An evidence-based approach to teaching plate tectonics in high school

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ABSTRACT

This article proposes an evidence-based and engaging approach to teaching the mechanisms driving the movement of tectonic plates that should lead high school students towards the prevalent theories used in peer-reviewed science journals and taught in universities. The methods presented replace the inaccurate and outdated focus on mantle convection as the driving mechanism for plate motion. Students first examine the relationship between the percentages of plate boundary types of the 14 largest plates with their GPS-determined plate speeds to then evaluate the three possible driving mechanisms: mantle convection, ridge push and slab pull. A classroom experiment measuring the densities of igneous and metamorphic rocks associated with subduction zones then provides a plausible explanation for slab pull as the dominant driving mechanism. Basalt and gabbro of oceanic lithosphere, that is positively buoyant compared to the peridotite of the asthenosphere, changes to denser negatively buoyant eclogite as it descends so that it sinks into the mantle and pulls the tectonic plate along behind it.

INTRODUCTION

One of the richest and most engaging concepts in Earth and environmental science is plate tectonics and it is covered in the Australian Curriculum in Year 9 earth and space sciences. The relevant science understanding content description is "The theory of plate tectonics explains global patterns of geological activity and continental movement" (ACARA, 2019a, ACSSU180). The elaborations to ACSSU180 are:

1. recognising the major plates on a world map;
2. modelling sea-floor spreading;
3. relating the occurrence of earthquakes and volcanic activity to constructive and destructive plate boundaries;
4. considering the role of heat energy and convection currents in the movement of tectonic plates; and
5. relating the extreme age and stability of a large part of the Australian continent to its plate tectonic history.

The problem with this list is the fourth elaboration, because the idea that convection currents in the mantle drive the movement of tectonic plates is a myth. This convection is presented as whole mantle or whole asthenosphere cells with hot material rising under the Earth's divergent plate boundaries and cooler material sinking at the convergent boundaries with the lithosphere dragged along by the horizontal flow of the asthenosphere (Figure 1). This was the preferred explanation for plate motion until the early 1990s but it does not stand up to a frequent deduction made by Year 9 students: how can there be large-scale mantle convection if hotspots (like Hawaii) don't move? Most science teachers quickly cover convection as the mechanism driving plate tectonics and focus on teaching the structure of the Earth, the evidence for plate movement, descriptions of the types of boundaries, and the earthquakes, tsunamis and volcanoes associated with them. A rich teaching and learning experience is lost if plate tectonic processes are reduced to description rather than evidence-based science.

Science students get a chance to go into greater depth on the topic of plate tectonics if they choose Earth and environmental science in Year 11 and 12. In Unit 2: 'Earth processes — energy transfers and transformations', the "Students examine how the transfer and transformation of heat and gravitational energy in Earth's interior drive movements of Earth's tectonic plates" (ACARA, 2019b). The Science Understanding content description in Unit 2 relevant to plate tectonics is "Transfers and transformations of heat and gravitational energy in Earth's interior drives the movement of tectonic plates through processes including mantle convection, plume formation and slab sinking" (ACARA, 2019b, ACSES047). This gives the teacher greater scope to guide students through the fascinating complexities of plate tectonics but still emphasises mantle convection as the dominant mechanism driving plate motion.

This article proposes an evidence-based approach to teaching the mechanisms driving the movement of tectonic plates that should lead students towards the prevalent explanation appearing in peer-reviewed science journals and taught in universities. This has been trialled successfully with Year 9 science and Year 11 EES classes. It is much more engaging because it allows students to build an internally consistent, complete, and satisfying picture of plate tectonics.

POSSIBLE DRIVING MECHANISMS FOR PLATE MOTION

The starting point for students to gain an evidence-based explanation of plate motion is to present the three possible mechanisms for driving the motion of tectonic plates: mantle convection, ridge push and slab pull.

Mantle convection: Convection is driven by heat from the core and involves either the whole mantle or convections cells within the plastic asthenosphere (Figure 1). The upwelling in the convection cells occurs under the Earth's divergent plate boundaries, and cooler material sinks at the convergent boundaries. The lithosphere plates are dragged along by the horizontal flow of the asthenosphere like a conveyor belt.

