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Introduction

An inspection of the globe immediately reveals an imbalance of areas of land and sea and the almost infinite variation of shape and relief forms which characterise the continental and oceanic areas (Figure 1.1). It is the intention of this book to describe and account for the development of the large-scale features of the Earth's surface. An attempt will be made to indicate why the composition, configuration and structure of the Earth's crust is of fundamental interest to all geographers and natural scientists.

The development of geomorphology can be traced from nineteenth-century physical geography, through a study entitled 'Physiography' which was propounded by T.H. Huxley, to the geomorphology of W.M. Davis at the beginning of the present century. Davis was responsible for introducing the three basic elements of geomorphology: structure, process and stage. Structure embraces the materials of the Earth's surface from which landforms are produced by the active processes of weathering, erosion and sedimentation. The stage, or morphological development of a landform, was related to the factor of time through which the processes had worked. In the last 20 years geomorphologists have tended to concentrate much of their energies unravelling the processes which operate and on how to measure them. Whilst in no way decrying this trend, this account of world geomorphology attempts to refocus attention onto the major physical features of the Earth's surface, emphasising their significance in terms of man's environment and economic well-being.

It would appear that the time is ripe to bring back to to geomorphology a wider perspective which is implicit

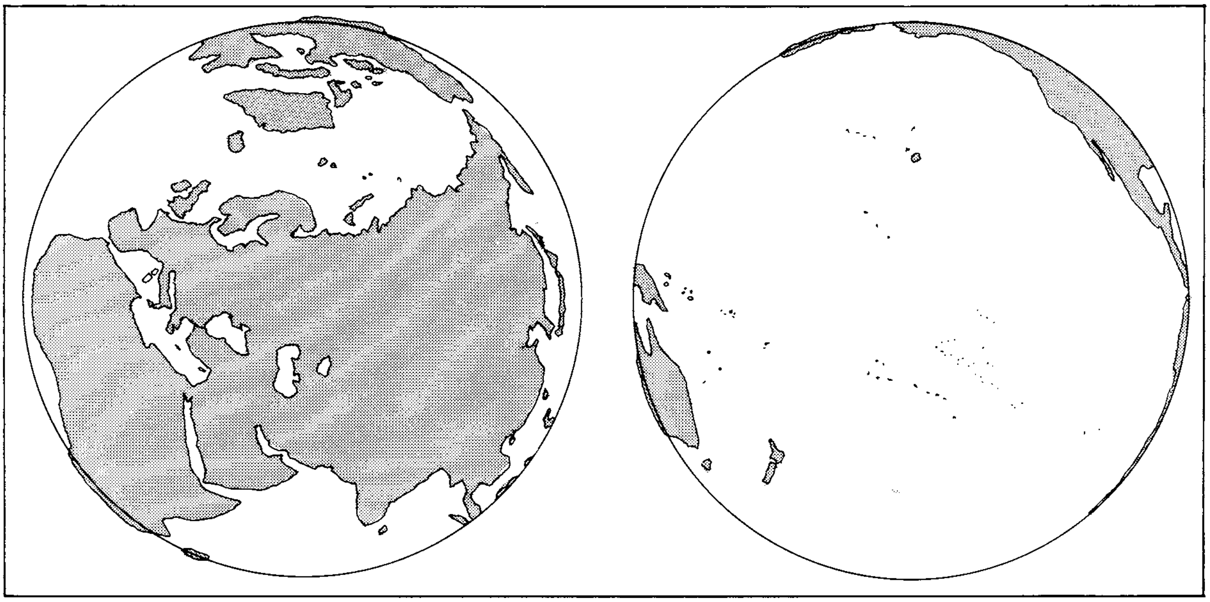

Figure 1.1. The unequal distribution of land and sea.

in the title *World geomorphology*. By definition geomorphology is concerned with the configuration of the Earth's surface, with relief and the way relief forms have developed into the landscape of the present day. The underlying significance of landscape, with its natural resources, is that the whole of human economic and social activity takes place upon it, and is inescapably linked to it.

Geographers require the analysis of geomorphology as a basis for an understanding of land form development and regional synthesis. Landforms are used extensively by geologists in mapping the distribution of rock outcrops. Soil scientists find a geomorphological analysis of the landsurface invaluable for mapping the distribution of the different types of material and soil; different sites tend to show different combinations of the soil forming factors. Ecologists and hydrologists also find the scientific description of landforms, as well as an understanding of landform evolution, to be significant in their studies. Land-use planners and civil engineers have found a knowledge of the origin, character and distribution of landforms useful in avoiding unnecessary expense in planning urban development and carrying out large-scale civil engineering projects.

As an explanation of the past and present distribution of continents, the theory of plate tectonics provides the most coherent account available. Besides giving an explanation of the fundamental relief of the Earth and why the continents are in the positions they now occupy, it can also be extended to explain the origin and distribution of mountain ranges, plains, plateaux, deep sea trenches and other major geomorphological features. Secondly, hazards such as earthquakes and volcanicity are not random in their distribution but are related to the margins of lithospheric plates. Thirdly, the occurrence of many economically valuable minerals and fuels has been shown to coincide with the plate margins. Fourthly, the break-up and movement of the continental masses provides some answers to the puzzle of palaeontological and present biogeographical distributions.

