1

Introduction

Mantle convection is the fundamental agent driving most geology, yet many geologists still have only vague ideas about what mantle convection is, how it works and how it might inform their specialty. Because it is so fundamental, the better every geologist understands mantle convection, the better scientist he or she is likely to be. Of course, not everything is affected by mantle convection, but only by being well informed will a geologist recognise when it is relevant, and what that relevance is.

Misconceptions about mantle convection also seem still to be quite widespread. Some aspects of mantle convection are debated. Much of that debate concerns refinements, so the debate is quite legitimate, but some of the debate is based on misconceptions or incomplete understanding of current theories or observations. The latter debate is not productive. This is not to claim that alternative versions are inconceivable, but just to note that debaters need to be informed about the theories they wish to challenge if they are to make useful contributions.

For these reasons it seems worthwhile to offer an account of our current understanding of mantle convection in terms that are reasonably accessible to most geologists. That means the account should be fairly short, and there should be little mathematics beyond basic algebra and arithmetic. Nor should a strong grasp of physics be assumed, and such physics as is required (notably heat conduction and viscous fluid flow) should be explained in simple and reasonably familiar terms. These are the constraints I have set in writing this book.

Actually I thought I had already done this in *Dynamic Earth* [1]. The essential arguments are presented there in fairly simple terms, and mathematical or detailed sections are clearly flagged and can be skipped. However, that book is quite long, it is not cheap, and the appearance of equations is doubtless intimidating. Also, *Dynamic Earth* is probably regarded as *geophysics*, and few geologists might therefore bother to peruse it. So, it seems *Dynamic Earth* has not accomplished my present purpose and a separate account is required that is explicitly directed to geologists.

I use the term *geologist* in the broad sense of anyone who studies geological processes. This includes not only field geologists of various kinds, such as structural geologists, but also petrologists, geochronologists, geochemists, ore geologists, sedimentologists, palaeontologists and so on. It also includes geophysicists. For example, seismologists are often so specialised in the intricacies of their discipline that they have little understanding of other aspects of geophysics.

So, returning to the relevance of mantle convection to geology, there are two energy sources driving geological processes. Solar energy drives surficial processes related to the weather and life, such as weathering, erosion and sediment transport. All other geological processes are driven by the Earth's internal heat. These include mountain building, or more generally tectonics, magma generation, water flows in the deeper crust, metamorphism and much mineral deposition.

Tectonics, meaning the movements of the crust that result in mountains, rifts, faults, folds and so on, is driven by the Earth's internal heat and is obviously fundamental to a large proportion of geological processes. The connection between heat and tectonics is through convection: convection in the mantle is driven by the Earth's internal heat, and it generates the movements that manifest as tectonics. Plate tectonics is the primary agent of tectonics, and its existence is now widely accepted. Volcanic hotspots (by which I mean surface features like the Hawaiian and Icelandic volcanic centres) and their relatives, the flood basalts, are a secondary tectonic agent, and their existence and basic features are also widely recognised. There may be other tectonic agents, but evidently they are minor.

This much is well known and widely understood. However, the causes of plate motions and volcanic hotspots still do not seem to be clearly understood in the broad geological community. They are usually understood to involve mantle convection, but the relationship of plates and plumes to that convection seems to be understood only vaguely, and often with some basic misconceptions – or so it seems from my encounters with non-specialist colleagues and students.

To many non-specialists, mantle convection seems to be something rather mysterious that happens 'down there'. Its relationship with plates is not very clear. The idea of mantle plumes is hotly disputed by a few, and plumes are not uncommonly regarded as arbitrarily adjustable to fit circumstances and therefore not real science. Other confusions may exist, such as between crust and lithosphere, and misconceptions are not uncommon, such as that there are warmer upwellings rising under mid-ocean ridges, that 'plume tectonics' is an alternative to plate tectonics, or that mantle plumes are molten.

Yet there are now straightforward and well-quantified physical theories that account for the main features of plate movements, volcanic hotspots and flood basalts. Furthermore you don't have to be a rocket scientist to understand the essence of the physical theories – they can be understood fairly readily without a lot of mathematics or a PhD in physics.

The main purpose of this book is to focus on the questions of why plates move and what causes volcanic hotspots and flood basalts, and to present answers in a way that any geologist should be able to understand. In the view presented here, moving plates and volcanic hotspots are manifestations of convection in the Earth's mantle. Convection can be understood on the basis of two kinds of basic physical process (heat conduction and viscous fluid flow), which are explained through simple examples. Putting these two physical processes together allows one, for example, to calculate fairly simply how fast plates should move, and to get an answer that is close to what we observe. In the process, the relationship between plates and convection becomes clear, the likelihood of narrow, warm, columns rising through the mantle becomes evident, and other major features of Earth's tectonic system fall into place.

