

Volcanoes, molten magma, ... and a nice cup of tea!

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ABSTRACT Throughout Earth's turbulent geological history, volcanoes have relentlessly erupted vast quantities of molten rock onto the Earth's surface. Of the 1500 or so 'active' volcanoes around the world today, about 60 erupt each year and there are around 20 currently in eruption at any one time. But with its upper 2900 km essentially solid, how does the Earth produce so much molten rock, where does it all come from and why are volcanoes confined to certain well-defined zones?

The Earth's mantle is *not* liquid

The evidence from seismic data, in particular the velocity of shear waves through the Earth (S-waves which are not transmitted through liquids), demonstrates that the Earth has the elastic properties of a solid (Figure 1) except for the outer core where the physical state of the material changes from a solid to liquid. This is a result of changes in temperature, pressure and the composition at depth. So there is no evidence of a continuous liquid layer below the sub-surface

that provides volcanoes with molten rock, despite the ways in which some school textbooks (even in science) portray the mantle. This misunderstanding probably arises from confusion between the zoning of the Earth based on its chemical properties (for example, into crust and mantle) and the zoning of the Earth based on its mechanical properties (for example, lithosphere and asthenosphere), as shown in Figure 1.

Figure 1 shows that there is a zone within the upper mantle where the velocity of seismic

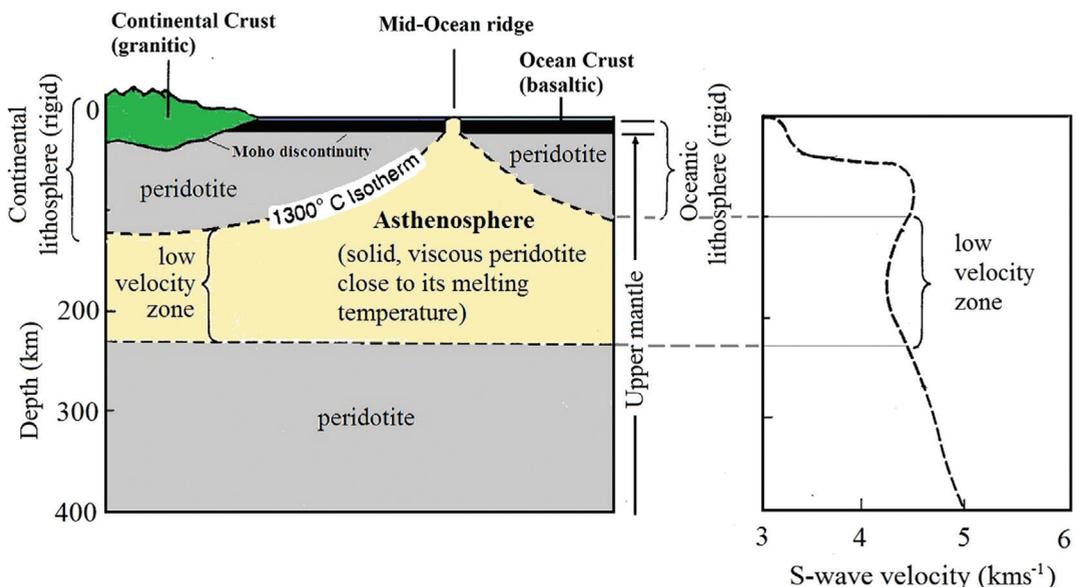


Figure 1 The variation in S-wave velocity through the upper mantle, showing that it is solid

waves slows down – the ‘low-velocity zone’ – which indicates that mantle rock (peridotite) is weaker in this area and so is capable of flowing like a viscous fluid, while still remaining in a solid state. This zone, the asthenosphere, is therefore weaker than the overlying more rigid part of the upper mantle and crust, which together make up the lithosphere (commonly broken up into tectonic plates). The weakness of the asthenosphere does not depend on the presence of molten rock, thus, while remaining entirely solid, it is a zone of relatively low strength compared with the overlying colder lithosphere and it flows (plastically) like a viscous fluid. Flow in the asthenosphere enables the more rigid lithospheric plate above to move.