Following this introduction in which the geomorphological units of study are described, as well as the geological time-scale, the internal structure of the Earth is considered. This is an essential precursor for the understanding of the shape and disposition of the continents. In Chapter 2 the evolution of the sea floor and the continental masses is considered, setting the scene for discussion of the geomorphology of the major lithospheric plates. The general geological history of each lithospheric plate, including both continental and related oceanic areas, is described and the major divisions introduced in Chapters 3–9. The geomorphology of each province within these major divisions is then

Table 1.1. *The geological time-scale (in millions of years: my)*

Cenozoic era	Quaternary		Holocene	
			Pleistocene	2 my
	Tertiary	Neogene	Pliocene	7 my
			Miocene	26 my
		Palaeogene	Oligocene	38 my
			Eocene	63 my
			Palaeocene	65 my
Mesozoic era	Cretaceous			135 my
	Jurassic			190 my
	Triassic			225 my
	Permian			280 my
Upper	Carboniferous			345 my
	Devonian			395 my
Palaeozoic era	Silurian			430 my
Lower	Ordovician			500 my
	Cambrian			570 my
Eozoic or Pre-Cambrian time	Upper Proterozoic			1000 my
	Lower Proterozoic			2000 my
	Archean			3000 my
	Katarchean			4500 my
	Origin of the Earth			

presented in so far as information is available. It will be obvious to the reader that the information is uneven in amount, content and reliability. However, within the broad scale employed, it is possible to present an outline account of the many geomorphological regions of the world.

The geological time-scale

The landscape which we see around us is the culmination of many millions of years of geological activity. The familiar relief of hills and valleys was formed by the operation of processes which, it is assumed, have been working in a similar manner throughout the Earth's history. Essentially, Earth history is deciphered from the evidence of rock strata and particularly the order in which they have been deposited. The sequence of sedimentary rocks was first worked out in the British Isles and the approach taken then has been applied and found satisfactory in other parts of the world. The sequence of rock strata is accompanied by the evolutionary development of their contained fossil fauna thus enabling correlation of rock strata across country from one outcrop to another.

The geographical formations and the evidence of evolving flora and fauna contained as fossils can be conveniently divided into four eras (Table 1.1). The *Eozoic*, a period in which there was little sign of life forms, was followed by the *Palaeozoic* in which there was a considerable variety of invertebrate fauna. The *Mesozoic* is characterised by the dominance of different forms of reptile, in particular the dinosaurs, and finally the *Cenozoic* covers the period of development of the mammals and other recent and present-day life forms. Geological formations of the Palaeozoic and Mesozoic are frequently referred to as the Primary and Secondary rocks respectively but the much shorter duration of the Cenozoic is unequally divided between the Tertiary and Quaternary, the latter referring to only the last two million years of Pleistocene and Holocene formations.

In terms of the evolution of the major continental areas of the world, developments since the Carboniferous formation was laid down are significant as considerable rearrangement of land and sea has occurred since that time. When considering the age of the oceanic floor, it has been found that there are few areas which are older than the Cretaceous. The Quaternary, including the glaciations of the Pleistocene, has great significance for the landforms of many regions of the world where glaciation took place. In many other regions the indirect effects of glaciation, such as those of low sea level, can be observed to have also had profound effects on landscape development.

The Earth is thought to have had its origin between four and five thousand million years ago. Evidence from the oldest parts of the continents indicates an age of over two thousand million years, but the application of normal stratigraphical methods of dating is made difficult in the Pre-Cambrian by the absence of palaeontological remains. A sub-division is made possible based on

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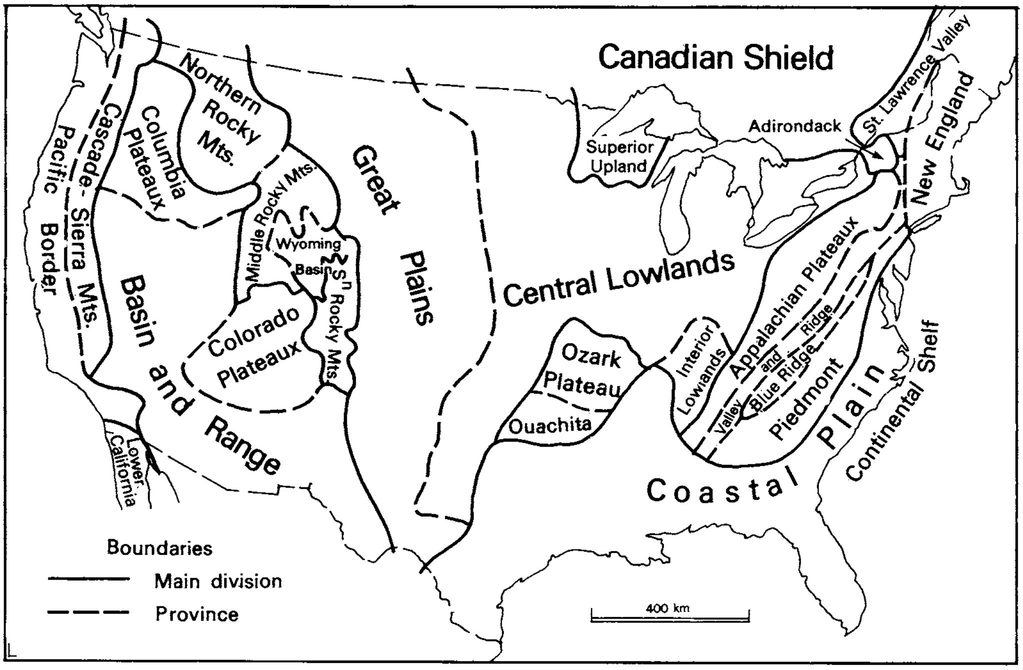

