Duncan Hawley and John Lyon

Plate update: refreshing ideas for teaching plate tectonics

To help ensure that your teaching on plate tectonics reflects the latest understanding, this article outlines some recent developments and provides a subject knowledge 'refresher'.

Accompanying online materials

Introduction

Somewhere in your curriculum you will teach about plate tectonics. Whatever your sources, it may be easy to think you are teaching ideas that reflect current understanding of the way the Earth works. But beware – our experience indicates that this is often not the case. We have found that some aspects of teaching about plate tectonics are based on sources of information and teachers' own knowledge that is often well out-of-date and over-simplified (albeit telling a 'neat' story), and in some cases just plain inaccurate. Similar concerns have been raised by Trend (2008), Dove (2016) and research into science teaching by King (2012).

This article provides a 'refresher' that updates subject knowledge about some key recent developments in understanding how plate tectonics works and which consequently offer improved explanations for the distribution and characteristics of earthquakes, volcanoes and some surface landforms. It is intended to help teachers decide if and how they should adjust what they presently teach to reflect current understanding about the way plate tectonics operates, thereby developing students' critical sense of the plate tectonic 'story' encountered in textbooks, on diagrams, in the news, via the internet and in other media. Not every aspect of the topic can be covered in this short article, but some relevant further sources of information are recommended.

Crust and lithosphere

The outermost layer of the Earth is commonly described as being split into 'crustal plates', but this idea is inaccurate and conceptually misleading. Plates are a function of the mechanical (physical) properties of the Earth's cold outer shell, the strong, rigid (but still flexible) and mostly brittle layer, termed the **lithosphere**. This extends for some depth below the crust, hence the correct term is '**lithospheric plates**' or '**tectonic plates**'. The lingering use of the 'crustal' misnomer is a case of historical inertia; the concept of the crust was established long before the discovery of the lithosphere and plates (and probably endures in the popular imagination as a hard thin casing, as on a pie). However, the Earth's composition is, in scientific terms, less intuitive. Its outer layering exists in two ways: by chemical composition (crust, mantle) and by mechanical properties (lithosphere, asthenosphere). The lithosphere is a coupling of crust and uppermost mantle due to cooling; its thickness varies, but its lower boundary is considered to be where the mechanical properties change from elastic to plastic behaviour (around the 1300°C isotherm) (Figure 1). Rigidity allows it to bend (elastically) when subjected to a load, which helps explain the structure of ocean trenches and the deep waters around oceanic volcanoes. The lithosphere (i.e. plates) under oceans is 50–100km thick (thickest under older ocean basins) including a 5–8km veneer of basaltic crust, and is relatively warm and dense.

