1 Evidence for Earth's Crust, Mantle & Core

A cut-away image of planet Earth, exposing its internal concentric layering, is shown in chapter one of almost every Geography Leaving Certificate textbook. Beneath a thin outer shell, called the crust, lies the mantle. The mantle extends to a depth of 2900km and comprises well over 80% of the Earth's volume. Below the mantle is the core — a fiery-hot, dense sphere of liquid iron (Figure 1).

The Earth's deep interior holds a special fascination for us because it is inaccessible. The greatest depth to which a borehole has penetrated is a mere 12 km, which is less than 0.2% of the Earth's radius. How can we possibly know what lies deeper down? How can we be sure that the crust, mantle and core really exist, and are not just fanciful ideas? How can we know what they are made of? The first part of this handout considers 5 pieces of evidence.

1.1 Earth's Density

Most rocks near Earth's surface have densities in the range 2500 to 3000$\mathrm{kg\,m^{-3}}$, i.e. they are 2.5 to 3 times denser than water. The density of the whole Earth can be obtained if we know the planet's mass and its volume [a]. The mass of the Earth, M, can be calculated from Newton's formula $g = GM/R^2$, where g is the acceleration of a falling object due to gravity (about $10\,\mathrm{m\,s^{-2}}$), $R \sim 6370$ km is the Earth's radius and $G = 6.67\,\mathrm{kg\,m^{-1}\,s^{-2}}$ is the gravitational constant. The mass turns out to be close to 6×10^{24} kg. The volume of the Earth, V, can be approximated using the formula for the volume of a sphere, $V = 4\pi R^3/3$, and is roughly $1 \times 10^{21}\ \mathrm{m}^3$. In fact the Earth is not a perfect sphere, partly because it is rotating and partly because its mass is distributed unevenly inside[b], but assuming it is spherical is adequate for this simple illustration. The average density of the Earth is therefore approximately $6000\ \mathrm{kg\,m^{-3}}$. Clearly, since rock at the surface has a density of between 2500 and $3000\ \mathrm{kg\,m^{-3}}$, then the deep interior must be made of a material whose density is considerably greater than Earth's average density of $6000\ \mathrm{kg\,m^{-3}}$ to compensate. This result, that the most of Earth's mass is concentrated near its centre, is also obtained by calculating Earth's moment of inertia from astrophysical data.

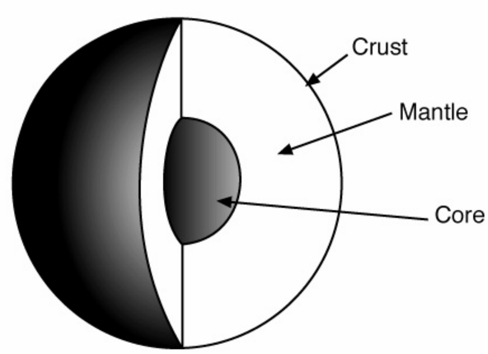

Figure 1: The internal structure of the Earth. On this scale the crust is too thin to be shown as a separate layer.

1.2 Mantle Rocks

There are three special circumstances when mantle rocks are brought to Earth's surface.

1. *Xenoliths* Sometimes, igneous rocks that have cooled from magma contain lumps of rock of different composition from the magma itself. These lumps are termed xenoliths, which means 'foreign piece of rock'. The xenoliths are formed when magma rising from deep levels rips off pieces of the rock which it passes through (the *country rock*) and carries these pieces along with it. Some xenoliths come from deeper levels within the crust, others come from the uppermost mantle, down to depths of about 200 km. The mantle xenoliths show us that the uppermost mantle is made of a rock called *peridotite* [c] (Figure 2).

2. *Ophiolites*[d] Oceanic crust is normally destroyed less than 200 Myr (million years) after formation by subduction. An ophiolite is the technical term for a piece of ancient oceanic crust that escaped destruction and was instead shifted onto a continental plate by natural tectonic forces. Rock exposures cut through ophiolites allow us to piece together the structure of oceanic crust and the uppermost mantle beneath. The mantle part of ophiolites consists of peridotite, similar to that brought up in xenoliths. The difficulty with using ophiolites to infer mantle composition is that they have sometimes been heavily deformed and chemically altered by the tectonic forces that shifted them onto the continent.

