Geo Factsheet

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Plate Tectonics: Digging Deeper into the Theory

Introduction

A key development in Geography over the last 100 years has been the evolution of plate tectonic theory so that the processes causing earthquakes, volcanic eruptions and tsunami are well understood. However, plate tectonics theory remains just that – a theory. The internal workings of Earth cannot be directly observed by scientists. In fact the deepest humans have drilled into Earth's crust is just 12,262 metres (Kola Superdeep Borehole, Russia, 1989) a mere 0.1% of the distance to the centre of Earth. Plate tectonic theory is still subject to new research and widespread debate.

Origins

The theory of plate tectonics as we know it today evolved slowly. There was no sudden 'light bulb' moment, rather a number of scientists (**Table 1**) contributed pieces of the jigsaw over time. The foundations of the theory were worked out in the 1960s, and it has been refined since.

A Complex Jigsaw

Earth has seven major tectonic plates (of over 20 million square kilometers) although the Indo-Australian plate is sometimes considered as two separate plates, and 10 minor plates (of 1-20 million square kilometers). There are over 50 microplates usually not shown on world maps of tectonic plates. Microplates are more important than is often assumed. **Figure 1** shows the complex pattern of major, minor and microplates in Oceania. The actual tectonic situation here is much more complex than the usual global overview suggests.

Numerous microplates move in different directions at different speeds. This builds up complex patterns of strain which in turn generate earthquakes and tsunami. Other microplate areas include the Caribbean and Turkey/Iran.

Figure 1 The Complex Pattern of Major, Minor and Microplates in Oceania

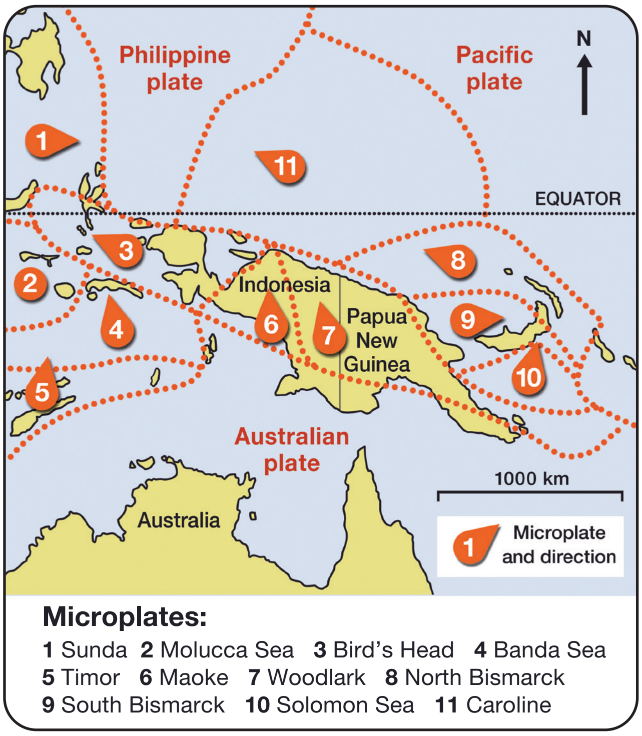


Table 1 Timeline of Plate Tectonic Theory Developments

Scientist	Date	Contribution
Arthur Holmes	1930s	Believed in the then unpopular 'Continental Drift' theory and proposed the idea that Earth's mantle contained convection cells that moved radioactive heat from the core towards the crust.
Hugo Benioff & Kiyoo Wadati	1949	Independently discovered a pattern of earthquakes descending on angled paths from ocean trenches to a depth of 600-700km into the mantle. The earthquakes are assumed to show the line of descent of the sinking (subducting) oceanic plate.
Harry Hess	1950s and 1960s	Investigated mid-ocean ridges and ocean trenches and hypothesized that new oceanic crust was created at ridges and ancient oceanic crust destroyed at trenches.
Fredrick Vine & Drummond Matthews	1963	Identified patterns of magnetic stripes in rocks on the ocean floor either side of mid-ocean ridges: this led to the theory of seafloor spreading.
John Tuzo Wilson	1960s	Identified mantle hotspots and transform faults (which we often call conservative plate boundaries) – both key parts of tectonic theory.
Dan McKenzie	1966	McKenzie made major contributions to the understanding of heat convection in the mantle, a key driving force of plate tectonics.