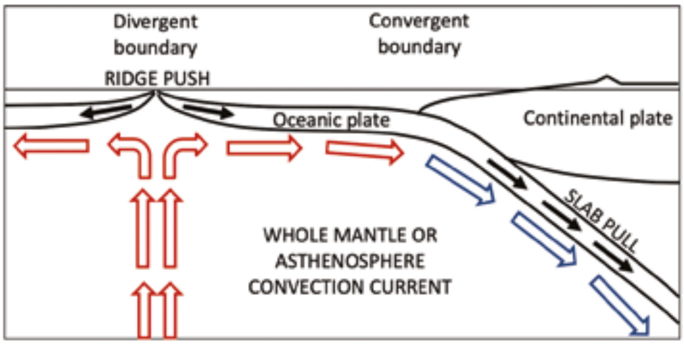


Figure 1: *Diagram showing mantle convection, ridge push and slab pull mechanisms for plate motion.*

Ridge push: Hot buoyant mantle lifts and pushes the plates apart at mid-ocean ridges where magma solidifies to form new oceanic lithosphere. Gravity pulls the oceanic plates downhill from the ridges towards the deep ocean and trenches (or downhill from uplifted continental rift zones like the East African Rift).

Slab pull: Relatively cool and dense oceanic plates (slabs) have negative buoyancy after subducting at ocean trenches and sink into the ductile, less dense asthenosphere, pulling the rest of the tectonic plate along behind it.

The question to put to students after these mechanisms are described and studied is: what evidence is needed to decide the dominant mechanism? A Year 9 class in 2013, with teacher guidance, decided on the following empirical test.

Mantle convection: plate speed should not be related to plate boundary types, and plate speeds should be similar either side of divergent boundaries if convection is symmetric (as presented in Figure 1).

Ridge push: plate speed should be related to the percentage of its boundary that is divergent.

Slab pull: plate speed should be related to the percentage of its boundary subducting under another plate.

Looking at any global map of tectonic plates coded for boundary types, for example the Digital Tectonic Activity Map of the Earth (NASA, 2019), a qualitative observation is that fast plates tend to have large parts of their boundaries where they are subducting under another plate, for example: the Pacific Plate. But these fast plates have an even greater part of their boundaries that is divergent.

GOOGLE EARTH AND APPLYING THE EMPIRICAL TEST

Google Earth is a fantastic tool for teaching plate tectonics and can be downloaded from https://www.google.com/earth/ (Google, 2019). Go into 'Earth Versions' and click 'Download Google Earth Pro on desktop'. Google have recently removed earthquake and volcano databases from the Layers menu, so these need to be downloaded separately. While the Google Earth Pro application and a browser are open, go to https://earthquake.usgs.gov/learn/kml.php (USGS, 2019). Download and then double click on the following files.

- **Earthquakes in Catalog** -> (recommended) Magnitude: 4.5+, Date & Time: Custom 1960–2019, Geographic Region: World, Output Options: KML, Color by depth, Magnitude — Largest First, Number of Events 20000.
- **Tectonic Plate Boundaries**
- **(optional) Real-time Earthquakes** -> Past 30 Days, M2.5+ Earthquakes -> Colored by Age

Now go to https://volcano.si.edu/learn_resources.cfm?p=3 (Smithsonian Institution, 2019) and click on the 'Download Quaternary Volcanoes Network Link' while Google Earth Pro is open.

These will now be part of "Temporary Places". When Google Earth is closed, you will be asked: 'Would you like to save them to your "My Places" folder?' — click 'Save'. Next time Google Earth is opened, these data presentation options will be listed in the My Places directory.

These options bring up earthquake icons with moment magnitude, timing and depth from the USGS's earthquake database; active volcano icons with volcano types and eruption histories from the Smithsonian Institution's volcano database; and colour-coded tectonic plate boundaries defined by the USGS (Figure 2). Allowing Year 9 students (and Year 11 EES students) the time to roam around this virtual geological globe and observe the pattern of earthquakes and volcanoes associated with each type of plate boundary leads to many 'aha' moments.

The author used the Google Earth ruler tool to measure the total distance around the boundaries of the 14 largest tectonic plates. For each plate, the total distance of divergent boundaries, and the total distance for the 'Subduction Zone' boundaries where that plate is the subducting plate, were also measured. These data were then converted to percentages (Table 1).