[a]The Solid Earth §8.1
[b]The Solid Earth §5.4
[c]See notes on Minerals and Rocks attached to handout for Lab 1
[d]The Solid Earth §9.2

Figure 2: The green patches are a xenoliths of the rock-type peridotite, which makes up the uppermost mantle. The xenoliths are encased in dark grey basalt, an igneous rock formed by partial melting of peridotite.

3. *Non-volcanic passive margins* Passive margins (also known as rifted margins) are plate boundaries where continental crust is rigidly attached to oceanic crust[e]. Non-volcanic passive margins form a class of passive margins that has been discovered within the past few decades. At non-volcanic margins, a transition zone exists between the continental and oceanic crust in which mantle is exposed at the seabed. The mantle is made of peridotite that has undergone major chemical alteration by interaction with seawater.

1.3 Seismic Waves (= sound waves)

Sound waves travel through air at about $300\,\mathrm{m\,s^{-1}}$. Sound waves also pass through water and rock. They travel about five times faster through water, at $1.5\,\mathrm{km\,s^{-1}}$, and faster still through rock, usually between 4 and $8\,\mathrm{km\,s^{-1}}$ depending on the kind of rock. Sound waves travelling through rock are called seismic waves because they are usually caused by earthquakes. The study of the Earth using seismic waves is called seismology [f]. When an earthquake happens, pent up forces are suddenly released and this creates, in effect, a very loud noise under the ground. It is so loud that it may be 'heard' on the far side of the Earth using a listening device called a *seismometer*.

Seismology is one of the most important branches of the Earth sciences. A very large number of measurements of the time taken for seismic waves from an earthquake to reach different seismometers is now available. These measurements can be plotted in terms of travel time (between earthquake source and the seimometer receiver) against distance around the world (usually expressed as an angular distance) [g]. The travel time graphs, in turn, can be used to reconstruct the velocity as a function of depth, all the way to the centre of the Earth [h]. In fact, seismic energy travels through the Earth as two types of wave, P-waves (P for primary, pressure or push-pull) and S-waves (S for secondary, shear or shake) [i]. P-waves and S-waves travel at different speeds, sometimes refered to as V_P and V_S respectively.

The velocity-depth curves show that P-waves passing beneath the continents, to a depth of about 35 km, travel at speeds of between about 4 and $6.5\,\mathrm{km\,s^{-1}}$. Where they travel deeper than about 35km, however, the speed jumps abruptly to $8\,\mathrm{km\,s^{-1}}$. The jump in speed at around 35 km is observed below all the continental regions of the Earth, and it defines the boundary between the crust and the mantle. It implies that the crust and mantle are made from different kinds of rock. The crust/mantle boundary is called the Mohorovicic discontinuity, or simply the *Moho*, in honour of the Yugoslav scientist who first recognized it in the early 20th century. The depth to the Moho beneath the continents (i.e. the thickness of the continental crust) is 35 km on average, and varies a little from place to place. Under mountain ranges such as the Himalayas it may be as much as 70 km.

The Moho is also present beneath the oceans, but here the jump in P-wave speed from 6.5 to $8\,\mathrm{km\,s^{-1}}$ occurs at a much shallower depth, generally between 6 and 8 km below the ocean floor. Clearly a distinction can be made between thick continental crust and thin oceanic crust. This important difference is now understood in terms of plate tectonic theory [j].

As seismic P-waves travel more deeply into the mantle, their speed increases from $8\,\mathrm{km\,s^{-1}}$ at the Moho to

[e] See notes on Sedimentary Basins and The Solid Earth §10.3.6

[f] The term *seismology* was first coined by Irish scientist Robert Mallett and published in 1862; he also performed pioneering seismic experiments on Killiney Beach

[g] The Solid Earth §4.2.7, in particular Figures 4.16 & 4.18

[h] The Solid Earth §8.1.1, in particular Figure 8.1

[i] The Solid Earth §4.1.2

[j] See handout on Plates

about 13 km s^{-1} at a depth of 2900 km. However, once the sound penetrates below 2900 km, V_P suddenly drops from 13 km s^{-1} back down to about 8 km s^{-1}. This dramatic reduction in speed at 2900 km defines the boundary between the Earth's mantle and core.