The Asthenosphere

The stumbling block for early ideas, such as Alfred Wegener's 1912 'Continental Drift' theory, was the lack of a convincing mechanism to explain how parts of the Earth's crust – the tectonic plates – could move.

To explain plate motion there has to be some mechanism to allow the solid, rigid lithosphere (the crust and upper mantle) to move over the mantle below. The mantle is believed to be solid. As far back as 1914-15 Joseph Barrell, an American Geologist, proposed a layer beneath the lithosphere which he termed the asthenosphere meaning 'weak layer'. Studying how seismic waves travel through the lithosphere and upper mantle geologists can identify a Low Velocity Zone (LVZ – see **Figure 2**) at about 100-200 km depth.

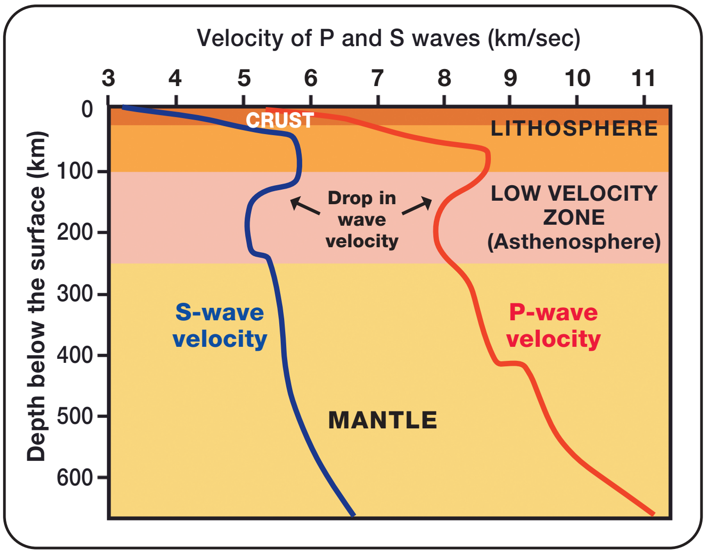
- The speed of seismic waves initially increases with depth into the lithosphere, as density rises.
- P- and S-wave velocities slow as they enter the LVZ and remain low
- At 180-200 km depth, seismic waves begin to speed up with increasing depth.
- Electrical conductivity is higher in the LVZ

The LVZ is essentially the weak asthenosphere layer proposed by Barrell. Its properties could be explained by:

- The presence of some water, which increases electrical conductivity
- The presence of molten rock (perhaps 1–4% is molten) because liquid reduces seismic wave velocity.

The asthenosphere plays a key role in plate tectonics, because it is a low-viscosity, plastic, partially molten layer on which lithospheric plates can slide.

Figure 2 Seismic waves and the Low Velocity Zone



How Do Tectonic Plates Move?

The asthenosphere provides a theoretical 'lubricating layer' on which tectonic plates can slide, but what is the force that causes plates to move?

There is consensus that convection in the mantle is an important part of tectonic plate motion, but debate about how it might work.

Convection currents carry heat from the core towards the Earth's crust. Convection is a familiar idea, but in the mantle (which is solid) it must be:

- Very slow, perhaps around 20 mm per year
- More of a very slow 'creep' than a flowing fluid

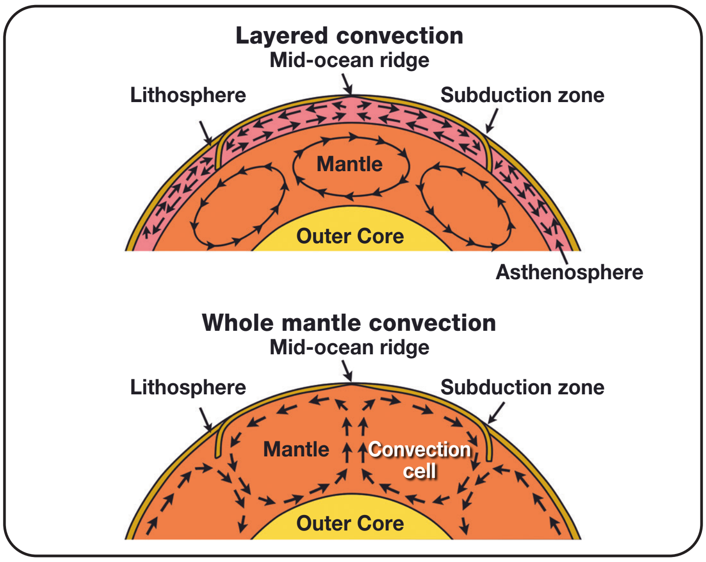
In fact, assuming average mantle thickness of 2900 km and a convection rate of 20 mm per year it would take 145 million years for mantle material to creep by convection from the core-mantle boundary to base of the lithosphere.