Figure 1.2. Physical provinces of the United States as prepared by Fenneman for the U.S. Geological Survey.

lithology and succession, backed by radioactive decay methods of dating. Four sub-divisions of Pre-Cambrian time are recognised: the Katarchean, the Archean and the Lower and Upper Proterozoic. There is evidence of several phases of mountain building throughout the Pre-Cambrian during which the continental nuclei were added to by geosynclinal action around their edges. This process is described in Chapter 2. Mountain-building episodes continued at intervals throughout the Earth's history and in part serve to sub-divide the long period of geological time.

Although the lithology of the rocks is more important than their age in the development of landforms, it is still necessary for the geomorphologist to have a clear picture in his mind of the sequence of events which has produced the materials upon which the processes of erosion act.

Divisions of relief

When using weights and measures it is convenient to have units of different sizes, and the same principle exists in descriptive geomorphology where landforms of vastly different sizes are being discussed. It is possible therefore to speak of several different 'orders' of relief. After the whole Earth, the first order of relief a geomorphologist must take into account is the fundamental division of the Earth's surface into ocean basins and continents. As Linton has written, 'nature offers us two inescapable morphological unities and two only; at the one extreme, the indivisible flat or slope, at the other the undivided continent'. Between these two extremes it is necessary for the geomorphologist to search for the geomorphological equivalent of the highest common factor which will enable the delimitation of successively lower orders of relief features.

In 1916 a map showing the physiographic regions of the USA was produced by a committee of the Association of American Geographers. N.M. Fenneman who chaired this committee also produced a detailed account of the *Physiography of the United States* in two volumes. This major contribution to physical geography has stood the test of time and is used by Thornbury and others as a basis of their more recent accounts of the physical geography of the USA's part of the North American continent (Figure 1.2). The approach of Soviet geographers is briefly outlined in *The Geographical Magazine* volume 48, number 5 (the issue for

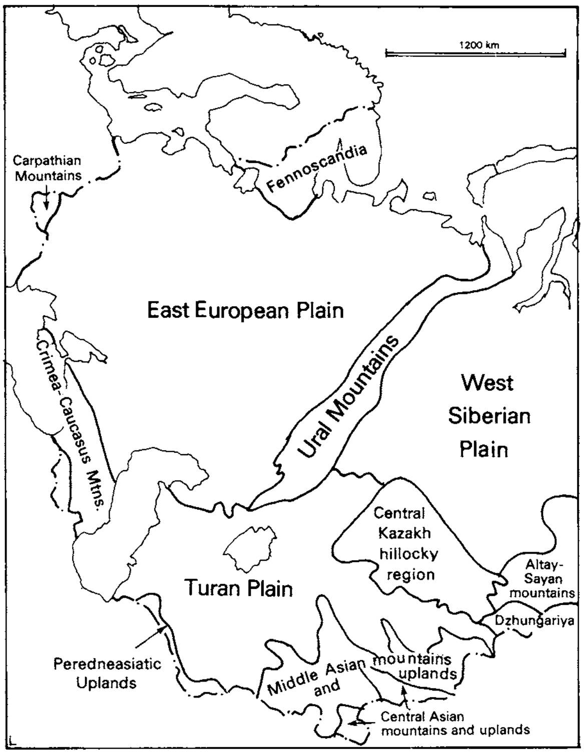

Figure 1.3. Natural environment complexes of the western USSR. (After *Geographical Magazine* 1976.)

