idaho in the north and southeast into western Texas. Extension may have also initiated tilting of the Sierra Nevada batholith, which outcrops along a 500 km strike-slip front in eastern California, although there is new evidence that tilting may be less than 10 Ma old. Its eastern fault scarp ~ which currently experiences post-lift isostatic uplift ~ fronts the Basin-Range system with the highest series of glaciated peaks south of Alaska. Locally, uplift of the Colorado Plateau triggered its dramatic incision by a number of rivers ~ most notably the Colorado River in the Grand Canyon ~ which have cut up to 1.5 km deep through rocks representing almost half of Earth’s history. This is only exceeded in the west-draining canyons of the Sierra Nevada, with the added impact of glacial erosion ~ but in less than half the time.

Much Cordilleran subduction and crustal shortening has taken place obliquely, with major strike-slip faulting and much northwest-wards movement of the Cordilleran terranes across perhaps 40° of latitude since the mid-Mesozoic 100 Ma ago ~ in a manner which continues today most notably along the San Andreas fault which will eventually move Los Angeles into eastern San Francisco ! One of the most active parts of the fault system is instrumental in creating the Transverse Range, where changes in
plate motion create a sharp bend in the southern Californian coast from Santa Barbara to Los Angeles. The Range extends for almost 500 km, dislocated by the fault system into linear, mobile mountain blocks in which Quaternary marine sediments are thrust alongside basement granites and gneisses over 1 Ga older. Intense seismicity, rapid uplift and associated landslides in the highest San Gabriel and San Bernadino Ranges (> 3 km OD) mark this northern rim of the highly-populated Los Angeles basin!

It is clear that the western Cordillera are morphotectonically active today, responding to crustal extension and shortening, but the classic subduction-tectonic “front” remains along the Pacific coast. In California it consists of a seismically active Coast Range of moderate elevation, separated from the Sierra Nevada by the 600 km long and 100 km wide Central Valley. Further north, from northern California through Oregon and Washington State to Vancouver in British Columbia, the volcanically-active Cascade Range (housing Mount St Helens amongst others) forms part of the active Pacific Ring of Fire. They are also high enough, at ≥ 3.5 km, to support small mountain ice caps today.

In summary, the North American Cordillera contain outstanding examples of almost all types of plate tectonic activity, with the sole exception of intercontinental-collision tectonics. The mountain and desert landsystems they promote make their rocks particularly accessible to the view ~ even if many localities are remote. Their true extent, perhaps, is somewhat less apparent through the rapid accumulation of thousands of metres of sediments in the intermontane basins ~ but they, too, are testimony to the dramatic rate and youthfulness of morphotectonic and geomorphic processes.

Learning objectives

- understand the mobile nature of Earth’s crust and the tectonic processes and supercontinental cycles which shape and reorganise it
- explain the fundamental architecture and age of the continents and oceans
- appreciate the extent to which tectonic processes and global landforms influence the distribution of climate, weather systems, living organisms and geomorphic processes across Earth’s surface

Essay titles

1. Explain how sea-floor spreading occurs and why it is considered to be central to plate tectonic processes.
2. Why are convergent plate margins said to be destructive and is this entirely true?
3. Write an explanatory account of the tectonic origins and geological character of the British Isles.

Discussion topics
Consider the concept of the ‘terrane’ and outline its importance to unravelling Earth history.

On what grounds might we include the hydrosphere, atmosphere and biosphere in a list of geospheres with the asthenosphere and lithosphere?

How far do tectonics extend their influence into global patterns of climate, vegetation and landsystems thought to be more attributable to global radiation balances?

Further reading

Hancock, P. L., and Skinner, B. J., ed.s (2000) The Oxford Companion to the Earth, Oxford and New York: Oxford University Press. This book remains a superb compendium for physical geographers, Earth and environmental scientists, with over 900 individual entries covering more than 1,000 illustrated pages. It is a major reference work combining key elements of an Earth science glossary, dictionary and source of short, definitive articles and cross-references in a very readable format, edited by two well known authors.

Ince, M. (2007) The Rough Guide to The Earth, London: Rough Guides Ltd, Penguin Books. This is the perfect foil to the other texts and anything but rough! Its pocket-sized 300 pages describe the essence of every major geosphere system, crammed with illustrations, and serves equally well as an introduction or revision text.


Kearey, P., and Vine, F. J. (2008) Global Tectonics, third edition, Oxford: Blackwell. This is the updated edition of an important but readable text on plate tectonics, supported by an unobtrusive level of technical explanation and by simple line drawings rather than photographs.

Ruddiman, W.F. (2001) Earth’s Climate: Past and Future, New York: W.H. Freeman & Co. A text of rare origins and quality, written in accessible form by one of the leading international climate-change scientists, who swaps his ocean-drilling programme boots to tell a fascinating story. Covering so much more than just climate, he crafts the interactions of tectonics, oceans, ice-sheets and the human landsurface into a climate-system masterpiece.

References


**Web resources**

An excellent digital shaded relief map of the conterminous states of the USA (*i.e.* excluding Alaska and Hawaii) is the subject of United States Geological Survey (USGS) MAP I-2206, compiled in 1991 by Gail P. Thelin & Richard J Pike, US Dept. of the Interior, USGS. Downloadable copies of the map in alternative formats and a copy of the related publication, together with an “added geology” version, are available on the *tapestry.usgs* website also listed here.

This is one of the best of many other useful websites and covers 35 principal structural, geological or geographical regions of the USA available with a search for the individual region. Those that are particularly relevant to this case study are: Basin & Range Province, Grand Canyon and Colorado Plateau, Sierra Nevada, Central Valley California, San Andreas Fault & Transverse Range, California; the Cascade Range & Mount St Helens; Rocky Mountains. This is all set out in a splendid, interactive website with text, satellite imagery and geological maps, linking the US continental geology with topography from the USGS MAP I-2206 website also listed here.

[http://www.bgs.ac.uk](http://www.bgs.ac.uk)
The British Geological Survey website, under the aegis of the UK Natural Environment Research Councils, provides an active, regularly updated source of data, information, events and activities of geological and related interest ~ primarily within the UK but also of wider, related international interest. An excellent source of Earth Science, data, services, products (including maps, geo-publications, images) and educational interest.

A comprehensive source for the wide range of work and specialist interests of the United States Geological Survey. Its home page directories link directly into comprehensive cover of US volcano observatories, earthquake, flood and tsunami watches and other geological
aspects of hazards and human health/wellbeing, with daily updating of active events. It is also a good source of geological images, information and interactive education.