Two main factors determine when and where the mantle will melt: temperature and pressure. Figure 2 shows that the temperature of the Earth (the geotherm) increases with depth and pressure. The graph also shows how the melting curve for the peridotite which forms the mantle changes with increases in temperature and pressure. As solids approach their melting temperature they ‘weaken’. The zone where the geotherm comes close to the melting curve for mantle rock marks the extent of the asthenosphere. The boundary between the asthenosphere and lithosphere is generally accepted to be where the mantle

is close to 1300 °C, but the loss of strength is gradual and the boundary is not sharp. The base of the asthenosphere occurs where the pressure and temperature result in the melting curve temperature becoming significantly greater than the geotherm so the mantle rock gains strength and flows less easily (chemical changes within the mantle may also be important).

Melting? – only *partial*

The concept of melting is also something that needs further explanation. As rock is a heterogeneous mixture of various minerals, there is no single melting point for the rock as a whole. Rather, as the temperatures and pressures rise, rock will begin to partially melt when individual minerals exceed their melting temperatures.

Experiments have shown that when rock partially melts the minerals with the lowest melting temperatures do so first along the edges of the crystals, and that all the pockets of melt produced are linked, much like a sponge. With the enormous pressures involved, and the plastic nature of the remaining rock at depth, the solid crystals are squeezed into the pockets of liquid melt which is forced to flow out, much like squeezing a sponge dry. This liquid flows outwards and collects into spherical regions of around a kilometre in diameter. These absorb melt from the

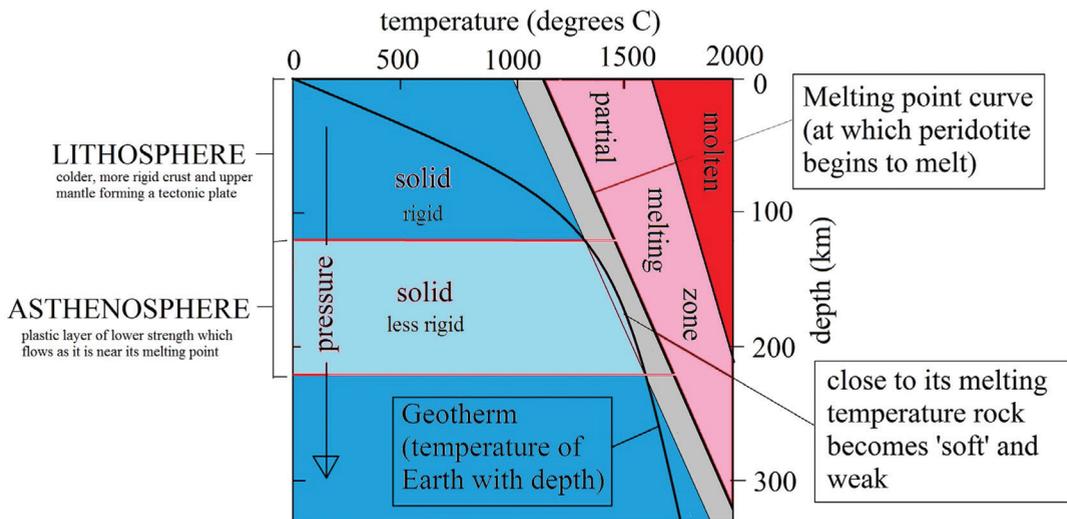


Figure 2 A phase diagram showing how the mechanical strength of the upper mantle is related to the temperature of the Earth (geotherm) and the melting point curve for mantle rock (peridotite) to form the lithosphere and asthenosphere

surrounding zone and can rise quickly towards the surface in waves. In this way the mantle source rock remains almost completely solid while still producing the liquid. Partial melting at depth is thus the key to producing the magma that will eventually be erupted as lava onto the surface.

Classroom simulations

Using phase diagrams (Figure 3), related to simple laboratory analogies, students can be made aware that partial melting of the mantle will begin when the Earth's temperature (geotherm) exceeds the melting point temperature for mantle rock.

Simulating the 'normal' situation

In a 'normal' situation, the mantle will not begin to melt, since the geotherm is below the temperature required to start melting peridotite (Box 1).

BOX 1 No volcanism – Figure 3A

This might be simulated with a beaker of near-boiling water to show that, whilst hot, the water does not have sufficient energy to boil under the atmospheric pressure of the classroom. Boiling is analogous to melting in these simulations.

It is only where these 'normal' conditions change – mainly at plate boundaries (Figure 4) – that partial melting will occur, which is why volcanoes are confined to specific zones. These clearly depend on changes either to the geotherm or to the local melting temperature of the mantle.