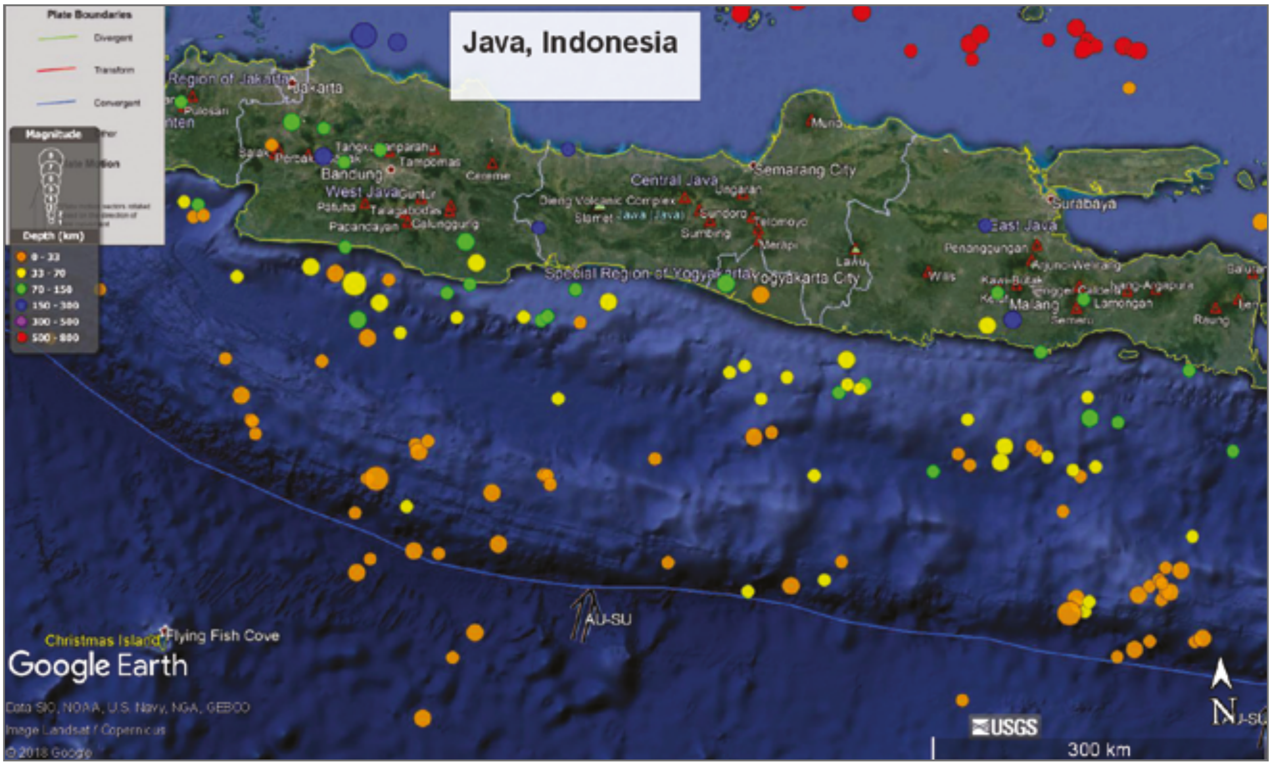


Figure 2: *An example of a subduction zone on Google Earth Pro with colour-coded tectonic plate boundary, volcanoes (red triangles) and earthquakes (> 5.5 MM) colour-coded for depth.*

TECTONIC PLATE	AREA (km²)*	Boundary (km)	Boundary subducting (km)	% subducting	Boundary divergent (km)	% divergent	Average speed cm/yr	Direction
Pacific	103,300,000	46,456	16,311	**35.1**	15,110	**32.5**	**7.5**	WNW
North American	75,900,000	33,670	810	**2.4**	11,740	**34.9**	**1.5**	NW–SW
Eurasian	67,800,000	44,150	1,990	**4.5**	10,630	**24.1**	**2.9**	NE–SW
African	61,300,000	40,560	1,960	**4.8**	20,790	**51.3**	**2.7**	NE
Antarctic	60,900,000	39,600	2,170	**5.5**	20,540	**51.9**	**1.0**	S–N
Australian	47,000,000	36,365	7,310	**20.1**	14,490	**39.8**	**6.5**	NNE
South American	43,600,000	33,380	1,890	**5.7**	8,660	**25.9**	**1.3**	N
Somali	16,700,000	20,410	0	**0.0**	11,820	**57.9**	**2.9**	NE
Nazca	15,600,000	19,300	6,500	**33.7**	7,480	**38.8**	**6.7**	E
Indian	11,900,000	17,010	1,490	**8.8**	3,530	**20.8**	**5.4**	NE
Philippine	5,500,000	11,260	4,300	**38.2**	2,223	**19.7**	**6.8**	WNW
Arabian	5,000,000	10,530	730	**6.9**	3,350	**31.8**	**4.3**	NE
Caribbean	3,300,000	9,070	0	**0.0**	130	**1.4**	**2.1**	NE
Cocos	2,900,000	7,920	2,790	**35.2**	3,980	**50.3**	**8.9**	NNE
Correlation coefficient with plate speed:				**0.89**		**0.06**		

** Plate areas from Alden (2017).*

Table 1: *The relationship between % of a plate boundary subducting or divergent and its speed.*

The velocity (speed and direction) of each plate was calculated as the average for a number of GPS ground stations from the NASA JPL GPS Time Series (NASA JPL, 2019), and is also given in Table 1. For example, GPS ground station PERT is at Perth, WA (https://sideshow.jpl.nasa.gov/post/links/PERT.html) and this GPS station is moving at 57.8 mm/yr north and 38.9 mm/yr east, so $\sqrt{(57.8^2 + 38.9^2)}$ = 69.7 mm/year or 7.0 cm/year NNE. The average velocity of the Australian Plate was estimated at 6.5 cm/yr NNE. The GPS Time Series data shows that different parts of a continent within a single plate are travelling at different speeds.

