Large Igneous Provinces: Origin and Environmental Consequences

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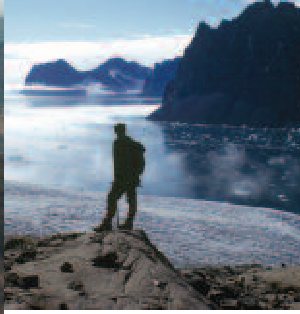

Thousand-metre basalt cliffs, Kivioqs Fjord, East Greenland. PHOTO IAN PARSONS

Episodically, the Earth erupts large quantities of basaltic magma in geologically short periods of time. This results in the formation of large igneous provinces, which include continental flood basalt provinces, volcanic rifted margins, and giant oceanic plateaus. These fluctuations in the Earth's system are still poorly understood. Do they owe their origin to mantle plumes, meteorite impacts, or lithosphere-controlled processes? Whatever their origin they correlate closely with major changes in oceanic and atmospheric chemistry and may trigger global mass extinctions.

KEYWORDS: Continental flood basalts, oceanic plateaus, mass extinctions, mantle convection and temperature

INTRODUCTION

It has been nearly 15 years since the term 'large igneous province' was introduced by Mike Coffin and Olaf Eldholm (1991, 1994). An umbrella term to include continental flood basalt provinces, oceanic plateaus, volcanic rifted margins and aseismic ridges, it rapidly entered common parlance even though it was, and remains, loosely defined. The key aspect of large igneous provinces (LIPs) is that they represent anomalously high magmatic fluxes. The magma is usually basaltic, but may be rhyolitic. They are large in area, covering many thousands if not millions of square kilometres, and they testify to unusual geological processes, involving large amounts of thermal energy. Where this energy comes from – deep within the Earth as a mantle plume, from a meteorite impact, or from sinking of dense roots from the base of the continental crust or lithosphere ('delamination') – is a matter of considerable debate. As will be seen from the papers in this issue of *Elements*, there is also debate about their environmental effects. Could the formation of such provinces cause the collapse of ecosystems, either by interrupting oceanic circulation systems or by releasing large masses of volcanic aerosols, and trigger mass extinctions? Certainly, the timing of LIPs and mass extinctions suggests some causality, but we do not, as yet, understand its nature.

LIPS AND LIPS

No two LIPs are the same. Just as Read (1948) recognised that there are 'Granites and Granites,' the term LIPs encompasses a wide range of geological structures and processes. For the purpose of this issue, we are focusing on the continental flood basalt provinces and their oceanic equivalents, the oceanic plateaus. Volcanic trails (forming aseismic ridges across the ocean floor), which often lead away from the main LIP, are an important part of the story, but will not be considered in detail here.

The locations and ages of the main LIPs are shown in FIGURE 1. This selection is biased: it does not include the large silicic provinces (e.g. Chon Aike in southernmost South America or the Sierra Madre in Mexico); the majority of the LIPs in Figure 1 are predominantly basaltic. It is also ageist: it does not include any LIP older than 250 Ma, for example, the Emeishan Province in China (Permian) and the numerous Proterozoic and Archaean LIPs. It is important to stress that LIP formation has occurred throughout Earth history and not just in the Mesozoic and Cenozoic, although they may occur in cycles (e.g. Ernst et al. 2005); there is an increase in LIP formation in the Cretaceous (Larson 1991), and Prokoph et al. (2004) have suggested cycles of LIP formation.

The information database is also strongly skewed in favour of the continental flood basalt provinces. Accessibility to the deeper parts of the dissected and faulted volcanic pile means that a greater range of compositions and a wider range of ages can be sampled in the continental sequences than in the oceanic plateaus. Some oceanic plateaus have, however, subsequently collided with a volcanic arc or a continental margin, with the result that important information can be obtained from the deeper crustal sections. Thus, the collision of the Caribbean Plateau with South America has provided a wealth of information about its petrogenesis (Kerr et al. 1997). Similarly, the collision of the Ontong Java Plateau with the Solomon Islands allows us to walk through the top three kilometres of the plateau's basaltic crust. Otherwise we would be totally reliant on cored material from the top few hundred metres of crust – metaphorically, pin-pricking the elephant (Tejada et al. 2004). The basements of many other plateaus are, however, sampled entirely by drilling and dredging (e.g. Kerguelen Plateau) or remain unsampled.