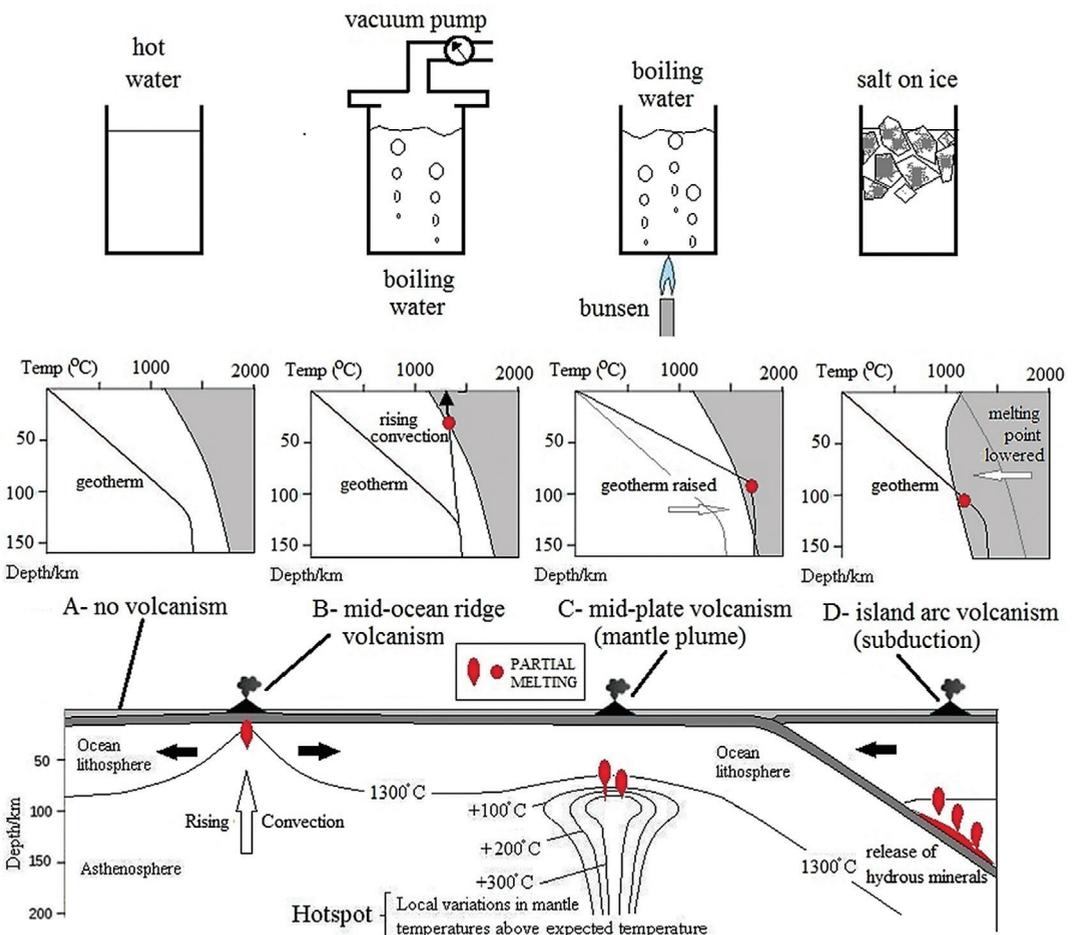


Figure 3 Plate model showing different conditions for partial melting and classroom simulations