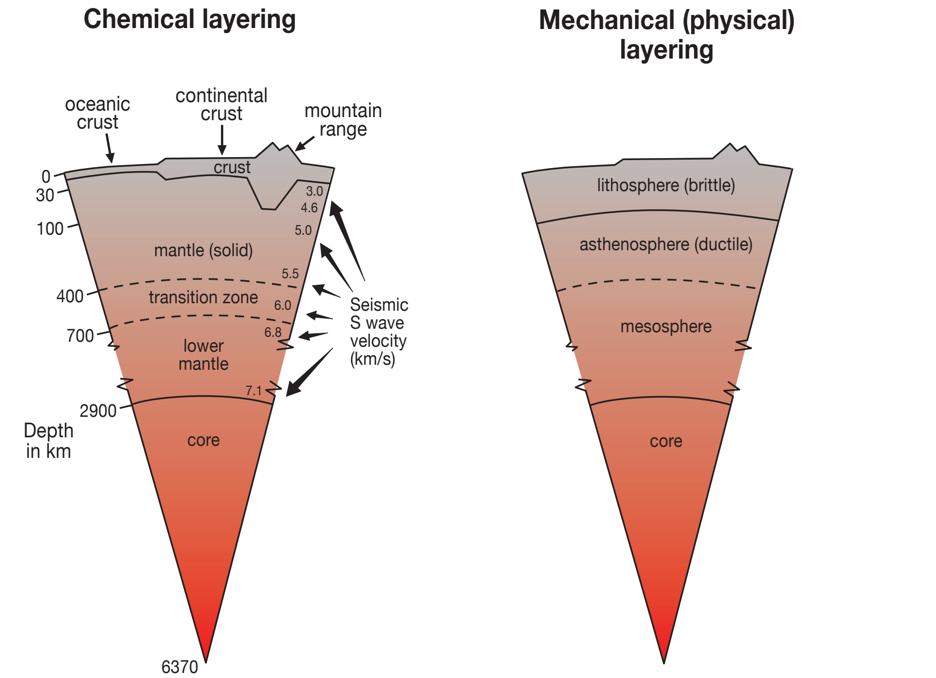

Figure 1: Two ways of dividing the Earth's outer layers. Plates function as mechanically coherent portions of the Earth so are formed from lithosphere which extends below the crust. **Source:** Trinity College Dublin (n.d.).

The lithosphere under continents is up to 300km thick, with a 30–40km crust of granitic rock (and sedimentary derivatives) that is relatively cool and buoyant. Plates can comprise portions of both oceanic lithosphere and continental lithosphere, although these are never vertically juxtaposed. Where one type passes laterally into the other is termed a **passive margin**; these are not seismically active but represent the site of former tectonic rifts, e.g. the Atlantic seaboards of South America and Africa.

The mechanics of material in the mantle

Some sources describe the mantle as 'semi-solid' or 'semi-liquid'. To many people 'semi-' implies around half, but in fact the mantle is almost entirely (99.9 %) solid. We know this because the mantle will transmit seismic S (shear or shake) waves that can only pass through solid material. In the upper mantle is a zone called the **asthenosphere**, identified by low seismic S wave velocities. Here the rocks are ductile, so will not fracture; but they flow and deform plastically, a process known as viscoelasticity, when subjected to stress over long periods. Glacial ice exhibits a similar behaviour, as although solid it will deform and flow slowly downhill over time. Silly Putty® is another material exhibiting plastic, elastic and brittle behaviours similar to the mantle, with each state dependent on the timescale and force of stress applied. The lower part of the mantle (mesosphere) is subject to greater pressure so although it can deform and flow, the material here is significantly more viscous. In 2015 geoscientists 'discovered' a distinct 10km-thick low viscosity layer containing about 2 % of melted material at the lithosphere/asthenosphere boundary under oceanic lithosphere. This 'slippery' rock is thought to provide clear evidence that plates slide and glide over the asthenosphere below, rather than that they are moved by a convective mantle coupling to the bottom of a plate (Stern *et al.*, 2015).

Top down tectonics

What exactly makes tectonic plates move is still being explored by geoscientists. However, the 'neat' classic model of giant convection cells rising up in the mantle with the tectonic plates just 'surfing' on the top, as frequently illustrated by the 'pan of water' or 'conveyor belt' analogies, is now an outdated paradigm. Seismic **tomography** (a 'CAT scan' of the Earth produced by image-processing the pathways and differential velocities of seismic waves as they propagate through the Earth) has not been able to identify convection cells in the mantle that are large enough to drive plate movement. Convection does take place, but heat is dissipated as patchy thermal **plumes** rather than a pattern of strong, regular cells. These help explain previously anomalous 'hot spots' such as Hawaii. A plume is also thought to be responsible for the volcanism of Iceland. Plumes are considered to originate at the mantle-core boundary: about ten major plumes are thought to exist (Courtillot *et al.*, 2003).