There has been some debate over whether convection in the mantle is 'whole mantle' or 'layered' (**Figure 3**):

- Whole mantle model: convection cells extend from the core-mantle boundary up to the base of the lithosphere.
- Layered model: convection cells in the mantle operate separately from ones in the asthenosphere.

The layered model was proposed because of the very different physical states of the rigid lower mantle and plastic, partially molten asthenosphere. Some scientists believed that convection currents would have difficultly crossing the mantle / asthenosphere boundary between layers which have very different physical properties. In the last two decades the whole mantle model has been accepted, especially because of very detailed seismology studies called seismic tomography which have not provided evidence of separate convection cells operating at different depths.

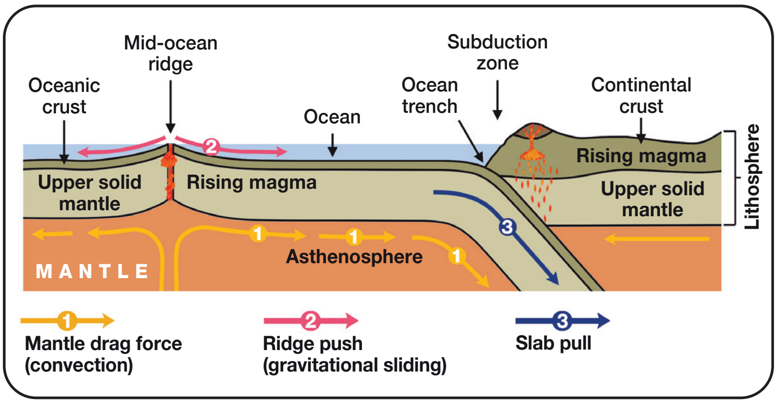
Figure 3 Whole and Layered Mantle Convection Models



Mantle convection is not the only force thought to cause plate tectonic motion. There are at least three possible forces (**Figure 4**):

- **Mantle drag:** the very slow creep-motion of convection currents in the mantle and asthenosphere drags the over-lying solid lithosphere along like a conveyor belt. It is sometimes referred to as 'basal drag'.
- **Ridge push:** beneath mid-ocean ridges there is an upwelling of hot, low density mantle material and localized melting that generates magma. The newly created oceanic plate at a mid-ocean ridge is itself hot and low density compared to surrounding, older oceanic plate. This creates the elevated mid-ocean ridge, and a slope between the ridge and the far edge of the oceanic plate.

Figure 4 The Forces of Plate Motion



The force of gravity causes the higher, newer part of the ocean ridge to push on the lower, older part. This force is sometimes called 'gravitational sliding'.

- **Slab pull:** old, cool oceanic plates sink back into the mantle at subduction zones because as they cool they become denser than the underlying asthenosphere. The subducting dense part of the plate pulls the younger, less dense part of the plate down as it sinks.

There is some debate over which of the three forces is the most important:

- Recent research suggests that convection-driven 'mantle drag' is a weak force.
- Slab pull appears to be more significant in plate motion, because tectonic plates with subduction zones move twice as fast as those without them.
- The ridge push force may be quite important, especially as motion at mid-ocean ridges can be quite rapid.

Table 2 explores the relative rates of plate motion at different tectonic settings.

Seismic Tomography Surprises

In order to better understand the interior of Earth geologists have used a technique called seismic tomography since the late 1980s. It uses seismic P-waves and S-waves to produce 2D or 3D images of Earth's interior. This is very similar to a medical CT scan, although on a much larger scale.