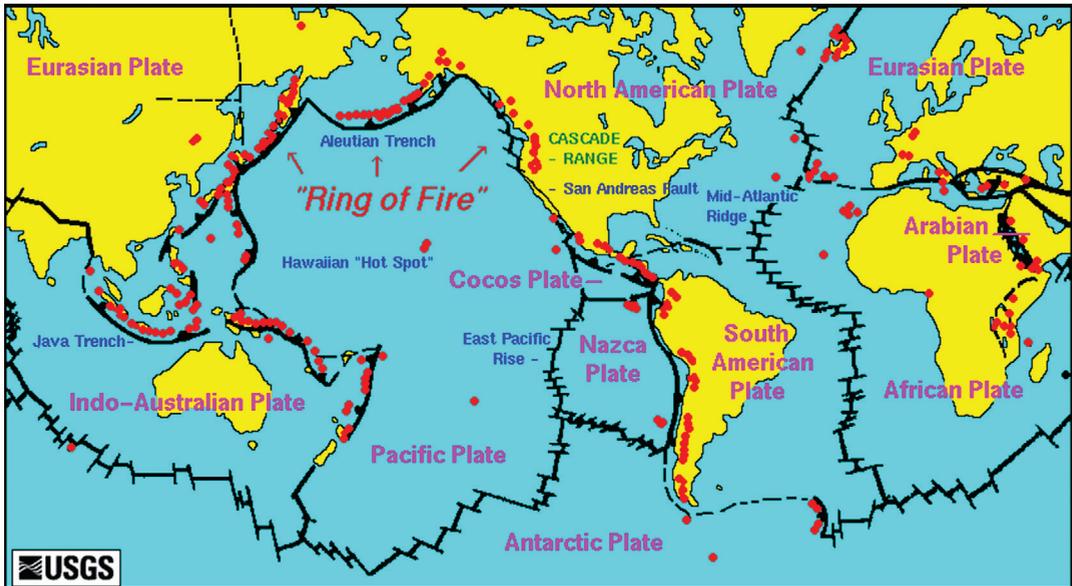


Figure 4 Active volcanoes, plate tectonics and the 'Ring of Fire'; image from USGS/Cascades Volcano Observatory

Simulating 'hot spot' melting

If the geotherm is locally raised and exceeds the melting point of mantle peridotite, this will induce the onset of melting. This situation occurs at 'hot spots', often linked to a mantle plume, where abnormally higher local temperatures result from the uprising of hot rock believed to be from the mantle-core boundary. Although their origin is the subject of debate, mantle plumes do provide an explanation for mid-plate volcanic activity in places such as Hawaii that are far from plate boundaries (Box 2 and Figure 4).

BOX 2 Mid-plate volcanism – Figure 3C

The hot water in simulation A can be made to boil by simply heating the water above its current temperature with a Bunsen burner. Figure 3C represents this situation, where the geotherm locally exceeds the melting temperature of mantle peridotite above a 'hot spot'. Here the pressure is not significantly changed and melting is mainly a function of the rise in temperature.

Simulating subduction zone melting

At a convergent (destructive) plate boundary, two adjoining plates are colliding, as in the case of the Aleutian Island Arc where the Pacific plate is in collision with the North American plate under

which it subducts. Partial melting is achieved by the release of water from hydrous minerals that have been drawn down the subduction zone and this locally lowers the melting temperature of the overlying mantle wedge (Box 3). The melting temperature curve here locally drops below the geotherm by the addition of water that induces partial melting.

BOX 3 Island arc volcanism – Figure 3D

This is more difficult to simulate in the classroom but students get the idea if they are directed to the effect of salt on ice to bring about melting by lowering the melting temperature.

Simulating mid-ocean ridge melting

At a divergent (constructive) plate boundary, such as in Iceland where the North American and Eurasian plates are moving apart, partial melting results from a very different process: rapid decompression of the mantle (decompression melting). Since most of us live at or near sea level, it is easy for us to think that melting is only achieved by the addition of heat. Students are usually unaware that melting (or boiling) can also be induced by reduction of the pressure of a system. The reduced atmospheric pressure at the summit of Mount Everest means that water boils

at around 65°C rather than the 100°C required to make a ‘nice cup of tea’ at sea level; an additional problem for an intrepid climber!

Beneath divergent boundaries, characterised in the ocean by a mid-ocean ridge, the mantle flows towards the surface in its solid state, leading to a reduction in pressure and rapid decompression. This can be represented in more detail on a phase diagram (Figure 5). At X, the mantle is solid (that is, below the melting temperature for mantle peridotite). As mantle rock rises rapidly (at about 2 cm per year), it generally retains its heat because rock is a poor conductor. The graph shows that on its ascent the mantle crosses from the solid into the partial melting area of the graph as a result of decompression. This can be simulated as described in Box 4. Magma formed in this way rises and collects below the crust, and some of it can be extruded onto the surface during an eruption at a mid-ocean ridge volcano.

Summary

Volcanoes are fascinating features of our planet and represent a physical manifestation of how the Earth works. Although they are widely studied across the curriculum, their origins are often poorly interpreted and, judging from the references made in some textbooks, these misunderstandings are easily perpetuated.