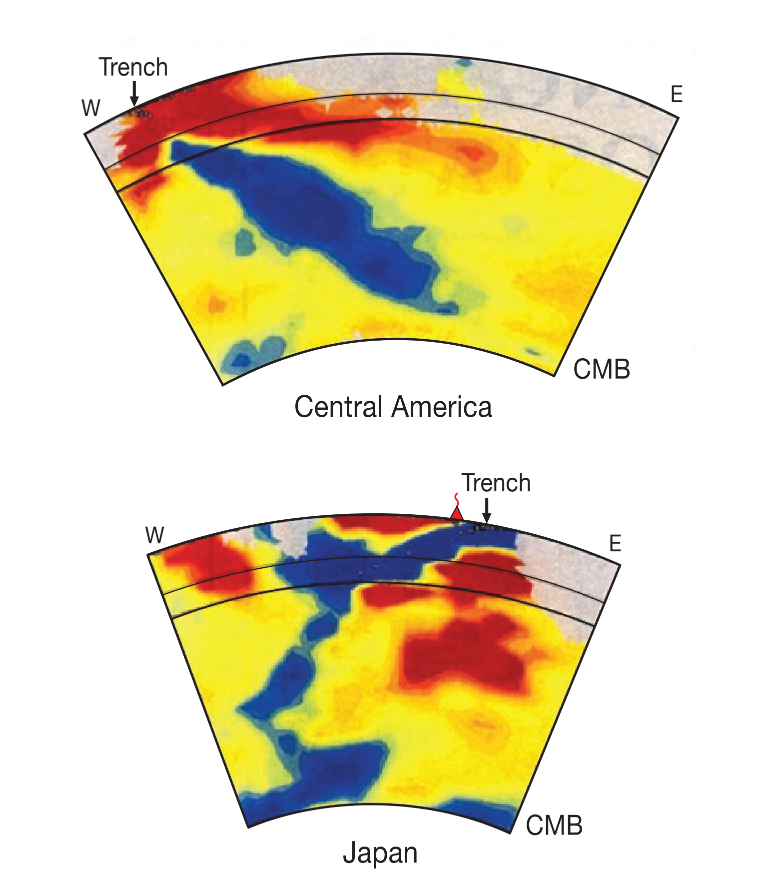

Figure 2: Tomographic slices through the lithosphere and mantle. Blue colours represent cold slabs of lithospheric plate descending to the core mantle boundary. **Source:** Based on the work of Van der Hilst *et al.*, 1997 and Fukayo *et al.*, 2001.

Tomography has revealed cold, dense slabs of plate material sinking deep into the mantle at **convergent margins**, which pulls on the rest of the tectonic plate (Figure 2). This process is called **slab pull** and it is the subduction of relatively cold, dense slabs that is now considered to be the key active driving force of plate movement. The idea that magma injection pushed plates apart at **divergent margins** (which was allied to the giant convection model) is now regarded as unsound. The current model has slab pull extending and thinning plates at divergent margins, which reduces pressure on the underlying asthenosphere, causing it to partially melt. The resulting magma wells up under the divergent margin, cools and is added to the plate as new lithosphere. Much of the magma never reaches the surface but it is buoyant enough to push up the crust at divergent margins to form **ridge and rift** features, e.g. mid-ocean ridges. This elevation produces a slope away from a spreading ridge, allowing gravitational force to slide the lithosphere towards the subduction zone, in a process misleadingly known as **ridge push**. As plates spread away from the divergent margins they become increasingly older, colder, thicker and denser. The discovery of the 'slippery' layer at the base of plates helps explain why plates move under slab pull. When the lower portion of a descending slab detaches it sets up deformation in the upper mantle: this induces weak convection motions that suck overlying plates together, a process known as **slab suction**. So the current view reverses the large-scale convectional cell model of the force behind plate movement, which is now thought to be driven by top-down cooling and sinking of lithospheric slabs.