One consequence of this surprising drop in speed is that the core tends to focus sound waves, rather like a lens focuses light. Sound waves entering the core are deflected inwards, converging towards each other, so that they arrive on the far side of the Earth within a somewhat restricted circular area directly opposite the earthquake source. Outside this circle there is a broad 'silent' zone, called the shadow zone, where no earthquake sound is detected (Figure 3). Earth's shadow zone was first observed and interpreted as evidence for a core by an eminent Irish scientist, R.D. Oldham, about 100 years ago.

S-waves travel more slowly than P-waves but most importantly, and unlike P-waves, they cannot pass through liquid. S-waves are never detected on the far side of the Earth from an earthquake — they simply do not get through the core. They are not detected in the shadow zone, nor are they detected in the region where P-waves are concentrated beyond the shadow zone. The total absence of S-waves arriving on the far side provides compelling evidence that the outer core of the Earth is not solid, but liquid. Some high-school textbooks misleadingly hint that the mantle is molten. This is untrue, of course. We can be sure that the mantle is solid because S-waves definitely pass through it.

Detailed seismic studies have shown that the innermost part of the core is not liquid but solid. They also show that the speed of P-waves in the mantle increases rather rapidly from about 9 to 11 km s^{-1} at depths between about 400 and 700 km, marking a layer called the *transition zone*. This zone separates the upper mantle from the lower mantle.

Although seismic evidence confirms that the Earth is divided into the crust, mantle and core, and while it provides a great deal of additional information about the interior, nevertheless it tells us little or nothing about what the crust, mantle and core are made of. We know of course what the continental crust is made of because it is exposed in cliffs and mountains, in quarries and road cuttings, and has been sampled by drilling. It consists of ordinary rocks like granite and basalt, like sandstone, mudstone and limestone, like

Figure 3: The shadow zone cast by the Earth's core from an earthquake in Japan.

slate, schist and gneiss [k]. Furthermore, these rocks are known to transmit P-waves with speeds between about 4 and 6.5 km s^{-1}, reassuringly the same speeds as P-waves travel through the crust. In a similar way, samples recovered in dredge hauls and drill cores from the ocean floor confirm that the oceanic crust, beneath a thin covering of mud, is made from basalt. Xenoliths and ophiolites provide samples of the top 100 km or so of mantle. However information on the composition of the deeper mantle and core is not so easily available and has to be inferred from an indirect source of evidence — meteorites.

1.4 Meteorites

Every few weeks a new meteorite is picked up in some country or other after falling from the sky as a bright fireball. These strange gifts from space are known from their speed of arrival, and from the angle at which they enter the upper atmosphere, to come from the asteroid belt. The asteroid belt is a zone in the solar system between the orbits of Mars and Jupiter, and it is occupied by numerous small rocky 'mini-planets' called asteroids (Figure 5). The largest asteroid of all, Ceres, is about 1000 km in diameter.

The great majority of meteorites are made from a very unusual kind of sandstone in which most of the sand grains are made from a green stony material. The green colour is due to an abundance of olivine. Olivine is a mineral (i.e. a natural chemical compound) made from the elements magnesium, silicon, iron and oxygen. Mixed in with the green olivine-bearing grains are different grains, perhaps 10% of the total, made from tiny bits of shiny, magnetic iron metal. These 'sandstone' meteorites are called chondritic meteorites. Figure 6 shows a sawn surface of a chondritic meteorite that fell at Dundrum near Cashel in