This is a data set that allows students to apply an empirical test that should indicate which of the three possible mechanisms driving plate tectonics is the dominant one. The students are then asked to graph the data highlighted in bold in Microsoft Excel or a similar spreadsheet program (Figures 3 and 4) or on graph paper. Another approach is to use the spreadsheet program to calculate correlation coefficients (see bottom of Table 1).

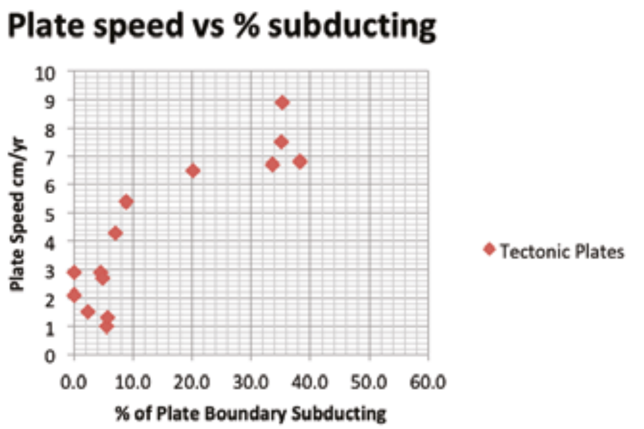


Figure 3: *Plate speed versus the percentage of plate boundary that is subducting for the 14 largest tectonic plates.*

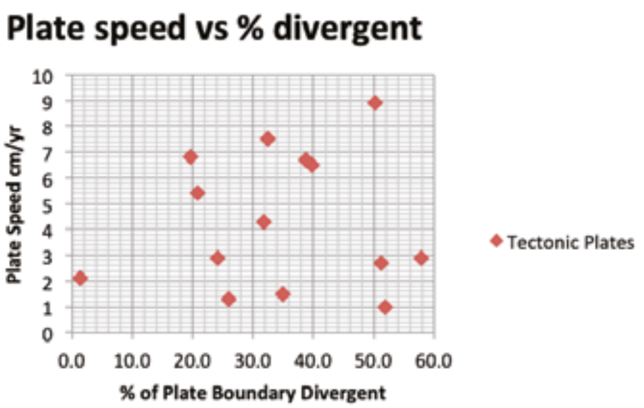


Figure 4: *Plate speed versus the percentage of plate boundary that is divergent for the 14 largest tectonic plates.*

There is a strong positive correlation between the speed of a plate and the percentage of its boundary where it is subducting under another plate (Figure 3). This indicates that slab pull is the dominant driving mechanism for plate motion.

There is no correlation between the speed of a plate and the percentage of its boundary where it is divergent (Figure 4). This suggests that ridge push has no significant effect on the speed of a plate. There is a case for saying that ridge push could be a significant driving force for the slower plate motion (0–2 cm/yr). Ridge push may also be a subsidiary driver of fast-moving plates (again a 0–2cm/yr component), but slab pull must provide the dominant driving force.

The empirical test for whether mantle convection is the dominant driving mechanism is that all plates should have similar speeds, and this is not the case. Also, there are examples where the speeds of plates either side of a divergent boundary are very different. For example, the mid-ocean ridge boundaries between the Antarctic and Australian plates, and the Antarctic and Pacific plates. This evidence rules out symmetric mantle convection as a significant driving force.

This is a set of interpretations at a very appropriate level for teaching plate tectonics at Year 9 or Year 11 level. A fascinating aspect of the graph in Figure 3 is that there is a cluster of slow plates with little or no subduction, and a cluster of fast oceanic plates with >30% of their boundary subducting. The three plates in between are the Arabian, Indian and Australian plates, and these appear to be fast-moving, previously subduction-dominated plates in the process of slowing down due to continental collisions.

SLAB PULL, BUOYANCY AND METAMORPHISM

The next step is to provide students with a path towards an explanation of slab pull. In Unit 2 of the ACT version of the ACARA EES course, "students explore how the transfer and transformation of energy from the Sun and Earth's interior enable and control processes within and between the geosphere, atmosphere, hydrosphere and biosphere" (ACT BSSS, 2019). Buoyancy is a key scientific concept that connects solar energy to the circulation in the atmosphere and oceans, and the Earth's interior heat to slab pull. Hotter, less-dense material has positive buoyancy and rises, and colder, denser material is negatively buoyant and sinks.