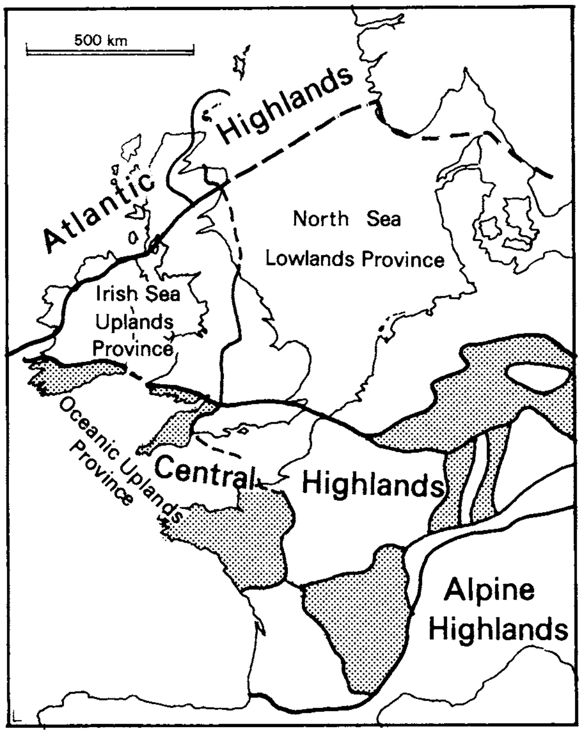

Figure 1.4. The major physiographic divisions of western Europe and their component physiographic provinces. (After Linton, in *London essays in geography*, 1950.)

February 1976). It is explained that the assessment of the complex natural regions of the USSR is 'essential for planning decisions and for constructive tasks on a regional or global scale' (Figure 1.3).

A second order relief feature would appear to be the primary continental sub-division which is referred to as a *major division* in the USA and as a *land* in the Soviet Union. These second order relief features are large and can only be applied to areas of sub-continental size. Examples are the central lowlands of America or the lowland of the European plain, areas of 500 000–800 000 km^2. The third order of relief recognised is the *province*, and the same term is used in both the USA and the Soviet Union. In the USA there are only three provinces which are smaller than the whole of England, so the dimensions of these third order features are still large, ranging up to 500 000 km^2.

If the concept of the highest morphological common factor is taken a stage further, a fourth order of relief can be determined: the *section*. A well-known example is the Black hills of Dakota, which form a structural dome of 8000 km^2 which, if further sub-divided, would lose the obvious unity of the area. The major physiographic divisions of western Europe as envisaged by Linton are shown in Figure 1.4.

It is at this point that there is a break in the classification and uncertainty exists, with various authors taking slightly different approaches. However, if a fresh start is made at the other end of the relief spectrum, with the indivisible flat or slope, it is possible to work upwards in size to meet the sequence established so far. A *site* is the indivisible flat or slope which Linton referred to as 'the electrons and protons' from which landscapes are built. The sites can be assembled into *facets*, units of the land surface which have similarity of surface form and uniformity of age and origin. In turn, facets can be assembled into characteristic associations referred to as *recurrent landscape patterns*. These are of such a size that they can be identified fairly readily upon air photographs and are much used in resource surveys of undeveloped regions. Several years ago, Linton suggested the terms stow and tract to

Table 1.2. *Orders of relief*

Order of relief	Term	Approximate size
First	Continent or ocean basin	–
Second	Major division	500 000 – 800 000 km^2
Third	Province	50 000 – 500 000 km^2
Fourth	Section	500 – 50 000 km^2
Fifth	Recurrent landscape pattern	50 – 500 km^2
Sixth	Facet	5 – 50 km^2
Seventh	Site	5 km^2

equate with facet and recurrent landscape pattern but his suggestions have not been widely accepted. The orders of relief are listed in Table 1.2.

In *Geography: a modern synthesis*, Haggett (1973) observes that geographers have to deal with objects which vary greatly in size. So, the examples used in his book have been allocated to one of five orders of magnitude: first order – the Earth itself down to features of 12 500 km^2; second order – 12 500 down to 1250 km^2, e.g. USA or Australia; third order – 1250 down to 125 km^2, e.g. a state such as New York; fourth order – 125 down to 12.5 km^2, e.g. a city; and fifth order features – less than 12.5 km^2. In the present account the emphasis is inevitably on large-scale features; consequently much of the analysis will be of second, third and fourth order features, which comprise the basic elements of world geomorphology.

The Earth as a planet

The Earth is a sphere, slightly flattened at the poles (an oblate spheroid) which has a mean radius of 6380 km, a volume of 1083×10^9 km^3 and a surface area of 510×10^6 km^2. The area of the landmasses is 149×10^6 km^2 (29.2% of the Earth's surface) and the area of the oceans is 361×10^6 km^2 (70.8%).

It is clear from historical records and religious accounts that mankind has been interested in the shape, size and origin of the Earth throughout civilised time. Many ingenious theories have been propounded which attempt to show how the Earth as we know it today came into being, one of the more widely known being the Judeo-Christian account of the Creation. Man's ideas of the cosmos were initially Earth-centred with the Sun, planets and stars revolving around. As early as the third century BC the Greeks were expressing doubts about this model and, although it was suggested at that time by Aristarchus that the Earth and planets revolved around the Sun, the idea only obtained grudging acceptance when it was again proposed by Copernicus in the sixteenth century. The Earth is a planet and part of the Solar System, which is where a discussion of the Earth's origin must begin.