[k] Handout for Lab 1

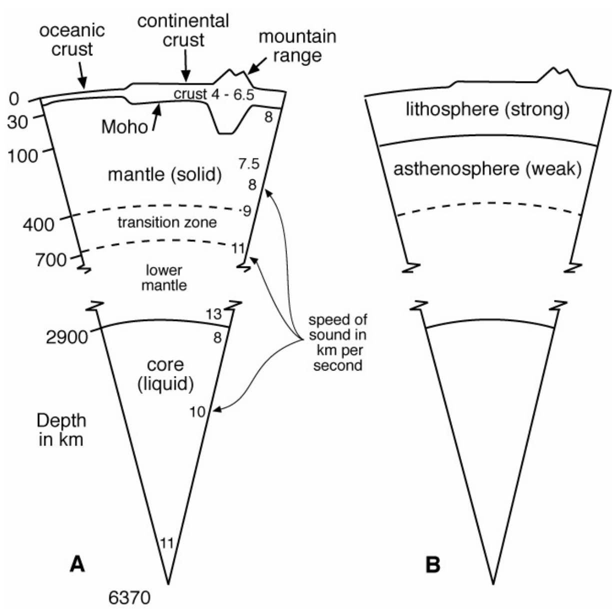

Figure 4: A (on the left). Sector of the Earth divided into crust, mantle and core, based on the speed of P-waves at different depths. The base of the crust, called the Moho, marks a jump in speed from about 6.5 to 8 km s^{-1}. The core-mantle boundary marks an abrupt drop in speed from 13 to 8 km s^{-1}. Note that the vertical scale is not linear and is highly exaggerated towards the surface to show the variation in the thickness of the crust between oceans, continents and mountain ranges. A break in the scale between about 800 and 2500 km leaves out most of the lower mantle. B (on the right) is the same sector with the outer two or three hundred kilometres divided on the basis of strength into lithosphere (rigid) and asthenosphere (weak). The position of the asthenosphere correlates with a slight fall in the speed of P-waves from 8 to 7.5 km s^{-1}.

County Tipperary in 1865. This meteorite has been kept ever since in the museum at the Department of Geology in Trinity College where it is on display.

Meteorites have been eagerly investigated by scientists over the past two centuries, and a great deal is known about them. The chemical elements they contain have been analyzed carefully, and what is most remarkable is that the chemical composition of chondritic meteorites is almost exactly the same as the chemical composition of the sun when gases like hydrogen and helium are not included in the comparison (Figure 6). The chemical composition of the sun has been inferred from studies of thin dark lines in the coloured spectrum that appears when sunlight is passed through a glass prism. Each dark line corresponds to a particular chemical element, and the darker the line, the greater the amount of that element.

The good chemical match between the sun and chondritic meteorites shows that both the sun and the asteroids (the source of meteorites) were made from the same original batch of material. By implication the Earth, which lies between the Sun and the asteroid belt, is believed to have been made from the same starting material.

This view fits neatly with the current theory of the origin of the solar system. The theory holds that the sun and planets came into existence a little over 4500 million years ago when part of an enormous cloud of gas and dust, drifting in the Milky Way galaxy, became unstable and collapsed inwards on itself under the influence of its own gravity. The dust in the cloud had the same chemical composition as the sun and chondritic meteorites. Gravity brought most of the gas and dust together in a single central mass (the infant sun) but some of the gas and dust became spread out in a flat disk rotating around the sun. The dust in this disk included an abundance of olivine-rich grains and bits of metal. The dust eventually clumped together to form larger objects and larger objects, culminating in the planets and asteroids, all orbiting the sun in the same plane and moving in the same direction. The gas (hydrogen and helium) was soon lost from the asteroids and the inner, terrestrial planets (Mercury, Venus, Earth and Mars) because their gravity was too feeble to hold on to it, but the gas did stick to Jupiter and the other icy-cold giant planets beyond.

So the Earth probably began as a mixture of about 90% stony, olivine-rich material, and about 10% iron metal, just like that seen in chondritic meteorites. Soon after its formation the interior of the Earth is thought to have become very hot, so that the bits of iron melted and dribbled down towards the centre of the planet to form a dense liquid iron core. The less dense olivine-rich material, with its iron removed, is believed to have remained behind as the Earth's mantle. Geologists refer to a rock made largely from olivine as peridotite. Thus, the evidence in meteorites strongly suggests that the Earth's mantle is made

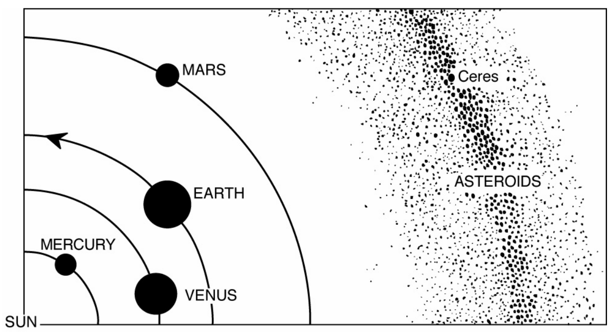

Figure 5: The position of the asteroid belt in relation to the Sun and inner planets.

from peridotite, and that the core is made from iron.