To understand plate tectonics, it is necessary for students to concentrate on the subduction zone setting where a dense oceanic plate subducts beneath another plate. So, the next step must provide a reason for the positively buoyant oceanic lithosphere to become negatively buoyant and sink into the asthenosphere at subduction zones.

Regional metamorphism involves the alteration of mineral assemblages in rocks as temperature and pressure increase with burial deeper in the Earth. This usually causes the metamorphic rocks to increase in density due to dehydration (loss of H_2O and OH- from minerals) and the formation of new minerals with tighter-packed structures (i.e. the atoms are closer together). Year 9 students should have been introduced to regional metamorphism as part of the study of the rock cycle in Year 8. Year 11 EES students should have covered regional metamorphism as part of the development of the geosphere in Unit 1: "Rocks are composed of characteristic assemblages of mineral crystals or grains that are formed through igneous, sedimentary and metamorphic processes, as part of the rock cycle" (ACARA, 2019b, ACSES019).

Students can be introduced to the links between metamorphism and plate tectonics by evaluating how plates behave sequentially from where they form through to where they are subducted. As oceanic crust is formed, saline ocean water circulates deeply through the basalt and gabbro forming in the hot environment of the mid-ocean ridges (divergent boundaries). This hot fluid changes the rock so that minerals without hydroxyl groups (OH-) or water in their structures (pyroxene, plagioclase feldspar and olivine) are often altered to minerals with hydroxyl groups (OH-) in their structures, such as chlorite, epidote, actinolite and serpentine. The action of circulating hot ocean water at mid-ocean ridges in forming hydroxyl-bearing minerals in the oceanic crust plays a vital and controlling role in all of the geological processes at the subduction boundaries.

As the oceanic crust subducts, it experiences a very high pressure but relatively low temperature style of regional metamorphism, and the basalt and gabbro are transformed to blueschist (or glaucophane schist) and then to eclogite (Figure 5). This is a remarkable transformation and involves complete dehydration and an increase of over 10% in density, but blueschist and eclogite are rare rocks at the Earth's surface. There is only one small outcrop of eclogite in Australia, at Port Macquarie, NSW, but the rocks are strongly deformed and the classic garnet–omphacite eclogite is missing (Och, 2017). Welsh blueschist and Norwegian eclogite samples (Figure 5) can be sourced from Northern Geological Supplies Ltd of Bolton, England, who trade online as the Geology Superstore (http://www.geologysuperstore.com/).

Figure 5: *Basalt, blueschist and eclogite.*

Figure 6: *A class set of igneous and metamorphic rocks related to subduction zones.*

The details from a worksheet for a density experiment that Year 9 and Year 11 students can carry out with a rock set similar to Figure 6 is shown below. Experimental data collected by a Year 11 student is included in the results table to show typical measurements and calculated densities. Students plot their calculated densities on the subduction cross section (Figure 7). Except for blueschist and eclogite, the rocks used in the experiment are readily available in school rock collections or from Australian outcrops (Figure 6). For example, xenoliths in Eastern Australian basalts are a good source of mantle peridotite. (It is a good idea to refer to all olivine-rich mantle rock as peridotite rather than using a more detailed classification.)

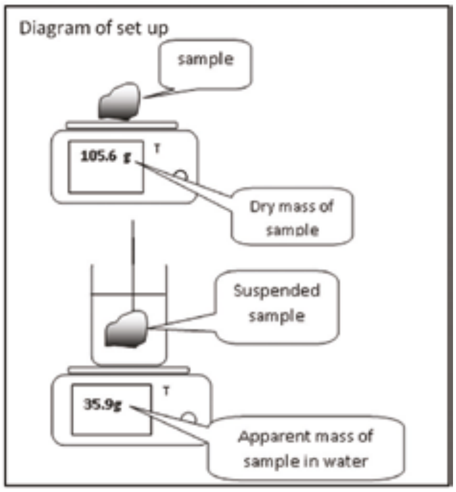
A worksheet for a density experiment that Year 9 and Year 11 students can carry out with a rock set similar to Figure 6

Worksheet: Density of Lithosphere and Mantle Rocks Experiment

Aim: To determine the role of rock density and buoyancy in tectonic plate motion.