Of particular interest are convergent (destructive) margins with active subduction zones. These are locations where:

- The largest, potentially most destructive earthquakes of MMS 8.0–9.4 are generated.
- Volcanic eruptions are violent, andesitic Plinian-style eruptions with deadly pyroclastic flows.
- Most high-magnitude tsunami originate, caused by tsunamigenic sub-sea earthquakes.

At many subduction zones the sinking oceanic plate descends into the mantle at an angle of around 40–45° (as shown on **Figure 4**). Seismic tomography has revealed that this is not always the case. Subduction can also be:

- **Flat:** some oceanic plates descend at an angle of 30° or less, called 'flat-slab subduction'. This is happening along parts of the Peru-Chile trench and the Cascadia subduction zone. The cause it not fully clear. One explanation is that the subducting oceanic plate is much less dense than normal, so is reluctant to sink. Another explanation involves the continental plate being pushed over the oceanic plate rather than being relatively stationary.
- **Steep:** some oceanic plates have very steep angles, of over 70°. An example is the Mariana Trench in the western Pacific. The oceanic plate here is among the oldest in the world (it formed at an ocean ridge in the Jurassic geological period, when plesiosaurs swam the oceans), and is therefore cold and very dense, so it descends at a very steep angle.

Tomography has also revealed 'torn' slabs of oceanic plate which have ripped apart as they descend, as well as 'detached slabs'. These are the ghostly remains of ancient oceanic plates suspended in the mantle. The Farallon plate (or ex-plate!) under North America is a good example.

Hotspots

A very large proportion of the world's earthquakes and volcanic eruptions are found either at locations of seafloor spreading (mid-ocean ridges / divergent margins) where new oceanic plate is formed, or at subduction zones where an old oceanic plate re-enters the mantle (convergent / destructive margins). There are some volcanic locations – such as Hawaii and the Galapagos Islands - that are far from any known seafloor spreading location or subduction zone.

John Tuzo Wilson suggested an explanation for these isolated volcanic 'hotspots' in 1963. This is the theory of mantle plumes, which was further developed by WJ Morgan in the 1970s.

Whereas at a zone of seafloor spreading heat rises in a linear 'sheet' from the mantle under the line of a mid-ocean ridge, Wilson and Morgan argued that in some places heat rises as a concentrated column or plume beneath isolated areas of vulcanism. Plumes are thought to be 100–200 km wide and originate at the core-mantle boundary.

No mantle plume has ever been directly observed of course.

Table 2 Forces of Plate Motion and Rates of Motion

Location & rate of motion (mm per year)	Tectonic setting	Forces	Explanation
East African Rift Valley 6-7	Divergent (constructive) continental rift.	Mantle Drag	Geologically young rift zone lacking the large elevated ridge of a mid-ocean rift, so the ridge push force may be weak.
Mid-Atlantic Ridge 25	Divergent (constructive) ocean ridge, seafloor spreading.	Mantle Drag + Ridge Push	The slab pull force is not present, because there are few subduction zones around the Atlantic Ocean's edges.
Pacific Rim subduction zones 40-60	Convergent (destructive) subduction zone.	Mantle Drag + Ridge Push + Slab Pull	The Pacific Ocean is ringed by subduction zones as well as having divergent ocean ridges, so all three forces are present.

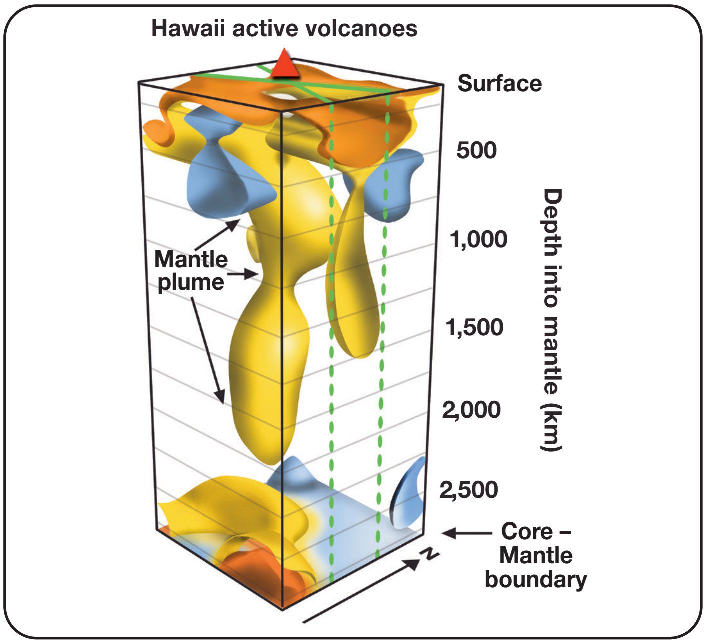
An alternative explanation for volcanic activity found at hotspots is the 'Plate Hypothesis'. This argues that:

- It's unlikely that there would be two types of convection in the mantle i.e. huge convection cells driving seafloor spreading and subduction, as well as small, isolated mantle plumes.
- Instead, in some locations the lithosphere is stretched and 'thinned' (called lithospheric extension) and in areas of thinning, magma more easily leaks to the surface.
- Pre-existing weaknesses in some parts of the lithosphere, such as large fault zones, might promote the movement of magma towards the surface.

Can seismic tomography settle the 'plume' versus 'plate' debate by providing 3D images of plumes? A detailed investigation in 2015 by seismologists at the University of California, Berkeley, and Lawrence Berkeley National Laboratory revealed 28 mantle plumes beneath Hawaii (**Figure 5**), Galapagos and the Canary Islands among others. However, the plumes were 600-800 km wide – much wider than the expected 200 km wide columns.

This discovery raises new questions. If plumes are larger and more numerous than once thought, they could be a much more important mechanism for transferring heat from Earth's core towards the surface.

Figure 5 Seismic Tomography Image of the Mantle Plume Beneath Hawaii



(*adapted from French & Romanowicz, 2015*)

Summary

- Plate tectonics remains a theory, rather than proven fact, because much of the evidence for it is indirect due to the inaccessibility of the interior of the Earth.
- The theory of plate tectonics evolved from the earlier theory of Continental Drift, when pioneering work in the 1960s led to the discovered of seafloor spreading, ocean trenches and subduction zones.
- The properties of the asthenosphere, which is thought to be partially molten and deformable, are important in understanding how convection, slab pull and ridge push cause tectonic plate motion.
- Despite decades of scientific research some aspects of tectonic theory, such as the existence of mantle plumes and the mechanisms of tectonic plate motion, are still incomplete or disputed.

Questions

1) Look at **Table 1**. Which of the scientists, in your view, made the most significant contribution to plate tectonic theory?
2) Explain why rates of plate motion (**Table 2**) are not the same in all places.
3) Why is seismic tomography indirect evidence rather than direct evidence?
4) Earth has many layers: why might the asthenosphere be considered the most important in terms of plate tectonic theory?

Further Reading and Research

- Scott W. French & Barbara Romanowicz (2015) 'Broad plumes rooted at the base of the Earth's mantle beneath major hotspots', Nature volume 525, pages 95–99 (2015)
- Foulger, G. (2002) 'Plumes or plate tectonic processes', Astronomy & Geophysics Vol 43, 6.19–6.23
- Grotzinger, J. Jordan, TH. (2014) 'Understanding Earth: Seventh Edition', Bedford
- Roberts, P. (2016) 'Tectonic Plates - How the World Changed', Russet Publishing
- Livermore, R (2018) 'The Tectonic Plates are Moving, OUP
- Inside the Earth: Video explaining the Earth's structure and how the crust is often mistaken for the tectonic plates. www.iris.edu/hq/inclass/animation/layers_of_the_earth
- Plate Tectonics Explained: An excellent short 'cartoon' style video by Minute Earth on You Tube that explains slab pull and why geoscientists consider this is the key driving force of plate movement. youtube/kwfNGatxUJI
- Student and teacher pages from the Geological Society www.geolsoc.org.uk/Plate-Tectonics
- Seismic tomography. Leaflet explaining how tomography is created.

  www.iris.edu/hq/files/programs/education_and_outreach/lessons_and_resources/docs/es_tomography.pdf
- Revealing what happens beneath Earth's tectonic plates Online article explaining the discovery and significance of the 'slippery' layer at the base of the lithosphere. http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=11397050
- Plate Tectonics. Open Learn free course from the Open University. www.open.edu/openlearn/science-maths-technology/science/geology/plate-tectonics/content-section-0

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