The conclusion that the core is probably made from iron, and is molten, fits well with the Earth's magnetism. Scientists have shown how convective flowing motions within a molten iron core can produce the kind of strong magnetic field that the Earth has today [1]. As for the mantle being made from peridotite, it is reassuring to note that the speed of P-waves through peridotite, measured in the laboratory, is $8\,\mathrm{km\,s^{-1}}$, the same as the speed observed for seismic waves travelling in the mantle (i.e. below the Moho). Yet another line of evidence for a peridotite mantle comes to light when the origin of the igneous rock basalt is considered.

1.5 Basalt

Basalt is the most prolific kind of igneous rock on the Earth. Basaltic lava pours constantly from volcanoes along the system of mid ocean ridges where plates move apart, and it flows freely from volcanoes in many other places. The temperature of hot lava is over 1100°C. This very high temperature means that the lava must originate in the mantle because the temperature beneath the Earth's surface, measured in boreholes, increases by only about $20^\circ\mathrm{C\,km^{-1}}$, so that the temperature 35 km down, at the Moho, is unlikely to be more than 700°C. Thus the mantle must be made of some material that, when melted, yields basalt.

What could this material be? Geologists in the early 20th century reached the logical but incorrect conclusion that the mantle itself is made of basalt. After all, the easiest way to get liquid basalt is to melt solid basalt, surely? The conclusion was wrong because a rock typically consists of a mixture of several different kinds of minerals and therefore it will not melt like a pure compound, such as ice, which melts at a fixed temperature. Instead, when rocks are heated they melt gradually. They start to melt at one particular temperature (called the solidus) but only become completely liquid when a much higher temperature is reached (called the liquidus). At an intermediate temperature a rock is said to be partially molten, and resembles very hot slush. Besides, some minerals melt more easily than others, and the liquid part of the slush is therefore made largely from these easy-to-melt minerals, while the solid bits in the

[1] The Solid Earth §8.3.2

Figure 6: The Dundrum chondritic meteorite showing a flat surface that was cut by a diamond-tipped saw to expose the interior. Bright flecks are grains of shiny iron metal. The grey material surrounding the metal grains is stony and includes an abundance of the mineral olivine.

slush are made from minerals which are more difficult to melt. As the temperature rises through the melting interval, the liquid magma, being less dense than solid rock, begins to rise through the still-solid peridotite. In the case of mantle rocks, this process begins after less than about 1% of the rock has melted. Eventually the liquid magma separates completely from the solid peridotite and becomes an independent batch of magma with a different chemical composition from the starting material. It only takes around 1000 years for magma to travel from its source within mantle up to Earth's surface, or just below it.

In the 1960s scientists performed an important series of partial melting experiments using peridotite as a starting material, and they showed beyond doubt that when peridotite is about 25% melted, the liquid portion is molten basalt, and the residual 75% of solid material consists almost entirely of pure olivine. This result lends strong support to the idea that the mantle is made of peridotite.

These pieces of peridotite (called xenoliths) are almost certainly fragments that were broken from the solid mantle and then became entrained in the rising flow of basalt magma, which carried them to the surface.

But what process heats the mantle to the point where it starts to melt and produce basalt? The answer, perhaps surprisingly, is that nothing heats the mantle. The mantle melts without actually getting hotter. It is already very hot, and melts because it moves upwards. To understand this answer we have to be aware of three key issues: (a) the results of those experiments from the 1960s on how peridotite melts under conditions equivalent to a great depth inside the Earth, (b) the way in which temperature increases deep within the Earth, and (c) the question of what happens to the asthenosphere where the plates above it are sliding apart. These issues are discussed in the handout on Plate Tectonics.

2 Mantle Convection

The mantle comprises over 80% of Earth's volume. Motion of mantle rocks on geological timescales is associated with some of the most devastating earthquakes, and is also an important control on topography

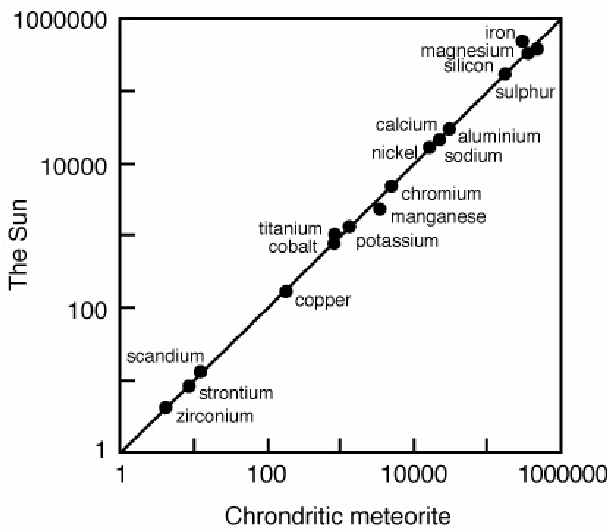

Figure 7: Graph comparing the relative amounts of various chemical elements in chondritic meteorites with the relative amounts of the same elements in the Sun.