Materials: Rock samples (basalt, gabbro, blueschist, eclogite, andesite, granite, peridotite, serpentinite), scales (+/- 0.1 g), cotton thread, 500 mL beaker or plastic container, tap water, retort stand, boss head, clamp

Method:



1. A dry rock sample is placed on the scales and the mass recorded.

2. A length of cotton is securely tied to the rock.

3. The retort stand, boss head and clamp are set up so that the rock sample could be suspended from the clamp.

4. A half-full beaker of water is placed on the scales and the scales are zeroed.

5. The rock is suspended and wholly immersed in the water and the mass recorded (this mass will be equal to the volume of the displaced water in cm³ because the density of fresh water = 1 g/cm³).

6. The density is calculated using the formula:

$$\text{Density (in g/cm}^3) = \frac{\text{mass}}{\text{volume}} = \frac{\text{dry mass in air (g)}}{\text{volume of rock (cm}^3)}$$

7. The rock densities are plotted on the cross-section of a subduction zone (Figure 7).

Results:

Rock type	Location	Dry mass in air (g) *	Mass in water (g) = volume (cm^3) *	Density (g/cm^3) *
basalt	oceanic crust (upper 0.5 km)	188.0	64.5	2.91
gabbro	oceanic crust (0.5–10 km)	105.6	35.9	2.94
blueschist	subducting oceanic crust	182.1	59.1	3.08
eclogite	subducting oceanic crust	185.9	54.1	3.44
andesite	continental crust (volcanic arc)	117.1	43.0	2.72
granite	continental crust	154.3	58.0	2.66
peridotite	upper mantle (lithosphere + asthenosphere)	310.9	95.6	3.25
serpentinite	hydrated mantle	102.8	39.2	2.62

* *These columns will be blank in the worksheet provided to students.*

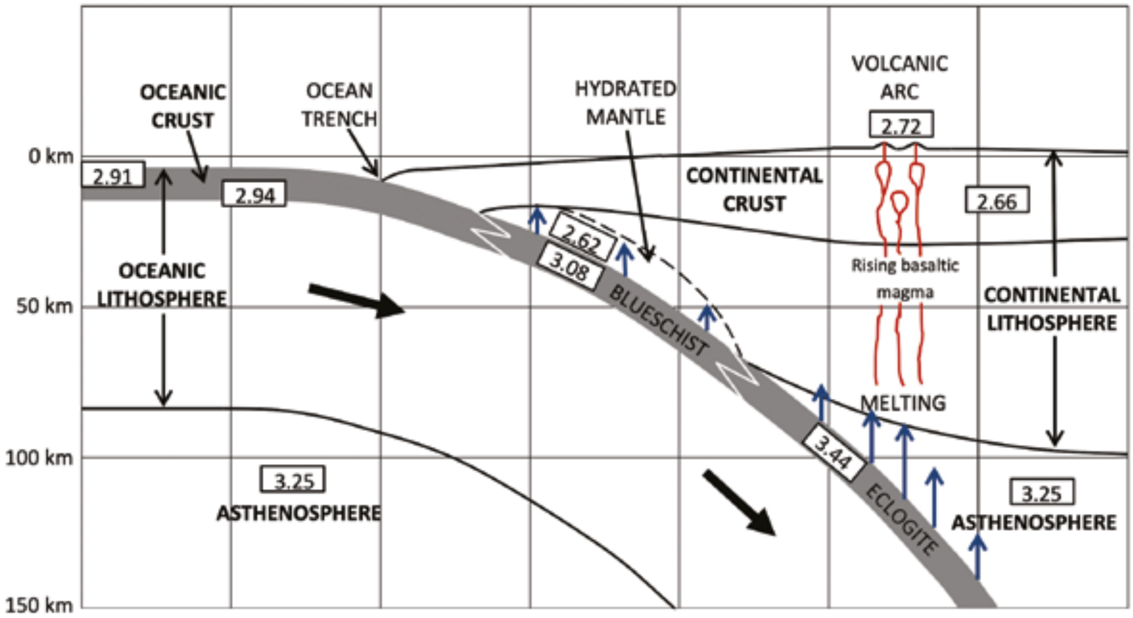


Figure 7: *Cross section of a subduction zone with measured rock densities in g/cm³ (see Worksheet). The boxes are blank in the diagram provided to students.*

The key data from this experiment is that the asthenosphere has a density of 3.2–3.3 g/cm³, while oceanic crust density increases from 2.9 g/cm³ (positive buoyancy) to 3.4 g/cm³ (negative buoyancy). Here is a convincing driving mechanism for slab pull supported by a classroom experiment. Denser eclogite sinks into the asthenosphere and pulls the oceanic lithosphere along behind it.