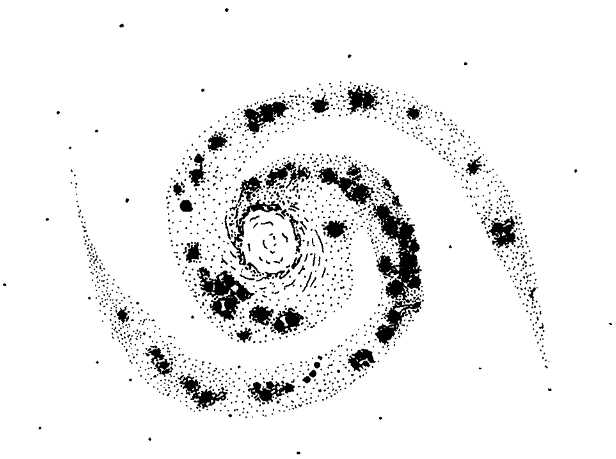

Figure 1.5. An impression of a spiral galaxy, one star of which is similar to the Sun.

The origin of the Earth

The sun and its attendant planets, known as the Solar System, comprise a very small part of the galaxy in which they are situated. In astronomy, distances are measured in light-years, the distance light travels in one year at a speed of 300 000 km per second. One light-year is almost 10 million million (10^{12}) kilometres. The distance across the Solar System is a mere 11 light-hours whereas the distance across the galaxy is 80 000 light-years. The nearest star, Proxima Centauri, is only 4 light-years away from the Solar System and is one of the hundred thousand million (10^{11}) stars which make up the galaxy. The galaxy can be seen from Earth as the 'Milky Way' and is a flattened disc of gas, dust and stars arranged in two spiralling arms (Figure 1.5).

Many theories have been proposed to account for the origin of the Earth and the Solar System during the last 200 years. They fall into two groups: earlier theories advocated a 'hot' molten origin for the Earth but recent ideas have tended to favour a 'cold' origin. The first

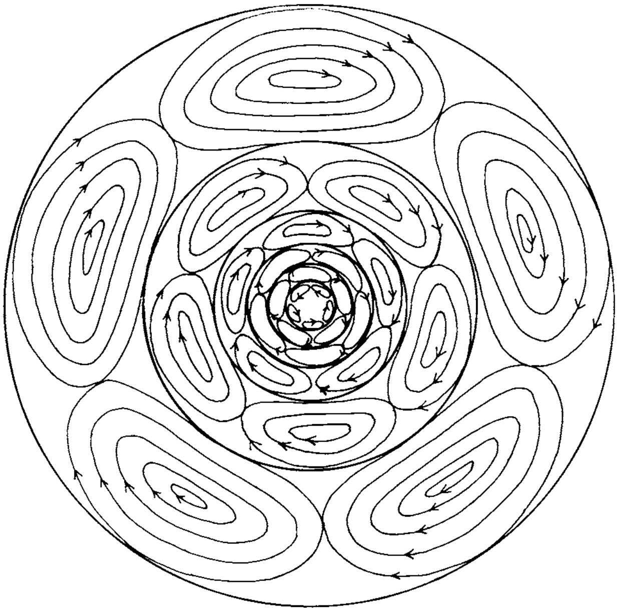

Figure 1.6. Origin of the Solar System as a cloud of dust. Individual eddies coalesced to form the planets. (After C.F. Wiezächer.)

significant proposal is an hypothesis originally suggested independently by Kant (1755) and Laplace (1796) which stated that the Solar System condensed from a gaseous nebula. This nebula was very hot and rotating, with subsequent developments resulting from the effects of cooling. This approach has been conveniently called the 'hot' origin for the Solar System

Other information has gradually been acquired which supports the 'cold' or dust cloud theory for the origin of the Earth and which tends to refute the other theories (Figure 1.6) Urey, the American astronomer who proposed the dust cloud hypothesis, supports his ideas with evidence from the distribution of chemical elements which occur on Earth, compared with those known to occur on other planets and the moon. If a hot molten origin is proposed, then Urey argues that the denser iron mineral should be below a lighter siliceous crust which would form a 'scum' on the Earth's surface. Evidence from Mars indicates that it has a uniform composition which suggests that it was never in a molten state. In the case of the Earth, it has been argued that if it had been molten, a smaller amount of iron and a greater amount of silica should be present in the outer layers than is known to occur. From the evidence of impact craters on the moon, astronomers in America have suggested that fragments of nickel–iron have been falling on to the planets steadily since their origin. Nickel–iron fragments do float around in space, and when one comes into the Earth's atmosphere it glows brightly and is referred to as a meteorite. Occasionally one of these reaches the surface and forms a crater as has occurred at Meteor Crater, Arizona in North America and at Wolf Creek, Western Australia. On the Moon, which lacks an atmosphere, these fragments would crash directly upon the surface where they have caused grooves up to 80 km long and with final impact areas known as 'mare' or 'seas', where the moon's surface has been altered by the heat of impact.