		Units	Upper Mantle	Lower Mantle
Ra	Rayleigh Number			
Ra_c	Critical Rayleigh Number		700	700
Re	Reynolds Number			
d	Convecting layer thickness	km	700	2300
g	Acceleration due to gravity	m s^{-2}	10	10
w	Upwelling veolcity	m s^{-1}		
ΔT	Temperature difference between top and bottom of layer	°C	200	200
α	Thermal expansion coefficient	°C^{-1}	3.4×10^{-5}	1×10^{-5}
δ	Thermal boundary layer thickness	km		
η	Dynamic viscosity	Pa s	1×10^{20}	1×10^{22}
κ	Thermal diffusivity	m^2 s^{-1}	8×10^{-7}	3×10^{-6}
ρ	Density	kg m^{-3}	3.5×10^3	5×10^3

Table 1: Definition of some standard numbers and scales in fluid dynamics, and typical values of parameters required to calculate them.

and volcanic activity at Earth's surface. How can we determine how the mantle behaves through time?

2.1 Theoretical case for mantle convection

The mantle is composed of olivine and pyroxene and their high pressure/temperature equivalents. These constituent minerals deform by ductile creep in the ambient pressure/temperature conditions. Hence although the mantle beneath the plates is *solid*, it *behaves as a fluid* over geological timescales. Loss of heat from the Earth drives convection within the mantle. There are two sources of heat to the mantle: basal heating from the core and internal heating from decay of radioactive isotopes. Heat is lost by conduction through the overlying plates to Earth's surface. Heat is transported through the mantle by convection because differences in heat cause density differences which generate sufficient stress to deform the weak mantle material.

Rayleigh Number The Rayleigh number can be considered as the ratio between the characteristic timescale for conduction of heat over a given distance, τ_c, and the characteristic timescale for advection of heat, τ_a [m]. Such ratios are common in fluid mechanics, and they are always given someone's name. This one is named for Lord Rayleigh, who first discovered it, and it is usually written as

$$Ra = \frac{g\ \rho\ \alpha\ T\ a^3}{\kappa\ \eta} \tag{1}$$

or

$$\frac{\tau_c}{\tau_a} = \frac{Ra}{\pi^2} \tag{2}$$

The meanings of the parameters and typical values in the mantle are given in Table 1. Equation (2) is the ratio of two times and is therefore dimensionless. This means that the value of τ_c/τ_a is independent of what units are used to measure length, time, mass and temperature. If the Rayleigh number is larger than a critical Rayleigh number for the geometrical arrangement under consideration, τ_c will be much greater than τ_a and the layer will be able to advect hot fluid on a time scale that is short compared with the cooling time. The thermal convection will then be vigorous. If the Rayleigh number is small, the

[m] The Solid Earth §8.2.2

convection will be feeble or absent. The critical Rayleigh number for Earth's mantle is about $Ra_c \sim 700$. Using the values in Table 1, one obtains Rayleigh numbers of about 1×10^6 for the upper mantle and 4×10^4 for the lower mantle. We therefore expect the upper mantle to convect vigorously on geological timescales. The lower mantle is convecting, but less vigorously.

Mantle convection takes place on two distinct scales. On the larger scale, subduction of old, cold oceanic plates form the main downwelling and is balanced by mantle being draw upwards passively beneath the mid-ocean ridges. The other type, known as Rayleigh-Bérnard convection, results from instabilities that occur at thermal boundary layers [n]. Instabilities on boundary layers heated from below (such as the core/mantle boundary or the lower/upper mantle boundary) give rise to upwellings of hot material known as *mantle plumes*. Instabilities on boundary layers cooled from above (such as the base of the lithosphere) produce cold sinking blobs; it is these convective instabilities maintain the Earth's plates at a roughly constant thickness. Further analysis using the Rayleigh number suggests that the typical time taken for hot mantle within an upwelling mantle plume to travel from the base to the top of the upper mantle is about 2 million years, a very short time compared with the age of the Earth.