The book then goes on to look at two kinds of implication. The first is the evolution of the mantle, and how that might relate to tectonic evolution. The second is how geochemistry might fit into the physical and dynamical picture. This has been a vexed issue for some time, but refractory trace elements have by now been plausibly and quantitatively incorporated, and the noble gases might now also be finding a place. This is important because the geochemistry provides information not available just from the physics.

I should be clear that in offering 'answers' I don't mean 'the truth', I mean theories well based in physics that can account for many of the main features we observe. As always in science, this does not mean that better theories might not emerge, nor that alternative theories do not exist. Choosing between alternative theories is not entirely a rational process, it also involves judgements, and this book reflects my own judgements. In my experience, some of the extant criticisms of the theories presented here reflect a lack of clear understanding of what the theories actually are. So there are two roles this presentation can play: to inform the professionally curious, and to focus debates more constructively on real issues instead of misunderstandings.

2

Context

Basic concepts and primary observations. Defining the crust, mantle and core. Distinguishing crust from lithosphere, continents from ocean basins. The distribution of topography and heat flux over the sea floor.

Mantle convection occurs, remarkably enough, in the Earth's mantle. It is affected by the crust, and part of the lithosphere plays a major role. There are peculiarities near the boundary of the mantle with the core that may significantly affect mantle convection, and that certainly tell us some important things about mantle convection. To discuss our subject sensibly, we had better be clear what all these terms refer to: mantle, crust, core, lithosphere and so on. That is one thing this chapter is about. There are also important constraints on mantle convection to be had from the form of the Earth's topography, and from the geographic variation of heat flow from the Earth's interior. These will also be summarised.

2.1 Crust, mantle, core

The major division of the Earth's interior is into crust, mantle and core. The boundaries between these regions were detected seismologically, in other words using the internal elastic waves generated by earthquakes, which are detected as they emerge at the Earth's surface. The variation of seismic velocities, and density, with depth in the Earth is shown in Figure 2.1. The boundary between the mantle and the core is at a depth of about 2900 km, where the seismic velocities drop, the shear velocity is zero and the density jumps.

The fact that the shear velocity is zero in the core indicates that it is liquid, except for a smaller region at the centre, the inner core, which is solid. The high density of the core is consistent with it being made mostly of iron, with some nickel and

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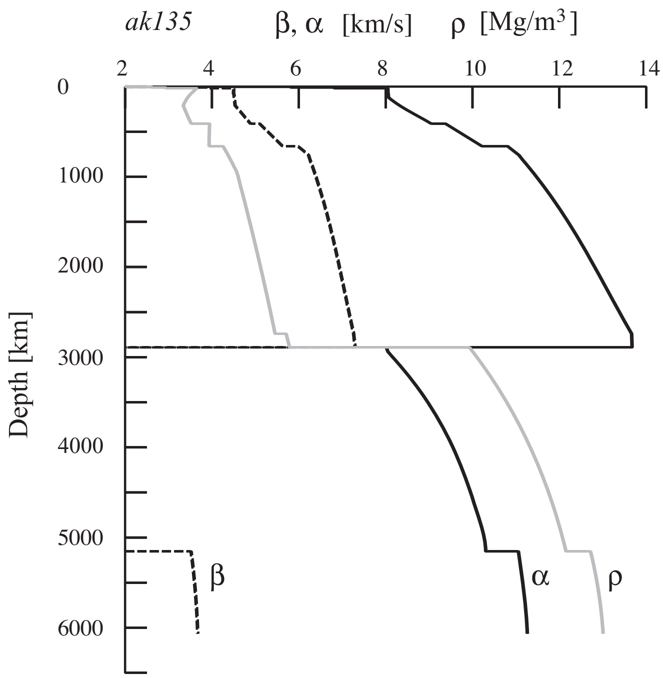

Figure 2.1. Variation of properties with depth in the Earth, defining crust, mantle and core. Profiles are of the seismic compressional velocity, α (solid black), shear velocity, β (dashed black), and density, ρ (solid grey). Curves from the model ak135. Figure courtesy of Kennett *et al.* [2, 3].

some lighter elements. The inference of iron and nickel comes from meteorites, some classes of which are made of an iron–nickel alloy.