If quantities of nickel–iron have arrived at the surface of the Earth in this manner, then there should be evidence of it in the outer mantle. It is thought that this iron would gradually migrate towards the centre of the Earth, and as it did so, the moment of inertia of the Earth would change, slowing the rotation of the planet. Astronomical measurements have demonstrated that the day length has lengthened by one or two thousandths of a second over the last 2500 years. Calculations indicate that there is agreement in the figures and that the change in moment of inertia as a result of the iron migration could be correct. Additionally, the amount of iron movement to form the present core of the Earth would have to be in the region of 50 000 tons per second from the mantle to the core, at which rate it would take between 500 and 2000 million years; a figure which begins to approach the age of the Earth. However, the proponents of these theories state that many more observations and measurements are necessary before the ideas are confirmed.

This is but a brief and elementary glimpse of some of the theories and hypotheses which have been put forward to account for the origin of the Solar System and our planet, the Earth. Most scientists seem to favour the condensation theory, in which a cold dust cloud came together and then proceeded to contract under its own gravity.

The interior of the Earth

To understand the geomorphology of the continents and oceans it is necessary to begin with the Earth's structure and internal properties. The interior of the Earth can only be studied indirectly by remote means as, unlike Jules Verne's imaginative story, it is not possible to journey to its centre to see what it is like!

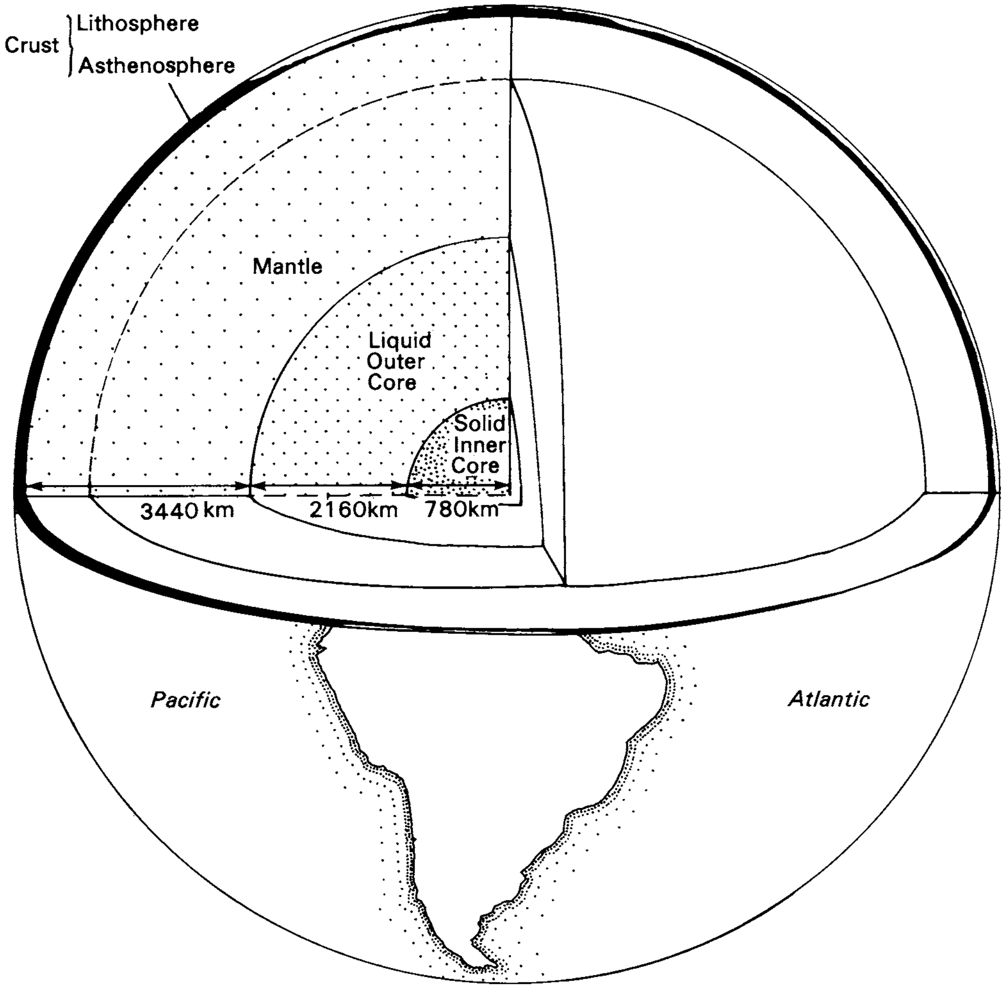

Figure 1.7. Section through the Earth showing its internal structure.

Information about the nature of the Earth's interior has come from the study of earthquake shocks. This study, the science of seismology, developed in the nineteenth-century after an Englishman living in Japan constructed the first seismograph and made it possible to record and measure earth tremors.