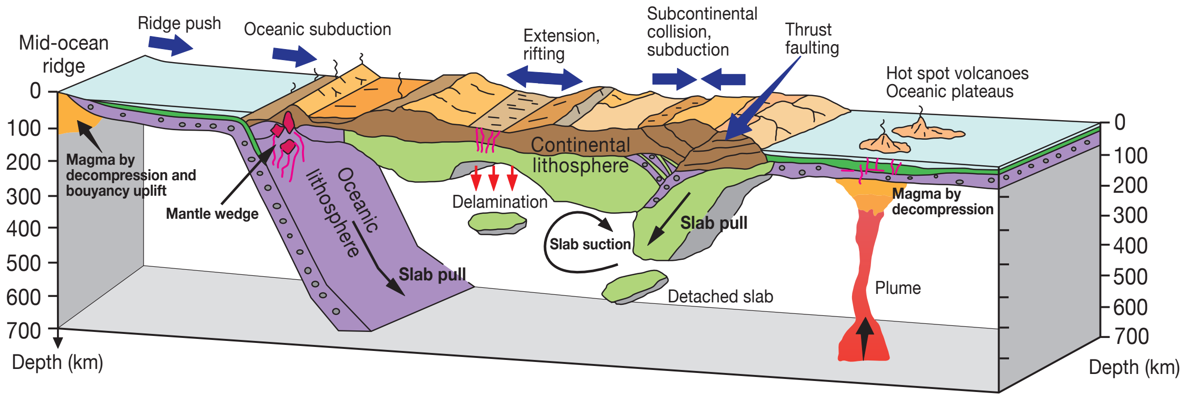

Figure 3: Summary illustration of lithosphere/plate processes and interaction with the mantle. Vertical and horizontal dimensions are not to scale. **Source:** adapted from an original sketch by Artemieva and Meissner, 2011.

Melting the mantle with water

Some sources attribute magma generation, and the formation of volcanoes along subduction zones, to the melting of the downgoing plate due to frictional heat created by pressure as it grinds against the overriding plate and mantle. Although this account is neat and intuitively convincing, it is erroneous and inaccurate for three reasons:

- slabs of lithosphere are relatively cold (which is why they can be picked out by tomography) so require considerable heating before reaching melting point
- as subducting slabs descend into the mantle and become hotter the frictional stresses diminish, so negligible heat is generated
- a frictional force would work against melting as pressure raises melting points, so any such pressure would lead to the plate or mantle remaining in a solid state at greater depth.

However, the **presence of water** in the rocks of a subducting plate results in **partial melting**, although the plate itself does not melt. Oceanic plates contain water locked up in the basaltic rock and overlying sediments, which is driven off by increasing temperature and pressure and acts to reduce the melting point of rocks in the mantle above the subduction plane, causing portions of the **mantle wedge** to melt. Some of the magma melt rises up through the mantle and overlying lithosphere to erupt at the surface, producing a linear belt of volcanoes. As the magma ascends it changes in chemical composition due to fractionation, with the magma becoming progressively less dense but more viscous as it rises to the surface. In addition, the water dissolved in magma acts as a volatile and expands rapidly (exsolves) when pressure is released, leading to the explosive volcanic eruptions associated with subduction zone volcanoes.

Mountain belts are more than folds

The 'classic' textbook model for the formation of mountains envisages a collision of continents causing sedimentary rocks to crumple into high peaks creating 'fold mountains' as the crust is shortened. However, compressed rocks do not only fold; they also fracture along low-angle fault lines causing massive slices of lithosphere to thrust over each other, stacking up to great height. The Alps were constructed by this process. Thrust faulting helps explain why earthquakes occur in 'interior' mountain regions like the Himalayas (e.g. in Nepal in 2015). Subduction plays a major role in mountain building by thickening continental lithosphere. At oceanic-continental subduction margins, partial melting creates magma that rises from the subduction wedge and intrudes into the lithosphere as massive granite plutons. A small fraction of magma can reach the surface to create volcanic mountains (e.g. the Andes) but most cools in the roots of mountains, and the added thickness provides more buoyancy to the lithosphere, uplifting the surface. Rapid erosion can counteract uplift but active plate tectonics always wins until subduction ceases. The great linear or arcuate mountain ranges of the world are formed by a combination of tectonic processes, so 'fold mountain' is a misnomer: it should be termed 'mountain belt' and closer attention should be paid to the tectonic position and geology to help identify what is likely to have caused its formation.

Duncan Hawley is Chair of the GA's Physical Geography Special Interest Group and is also a Consultant to the GA.

Email: *duncan.hawley.geography@gmail.com*

John Lyon retired as Programme Manager for the GA and is a member of the GA's Physical Geography Special Interest Group..

Email: *johnhlyon@gmail.com*

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