2.2 Imaging mantle convection in situ

Seismology is our most important means of imaging the mantle. Seismologists generate striking images of the mantle using a technique known as *seismic tomography*, which involves analysis of the relative travel-times of seismic waves for thousands of earthquake-receiver pairs [o]. We now have excellent images of the subducting slabs which form the downwelling limbs of the convective system. However, upwelling mantle plumes are more difficult to image, perhaps because they are less laterally continuous than subducting slabs.

2.3 Numerical modelling

Since we cannot see mantle plumes very clearly, much of our thinking on what they look like comes from numerical models [p]. The form and complexity of these models is strongly related to the physical properties assumed for the fluid and to computing power available to run them. In the 1970s and 80s, simple models were produced showing mushroom-shaped plumes in which the hot mantle travels up a narrow central conduit and then spreads out laterally beneath the overlying plate. Modern computers can model convection in a spherical shell representing the entire mantle. All sorts of strange spatial and time-dependent patterns are predicted depending on the material properties. These physical properties are reasonably well known for the uppermost mantle, but poorly known for the lower mantle because it is difficult to build experimental rigs capable of reproducing pressure-temperature conditions that exist in the lower mantle. Hence, laboratory and numerical models alone cannot tell us what mantle convection really looks like.

2.4 Surface effects of Mantle Plumes

Since convection models predict a wide range of behaviour and seismic imaging cannot resolve mantle plumes clearly, observations of the surface effects of mantle plumes are very important in constraining

[n] The Solid Earth §8.2.1
[o] The Solid Earth §8.1.4
[p] The Solid Earth §8.2.3

the nature of mantle convection.

Igneous activity Heat within mantle plumes causes melting. Sites of anomalously high melt production such as Iceland and Hawaii are known as *hotspots*. Mantle plume were originally postulated to explain hotspot igneous activity. *Hotspot tracks* are linear trails of anomalously high volcanic activity thought generated because mantle plumes remain roughly stationary whilst the plates migrate over them [q].

Large Igneous Provinces These are sites of anomalously high melt production in excess even of that occurring at hotspots. They are thought to result when a blob of hot mantle detaches from a thermal boundary layer within the mantle, rises and impinges upon the underneath of the plate; this are known as *starting plume heads*. Examples of large igneous provinces are the North Atlantic Igneous Province (related to the Iceland Plume) and the Deccan Traps, India (related to the Réunion Plume). Large Igneous Province magmatism includes *plateau (or flood) basalts* which are extruded in *fissure eruptions* (e.g. Antrim Plateau Basalts), *central igneous complexes* (e.g. Carlingford, Mourne Mountains, Mull, Skye) and *dyke swarms*.

Uplift Mantle plumes generate two types of uplift. *Dynamic support* is uplift caused when the rising mantle hits the base of the plate and is deflected sideways. Dynamic support is transient and disappears if the plume dies or the plate migrates away from it. It can affect a region often more than a thousand kilometres in diameter. *Thickening of the crust* by plume-related magmatism also generates uplift because of isostasy (i.e. Archimedes' Principle); this uplift is permanent [r].

Erosion and Sedimentation If uplift raises the seabed close to or above sea-level, erosion may occur. This erosion can be recognized in the geological record since it creates an unconformity, which can be used to map out an ancient plume swell. The eroded products accumulate as sediment in surrounding sedimentary basins, providing a further method for recognizing ancient plume swells [s].

[q]The Solid Earth §2.7
[r]The Solid Earth §5.6.2
[s]See Sedimentary Basins handout