The boundary between the crust and the mantle is barely discernible in Figure 2.1, because the crust is so thin on this scale, as will be discussed below. There are two jumps within the mantle, at depths of 400 km and 660 km. These define the *transition zone*, and are the locations of pressure-induced phase transformations, where the mantle minerals collapse into denser crystal structures. The transition zone may have played a large role in determining the form of mantle convection early in Earth's history. For many years there was also a major debate about whether the 660 km jump separated convection in the upper mantle from convection in the lower mantle, but there is strong evidence now that convection passes through the transition zone in the modern Earth. This will be discussed in later chapters.

Also visible in Figure 2.1 are changes in the bottom 200–300 km of the mantle. These changes are not well resolved in this model, but other seismic studies have clearly identified changes in seismic velocity and in some places discontinuities. This zone is known as the D″ region, terminology left over from early studies of

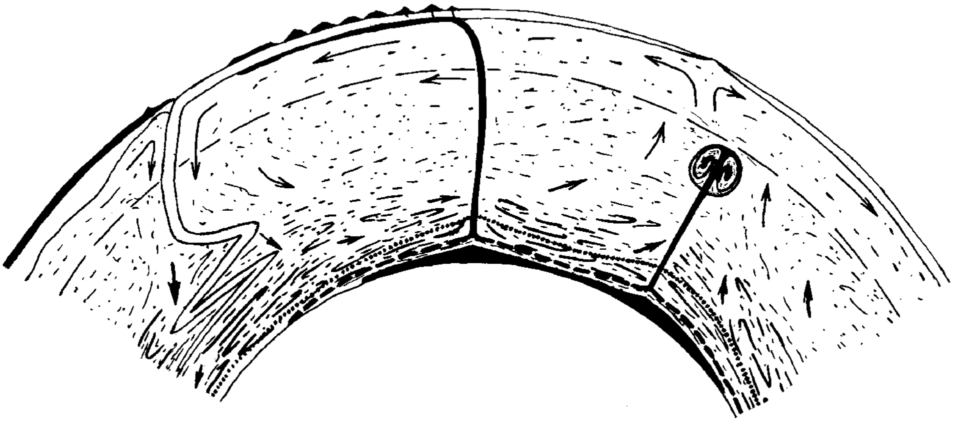

Figure 2.2. Sketch of the mantle, with crust and lithosphere roughly to scale. The core is defined by the bottom boundary of the mantle. From Davies [4]. Copyright by Elsevier Science. Reprinted with permission.

Earth's interior. There is now good evidence that it is due to a combination of a change in composition and one or perhaps two pressure-induced phase changes.

Based on this information, and other sources that we will encounter through the book, Figure 2.2 is a sketched cross-section of the crust and mantle, roughly to scale. The continental crust and some thicker parts of the oceanic crust show as black at the surface, though their thickness is exaggerated. The lithosphere, defined below, is outlined by the thin black lines. The lower boundary of the mantle outlines the extent of the core. Within the mantle, the 660 km discontinuity is marked by the long-dashed line. The D″ region is outlined by dashed and dotted lines at the bottom of the mantle. Other features in this sketch will be explained later in the book.

2.2 Lithosphere versus crust

The oceanic lithosphere plays a key role in the conception to be developed in this book. The role of continental lithosphere seems to be much less central, largely because continental crust is different from oceanic crust. The distinctions between crust and lithosphere, between continental and oceanic lithosphere, and between continental and oceanic crust thus need to be clear, otherwise the discussion of mantle convection will be confused. The distinctions are illustrated in cartoon form in Figure 2.3, which is not to scale.

The continental crust is commonly about 35–40 km thick. This was first determined in 1909 when Mohorovičić identified the seismic discontinuity named after him [5], also known as the 'moho'. The thickness is larger under mountain ranges,

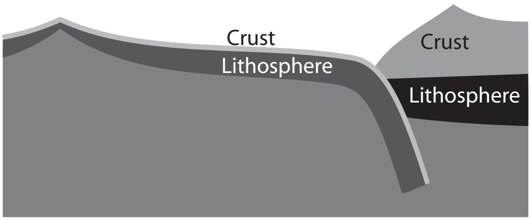

Figure 2.3. Distinctions between crust and lithosphere, and between their continental and oceanic forms.

reaching nearly double this value under the Himalayas. It is smaller in some regions where the crust has been horizontally extended. The average thickness seems to be determined by a long-term balance between horizontal shortening and erosion. This was first perceived by Hess [6], who argued that continental crust tends to be eroded down to sea level and pushed up by the plate tectonic forces that he was among the first to conceive.