An important point to also cover with Year 11 EES students is that most of the oceanic lithosphere is rigid upper mantle peridotite, similar in composition to the underlying asthenosphere. At subduction zones, the peridotite in the oceanic lithosphere is significantly colder (600–1200 °C) and therefore denser (3.27 g/cm³) compared to the plastic peridotite in the underlying asthenosphere (1200–1500 °C, 3.23 g/cm³). The oceanic lithosphere under the ocean trench has close to neutral buoyancy (combining the 2.9 g/cm³ 7–10 km thick oceanic crust with the 3.27 g/cm³ 50–90 km thick rigid peridotite upper mantle). The formation of dense eclogite is the decisive event in making the whole descending oceanic lithosphere slab negatively buoyant. There are other processes involved, such as the thickening of the oceanic lithosphere by underplating as it makes its journey from mid-ocean ridges to subduction zones, but greater detail and depth can wait for university.

The earthquake patterns under subduction zones (as documented by the USGS earthquake data on Google Earth) indicate that subducting oceanic plates continue to descend to at least 600–700 km depth, the interpreted bottom of the asthenosphere. So, the descending slab must maintain its rigid structure and negative buoyancy relative to the surrounding mantle until at least this depth. A lot of current university research focusses on the role of descending slabs in mantle processes, and this is best left as extension research for keen Year 11 EES students.

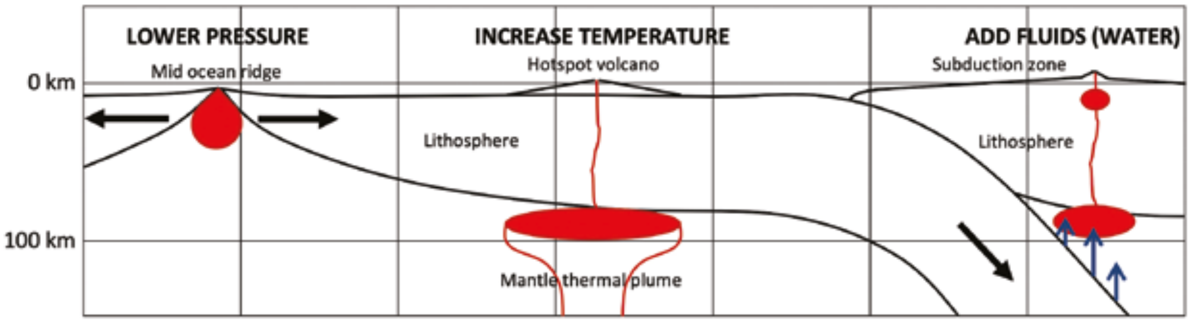


Figure 8: *Three causes of partial melting and basaltic magma generation in the asthenosphere.*

METAMORPHISM OF OCEANIC CRUST AND VOLCANISM

There are three ways to melt rocks: increase the temperature, lower the pressure, or add fluids (mainly water). Buried silica-rich crustal rocks can be melted due to the higher temperatures in the deep crust, or a mantle thermal plume can add heat to the upper mantle causing partial melting and basaltic hotspot volcanism (Figure 8). Enormous volumes of basaltic magma are generated from partial melting of peridotite under mid-ocean ridges due to the lower pressure in this shallow region of the asthenosphere. This replaces the inaccurate explanation presented in textbooks of mid-ocean ridges being above the hot upwelling part of plate and mantle-scale convection cells. Iceland is one of the few cases of a mantle thermal plume adding more heat and much more melting to a divergent boundary.

The water released in the metamorphism of basalt, gabbro and blueschist to eclogite moves towards the surface due to positive buoyancy and causes partial melting of the peridotite of the overlying mantle wedge by lowering the temperature required for melting (Figure 8). This melting produces basaltic magma that rises through or stalls in the lower crust, and the upward heat flow can also cause melting in the silicic lower crust. Fractional crystallization and partial melting then produces an intermediate magma and this process results in the spectacular andesitic stratovolcanoes typical of subduction zones (e.g., the Andes Mountains in South America and Java in Indonesia). The water from the dehydration of the descending oceanic crust also explains why these volcanoes have relatively water-rich explosive eruptions, and why huge porphyry copper–gold–molybdenum hydrothermal deposits form in the sub-volcanic environment (e.g., in Chile). This interconnection (with water as the link) makes plate tectonics a far richer and more satisfying field of study, particularly for Year 11 students.

Google Earth provides additional evidence of the link between eclogite formation and volcanism. The major earthquakes associated with subduction zones tend to be at the contact between the descending oceanic plate and the overlying plate. A Google Earth task to set students is to observe and record the deepest earthquakes, with a moment magnitude of >5, directly under the lines of active stratovolcanoes around the Pacific Ocean and north-eastern Indian Ocean (for example, under Java, see Figure 2). They will mostly find a restricted depth range of 80–140 kilometres, which must be the main zone of dehydration and eclogite formation. This is the 'sweet spot' in depth where water released from the descending plate causes melting of the overlying peridotite. There will also be numerous shallow (<30 km) earthquakes but these occur in the crust and are not directly related to the movement of the subducting slab.