BOX 4 Mid-ocean ridge volcanism – Figure 3B

To simulate decompression melting, a small hand-held vacuum pump (e.g. a Minivac pump) normally used for bleeding car brakes can be very effective (Figure 6). By filling the container with the hot water used in simulation A and reducing the pressure (shown on the gauge), the water can be seen to boil below its normal atmospheric pressure boiling temperature (100°C), thereby simulating the effect of rapid pressure reduction on partial melting in the mantle. This simulation works very well, although anyone with access to a school physics laboratory may be able to use a larger pump and pressure container to make water satisfactorily boil at only 45°C. Alternatively, releasing the top from a fizzy drink container (shaken beforehand to ensure that a lot of carbon dioxide is dissolved) reduces the pressure, allowing the carbon dioxide to ‘boil’ out. While this is easier to demonstrate than the above, it can lead to confusion with the release of volcanic gases during eruptions; a purpose for which this simulation is better suited.

There is no ubiquitous liquid layer within the mantle acting as a source for the lava erupted on the surface and local magma chambers beneath

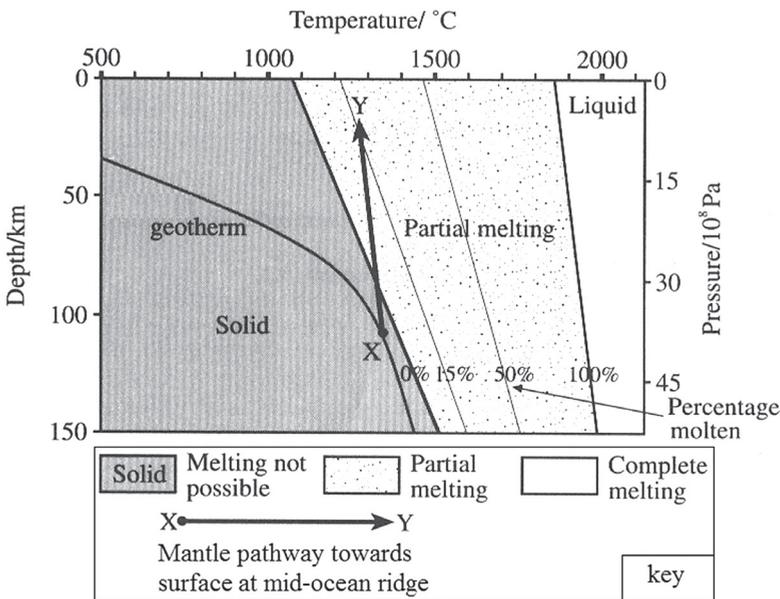


Figure 5 Phase diagram demonstrating how partial melting of the mantle is associated with rapid decompression beneath a mid-ocean ridge



Figure 6 Using a vacuum pump to demonstrate water boiling below 100 °C under reduced pressure

volcanic regions are seldom more than a few kilometres in diameter. The asthenosphere is a zone where the mantle is close to its melting point and behaves as a viscous fluid capable of flowing in its solid state. The strong rigid layer above the asthenosphere, composed of solid upper mantle and crustal rock, is called the lithosphere. This is divided on the surface of the planet into a number of tectonic plates that move independently of one another. Magma is generated when the mantle locally starts to partially melt. Partial melting is initiated by different processes in different tectonic environments, and these can be simulated in the classroom.

Further reading

GEOTREX – Partial Melting Tutorial (*PowerPoint presentation*): www.esta-uk.net.
 Jerram, D. (2011) *Introducing Volcanology: A Guide to Hot Rocks*. Dunedin: Academic Press.

Loader, P. (2012) Simulating partial melting in the classroom. *Teaching Earth Sciences*, 37(1), 52–53.
 The Geological Society – Plate Tectonics (an online resource currently in preparation): www.geolsoc.org.uk.

Pete Loader has been Geology Master at St Bede's College, Manchester, for 38 years, where he has also taught physics and geography. His 17 years' experience as chief examiner of WJEC A-level Geology has involved him in assessment, specification development and CPD for teachers. He is Chair designate of the Earth Science Teachers' Association and currently involved in the production of a new online teaching resource on plate tectonics for The Geological Society. Email: peteloader@yahoo.co.uk