The thickness of the oceanic crust was not determined until the 1950s and 1960s, using seismic surface waves and later ocean-going seismic profiling [7]. To most geologists' surprise, it turned out to be much thinner than continental crust, averaging about 7 km. It is thicker in some places where there is an 'oceanic plateau', and it is thinner in only a few places. Otherwise it is remarkably uniform in thickness.

Both kinds of crust were detected and defined seismically. Seismic waves travel more slowly in the crust than in the underlying mantle rocks. This contrast in wave velocity causes reflections and refractions, and these allow seismologists to infer the presence of interfaces or 'discontinuities' below the Earth's surface.

The difference in seismic velocity between crust and mantle implies a difference in composition. This inference is not a simple one, as there was debate for some time about whether the continental moho might be due to a phase change, in which the minerals comprising the rocks are squeezed into denser crystal structures due to the increase of pressure with increasing depth. Eventually detailed studies resolved the debate in favour of a change in composition. There was also a debate about the oceanic moho. Hess [6], for example, proposed that the oceanic crust was made of serpentinite, which is a hydrated form of the predominant upper-mantle mineral olivine. There are places where hydrated mantle is known, but drilling has established that most of the oceanic crust has a basaltic composition, different from the underlying mantle, whose dominant rock type is peridotite.

The concept of the lithosphere was established by early in the twentieth century. During the nineteenth century, geologists established evidence for continuing uplift and subsidence during geological history, as distinct from everything being frozen in place since early in Earth's history. This required the interior of the Earth to be deformable, though not necessarily liquid. Seismology established that the mantle is in fact not liquid, so the mantle was inferred to be a deformable solid. This history will be discussed in more detail in Chapter 4. Despite the evidence for continuing deformations, it was also evident that structures less than about 100 km in horizontal extent seemed to be supported without continuing deformation. These observations can be reconciled if the outer 100–200 km of the Earth is strong and usually not deforming, even on geological timescales.

This outer, strong layer became known as the *lithosphere*. In 1914 Barrell [8] proposed the term *asthenosphere* for the deformable region below the lithosphere. Thus the lithosphere is defined in terms of its *strength*. Since it is thicker than the crust, it must comprise the crust and the top part of the mantle.

The greater strength of the lithosphere was inferred to be due to lower temperatures near the Earth's surface, and this is confirmed in the modern picture, as we will see as we go along. The lower temperatures also cause seismic velocities to be higher, and modern techniques and instruments have allowed the lithosphere to be resolved seismically, although it is more subtle and harder to distinguish than the crust. In this way we have learnt that the oceanic lithosphere is up to around 100 km thick, though it is thinner near mid-ocean ridges. On the other hand, the continental lithosphere is rather variable, and over 200 km thick under older parts of the continental crust.

To summarise, the *lithosphere* is defined by its strength, which is sufficient to prevent it from deforming significantly on geological timescales. Its strength is inferred to be due to its lower temperature. It is up to about 100 km thick in oceanic regions, and from about 100 km to over 200 km thick in continental regions. The *crust* is defined by its lower seismic wave velocities. The lower velocities are inferred to be due to it having a different composition than the mantle underneath. In oceanic regions it is about 7 km thick and has a basaltic composition. Its density is about 2900 kg/m^3, in contrast to the upper mantle density of 3300 kg/m^3. In continental regions it averages 35–40 km thick. Its composition is quite variable, roughly from basaltic to granitic, and averaging to an intermediate rock type like andesite. Its density is also rather variable, and averages around 2700 kg/m^3. These properties are summarised in Table 2.1.

2.3 Topography

The Earth's topography has some striking features. To appreciate it fully, we need to see it without the oceans, as it is shown in Figure 2.4. In this view it is very clear that there are two predominant elevations of the Earth's surface, that of the continents and that of the ocean basins. This bimodal distribution of elevation is

Table 2.1. *Defining characteristics of crust and lithosphere.*

Characteristic	Continental	Oceanic
Crust		
Defining property	low seismic velocity	low seismic velocity
Reason	composition	composition
Average composition	andesitic	basaltic
Average thickness	35 to 40 km	7 km
Average density	2700 kg/m^3	2900 kg/m^3
Lithosphere		
Defining property	strength	strength
Reason	low temperature	low temperature
Thickness	100 to >200 km	0 to 100 km

a striking feature, not observed on any other body in the solar system. Hess [6] argued that it is due to the combined action of seafloor spreading, which sweeps continental material together, and subaerial erosion, which planes the continental surfaces down to sea level.