Water is also released from the metamorphic reactions forming blueschist, but this occurs at cooler, shallower depths where the addition of water cannot cause melting of the overlying mantle. Instead, this can be associated with the hydration of mantle rocks above the descending plate, changing peridotite to serpentinite instead (Figure 7). This is a simplification of a more complex story but is appropriate at Year 9 and Year 11 level.

CONCLUSION

An empirical test to determine the dominant mechanism driving tectonic plate motion out of mantle convection, ridge push and slab pull involves plotting the percentage of a plate's boundary that is divergent and subducting under another plate against the speed of the plate. This data can be derived from the USGS tectonic boundary data and the distance measuring tool on Google Earth, as well as from the average velocity of a number of GPS ground stations from the NASA JPL GPS Time Series. The strong positive correlation between the percentage of a plate's boundary that is subducting under another plate and the speed of the plate indicates that slab pull is the dominant driving mechanism for plate motion. There is no correlation between the percentage of a plate's boundary that is divergent and the speed of the plate, indicating that ridge push can only have a minor role in driving plate motion.

Convection does occur in the mantle, just not in the way shown in high school textbooks. It does not occur as huge symmetric dynamic cells that directly underlie each lithospheric plate with the lithosphere as a passenger on a convection cell 'conveyor belt'. The descending slabs of oceanic lithosphere from subduction zones represent the return flow of 'cold' dense material back into the mantle, but this is a process controlled from the top down, not by the upwelling of hot material. Heat loss from the mantle is strongest at the mid-ocean ridges where the lithosphere is thinnest, but mass flow is mostly passive and very slow with no large-scale, buoyancy-driven upwelling of material from below. Mantle plumes are the main dynamic upwelling process for negatively buoyant material and these originate at the outer core–mantle boundary. They produce the stationary hot spot volcanism which acts as a marker for plate motion, for example in Eastern Australia and the Hawaiian Islands. The other role of mantle plumes in plate tectonics is that the high heat flow and doming of one or more mantle plumes probably initiates the crustal thinning and rifting of continental plates. Then new divergent boundaries can propagate from here, like the Great Rift Valley of East Africa.

The classroom rock density experiment shows that regional metamorphism of oceanic crust in subducting tectonic plates causes its density to increase from 2.9 g/cm³ (basalt and gabbro, positive buoyancy) to 3.1 g/cm³ (blueschist) and then to 3.4 g/cm³ (eclogite, negative buoyancy), compared to the asthenosphere (peridotite) with a density of 3.2–3.3 g/cm³. The high density of eclogite together with the relatively cooler, denser peridotite in the rigid upper mantle causes the oceanic lithosphere to have negative buoyancy compared to the asthenosphere, so that it sinks into the mantle and pulls the tectonic plate along behind it. This is a convincing driving mechanism for slab pull supported by a classroom experiment.

Water plays a vital role in plate tectonics. It is incorporated into the basalt and gabbro of the oceanic crust at the mid-ocean ridges due to the deep circulation of seawater driven by the high heat flow. This produces minerals that contain water in their structure as hydroxyl ions (e.g., chlorite, epidote, actinolite and serpentine). The dehydration during metamorphism of basalt, gabbro and blueschist to eclogite at 80–140km depth causes melting in the overlying upper mantle and explosive volcanoes in volcanic arcs that are parallel to the ocean trench plate boundaries. The water-rich magma also has a direct role in forming hydrothermal metal deposits in volcanic arcs, particularly porphyry copper–gold–molybdenum deposits. The vital role of water on Earth also suggests that plate tectonics can only operate on planets in the Goldilocks Zone of a planetary system where water can exist in the liquid phase.

High school students should be taught the wonders of plate tectonics based on the current understanding of its driving mechanisms and the roles of water and buoyancy. Then they can develop an internally consistent, interconnected and far more accurate understanding of plate tectonics, rather than continuing to learn based on a model that was superseded over twenty-five years ago. This is far more likely to engage and fascinate them, as well as lead them on to university-level earth science studies. The key is having the right classroom teaching tools — Google Earth with earthquake, plate boundary and volcano data enabled; a rock collection that includes peridotite, blueschist and eclogite samples, and updated textbooks. Updates to the Australian Curriculum Science Understanding content descriptions relating to plate tectonics for Year 9 earth and space science and EES Unit 2: "Earth processes — energy transfers and transformations", are also recommended.

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