By the end of the nineteenth century three distinct types of shock waves, which emanate from the focus or epicentre of an earthquake, were recognised. Primary waves (P) take the form of expansion–compression waves, similar to sound waves in the atmosphere and although refracted at boundaries of different layers within the Earth, they can pass through molten material. Secondary waves (S), or shear waves, vibrate at right angles to the direction of travel of the shock and cannot pass through liquids because liquids have no shear strength. Surface waves (L) only occur in the surface layers of the Earth's crust not exceeding a depth of 32 km. These are known as Rayleigh waves when the ground has a motion like waves in water, and Lowe waves when the motion is horizontal and perpendicular to the direction of shock wave propagation. The speed of travel of each of these waves is different, the secondary waves travelling at about two-thirds of the speed of the primary waves. Their speed also varies with depth. Primary waves travel at about 5 km per second in the surface rocks and reach a maximum of 13.5 km per second at a depth of 2880 km.

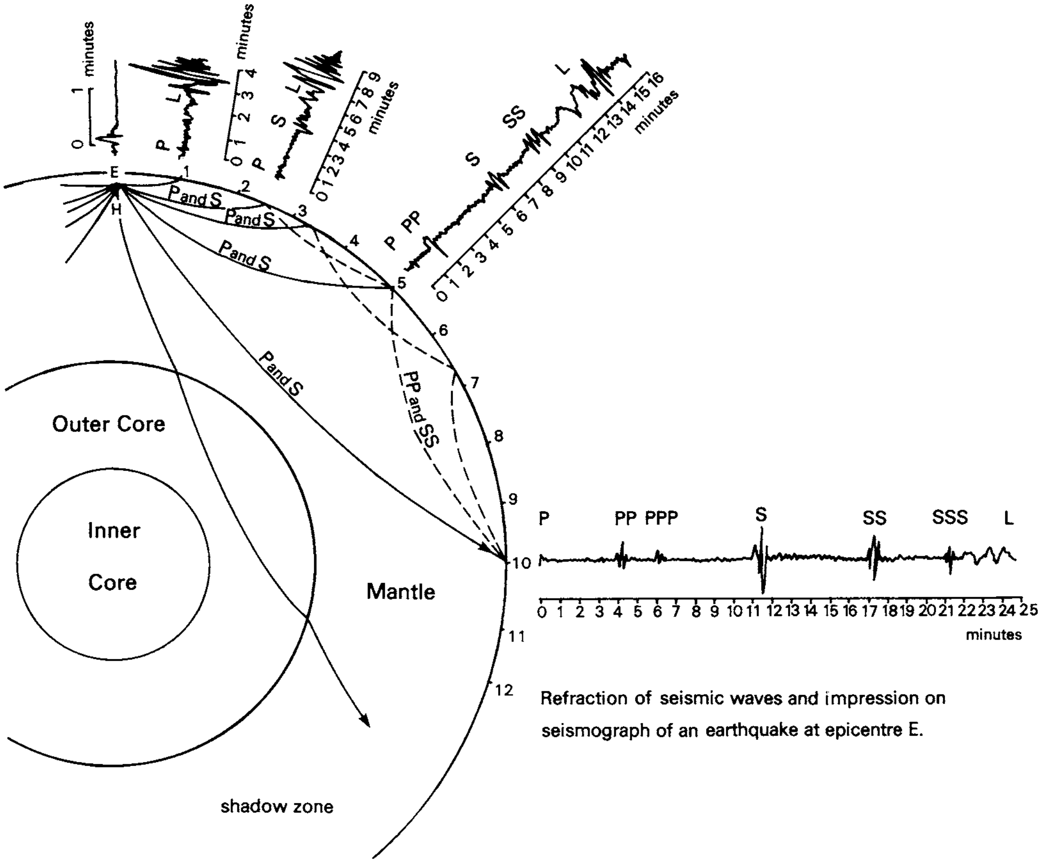

Figure 1.8. Seismic effects of an earthquake at E showing paths of P- and S-waves, the reflection of which leaves a shadow zone on the opposite side of the Earth.

These shock waves are reflected or refracted at the boundaries of layers with differing composition and physical properties, so it is possible to determine their path through the Earth's interior. In this way, it was discovered early in the present century that the earth possesses a central core with a radius of 2940 km. The radius of the Earth is 6380 km so the outer zone or mantel is 3440 km thick. As a result of subsequent investigations the core has been sub-divided into an inner core, radius 780 km, of extremely dense material reacting as a rigid body, and therefore probably solid, and an outer core (2160 km) which lacks rigidity and which acts more as a liquid (Figure 1.7). The composition of the inner core has been thought to be nickel–iron, but two German scientists have suggested recently that it may be highly compressed hydrogen (see note on 'expanding Earth', Chapter 2).

The principle whereby the presence of the core was determined is that there exist shadow zones where no direct seismic shock waves are experienced. Between 103° and 142° from a shock neither P- or S-waves occur; beyond 142° the P-waves reappear, but considerably retarded suggesting transmission through a liquid. The only S-waves which arise beyond 142° are those which have been reflected around the surface of the earth (Figure 1.8).