The next most prominent feature of the Earth's topography is the system of mid-ocean ridges, which form a continuous network within the ocean basins. These stand 2–3 km above the deeper parts of the ocean basins, which are 5–6 km below sea level. They will give us important information about mantle convection. Not very visible in this image are the deep ocean trenches, bordering the Pacific basin, Indonesia and a few other places. These extend to depths of around 10 km below sea level. Various plateaus and mountain belts are visible on the continents, and various plateaus and chains of seamounts are visible in the ocean basins. A broad swell in the sea floor is visible around Hawaii and the chain of seamounts extending northwest from Hawaii, in the mid-North Pacific. This, and a few features like it, will also tell us something important about mantle convection.

There is, in the seafloor topography, a surprising regularity that is not obvious just from a map like Figure 2.4. It is that seafloor depth correlates strongly with the age of the sea floor. More specifically, it correlates with the square root of the seafloor age. This is illustrated in Figure 2.5. Obviously there are deviations from the correlation, but overall the seafloor age is the main predictor of seafloor depth.

There is also some regularity in the deviations from the main correlation in Figure 2.5. The deviations are mainly positive, and they occur mainly on older sea floor. In other words, there is a tendency for older sea floor to be shallower than the correlation predicts. This tendency is not universal, however. For example, profiles 1 and 2 extend, with only minor deviations, to ages of 175 Ma and 100 Ma, respectively.

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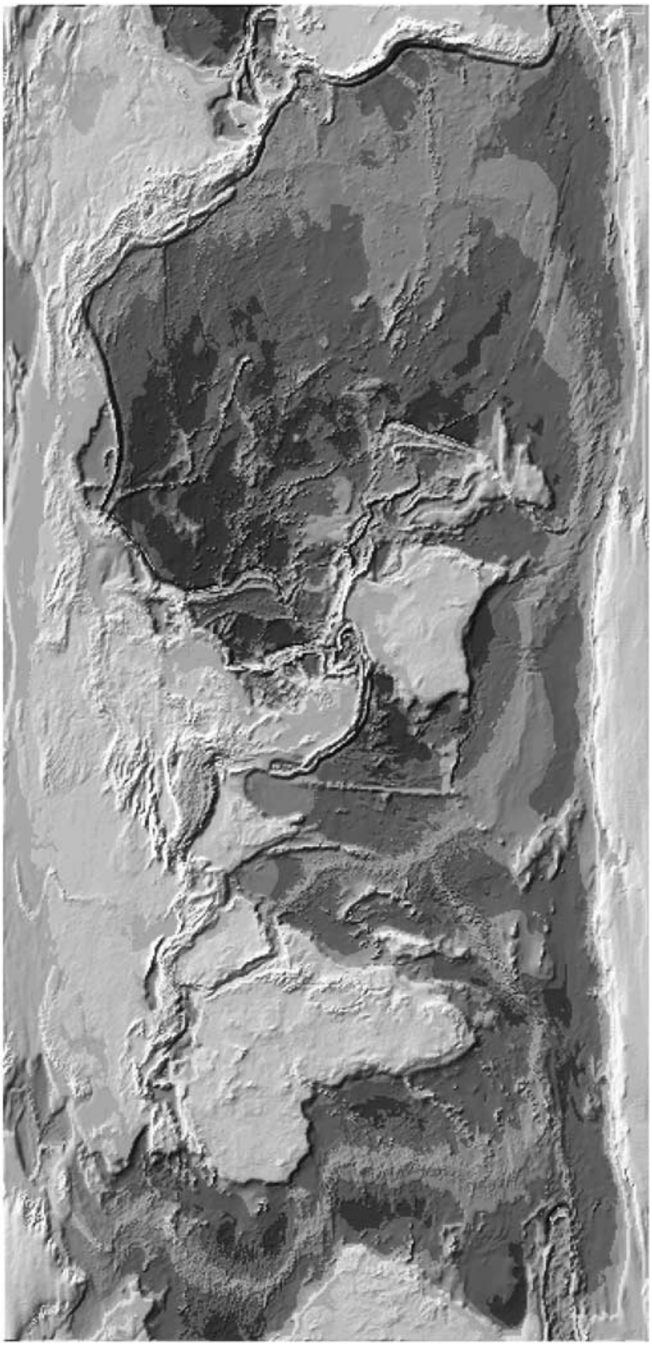

Figure 2.4. Topography of the Earth. The submarine breaks in the grey scale are at depths of 5400 m, 4200 m, 2000 m and 0 m. Shading of relief is superimposed, with a simulated illumination from the northeast. From the ETOPO5 data set from the US National Geophysical Data Center [9]. Image generated using *2DMap* software, courtesy of Jean Braun, Australian National University.