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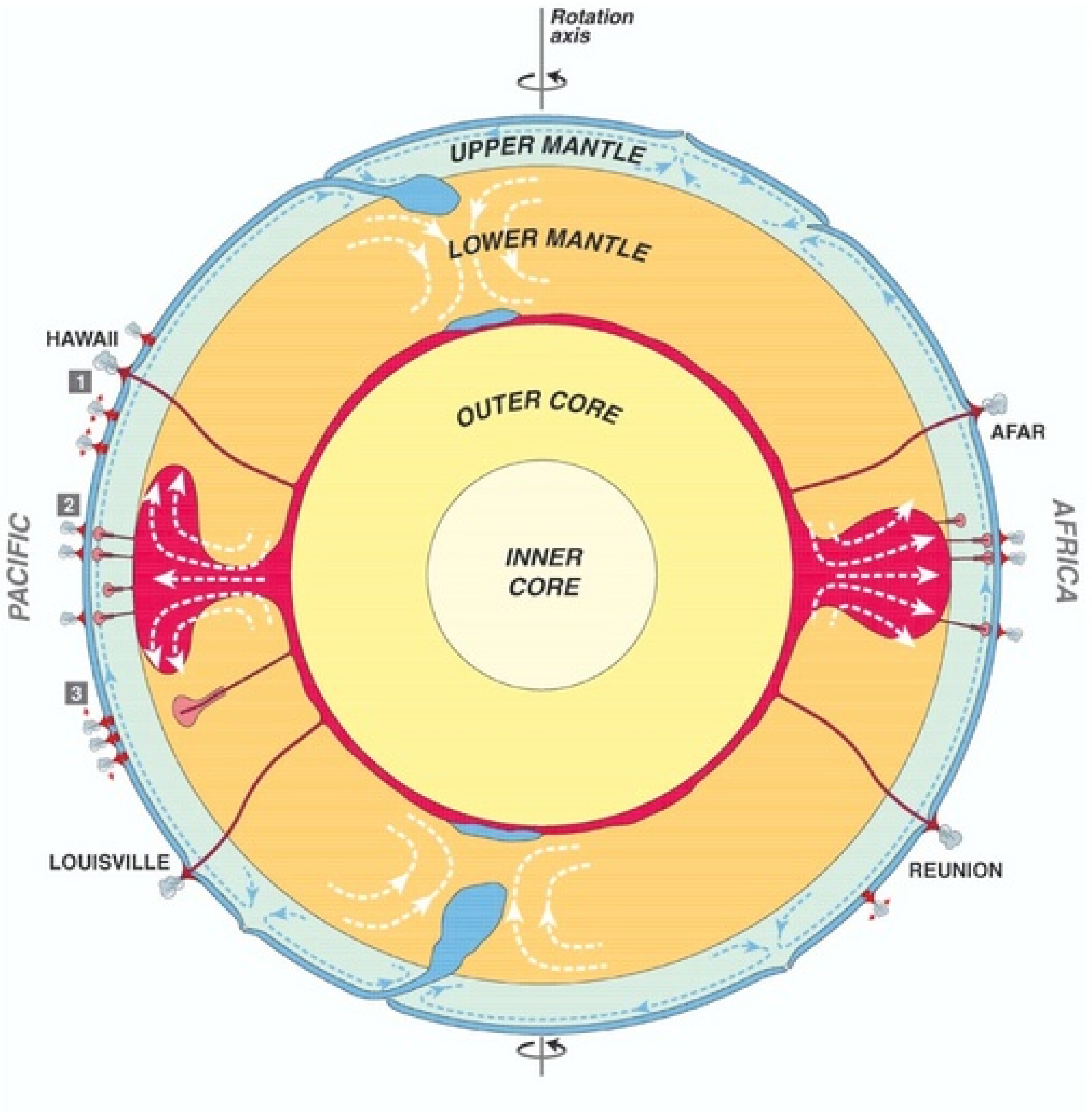

Fig. 4. A schematic cross-section of the dynamic Earth going through its rotation axis, outlining the sources of the three types of plumes/hotspots identified in this paper: the 'primary' or main, deeper plumes possibly coming from the lowermost mantle boundary layer (D″ in the broad sense) are the main topic of the paper; the 'secondary' plumes possibly coming from the top of domes near the depth of the transition zone at the locations of the superswells are indicated [46,47]; the 'tertiary' hotspots may have a superficial origin, linked to tensile stresses in the lithosphere and decompression melting [9,10]. There are on the order of 10 primary (deeper) plumes forming a girdle around the two antipodal domes upwelling below the central Pacific and Africa. At present only plume tails and no plume heads are active and close to the surface, and the number of plumes in a single cross-section is less. The fluid mechanics aspects are based on the experimental study of thermochemical plumes by Davaille et al. [57,58], and the lower mantle domes are based on seismic tomography [25,26]. The location of possible avalanches [63] at the downwellings of the lower mantle quadrupolar convection cells are indicated by sagging in the transition zone, though no such event is thought to be presently active.