Outside the core, and extending almost to the surface, is the mantle with a thickness of approximately 3440 km. The mantle is thought to be composed of ultrabasic rocks, rich in magnesium–iron silicates similar to the common mineral olivine. At one time an ambitious project was put forward to drill down to this mantle material but it has since been realised that small fragments of these deep-seated rocks occasionally become thrust upwards and appear amongst the surface rocks. This has happened in Newfoundland, south-west Scotland and a particularly good exposure appears in the Troodos mountains of Cyprus.

The crust itself is a comparatively thin skin on the surface of the Earth, compared with the core and mantle, and on the scale of the diagrams employed in this book it would appear as less than the thickness of the line depicting the Earth's surface. However, it is the crust with which the geomorphologist is concerned, together with the layers immediately below, rather than with the deeper layers of the mantle and core. The division between the mantle and the crust is generally taken to be the Mohorovičić discontinuity, named after an eminent Yugoslav seismologist. Examining the records of an earthquake in Yugoslavia which occurred in 1909 Mohorovičić found the P- and S-waves showed two distinct bursts of activity from which he inferred that there was a shallow discontinuity which was later found to be about 32 km below the surface. This discontinuity (the Moho) is thought to represent changes in chemical composition or crystal structure, rather than the important change from upper, rigid crust to the mantle material beneath. Although the discontinuity lies at an average depth of 32–35 km below continents, it is only about 5 km below the ocean floors. Beneath high mountains, the Moho is depressed to over 65 km below the surface. A further, but less distinct, discontinuity lies between 10 and 25 km beneath the continental areas. This division of the crust separates the ocean floors and deeper parts of the continental crust from the upper continental crustal material. In effect, this discontinuity distinguishes between the basaltic sea floor (sima) and continental roots and the granitic continental areas (sial). At first it was thought that the Moho discontinuity demarked the surface material from the mantle, but recent discoveries have indicated that there is a plastic layer, called the asthenosphere, between 100 and 200 km below the surface, which is the significant boundary (Figure 1.9).

The idea that rocks could become so hot that the centre of the Earth is molten was recognised many centuries ago as volcanic outpourings gave visible proof of molten rock from great depth. Descents into deep mines also show an increase of temperature with depth. The interplay of temperature and pressure with depth inside the Earth means that this idea is only partly true, for at about 200 to 250 km below the surface, the increase in pressure raises the melting point so that the material becomes rigid and is capable of transmitting seismological secondary waves. Between the rigid mantle and the rigid surface rocks the presence of a plastic zone at depths of 100 to 200 km is of utmost importance when the hypothesis of plate tectonics is considered.

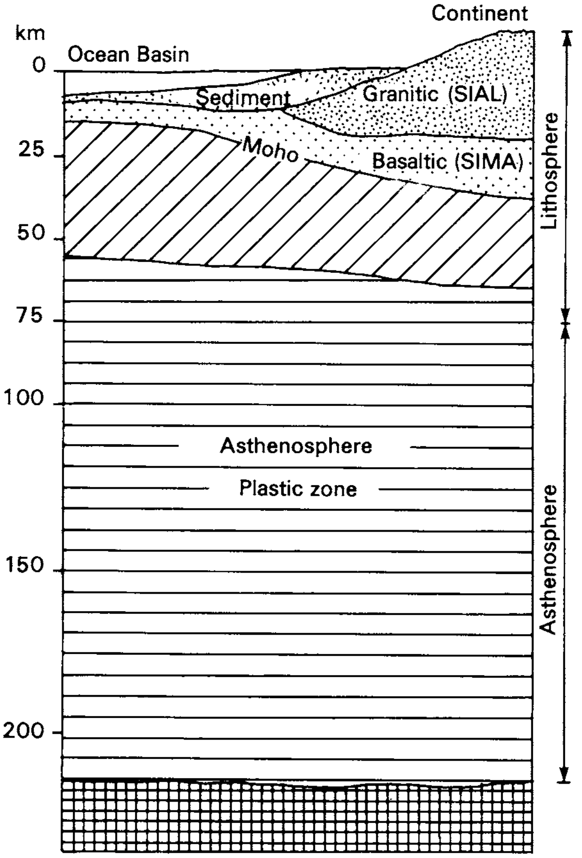

Figure 1.9. Section through continental (SIAL) and oceanic (SIMA) crust indicating the Mohorovičić discontinuity and, below the peridotite-rich base of the lithospheric plate, the asthenosphere.

The most convincing proof for the presence of the asthenosphere was provided by a Chilean earthquake in 1960. The shock was so violent that the whole earth vibrated and the frequency of vibration was such that the seismological records could only be interpreted by assuming the presence of a low velocity zone which transmitted horizontal and vertical shock waves at different speeds. Additional confirmatory evidence comes from the distribution of earthquake epicentres, most of which lie in the upper 60 km of the Earth's crust indicating the brittle state of the rocks. Below 60 km the number of shocks becomes less, suggesting that the rock is more plastic. However, in certain circumstances much deeper earthquakes are recorded in association