FORMATION

There are almost as many theories and models for the formation of LIPs as there are individual provinces. I have attempted to summarise these models, and some of the predictions that arise, in TABLE 1. It is likely that no single model can account for all LIPs, and the predictions from each model are not fully understood or known. Most models agree that large amounts of thermal energy are required in order to produce large volumes of magma over a geologically short period of time. Given that most LIPs are

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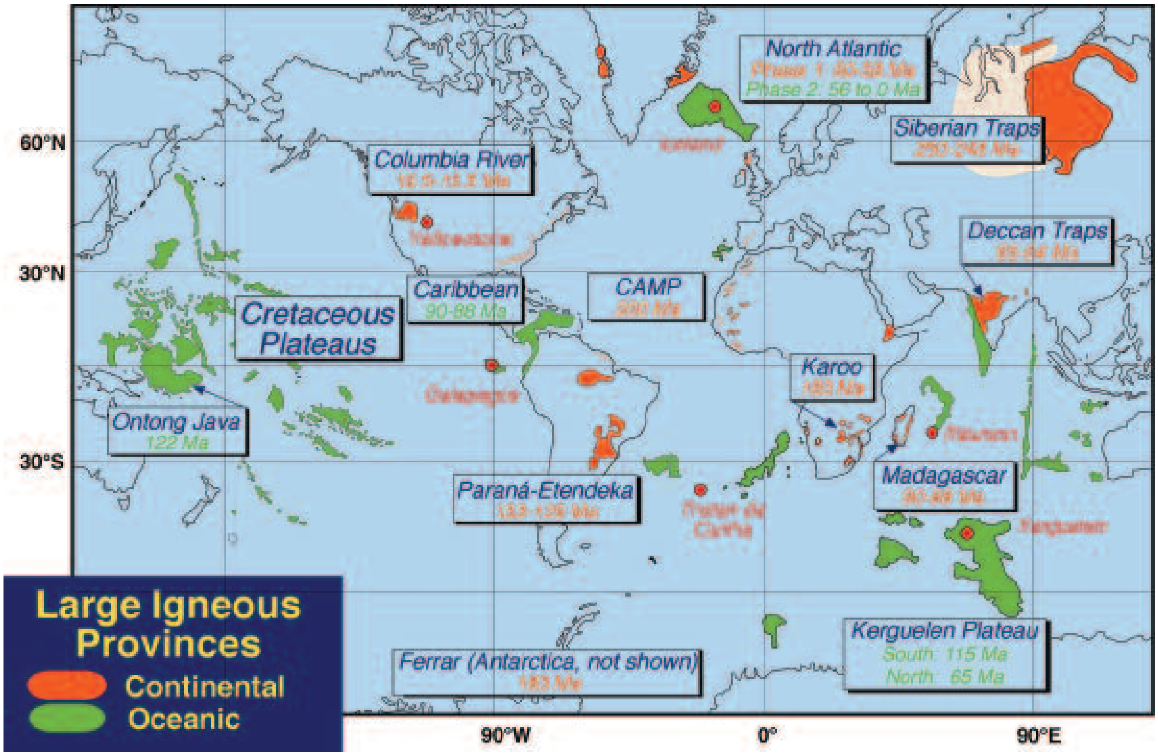

FIGURE 1 Map showing the distribution of the main Mesozoic and Cenozoic large igneous provinces (continental flood basalts and basaltic oceanic plateaus), modified after Coffin and Eldholm (1991). Also included are present-day hotspots (red spots), which may be related to individual LIPs (e.g. Réunion to the Deccan Traps; Galapagos to the Caribbean Plateau) via plate reconstructions and volcanic chains. The Siberian Traps are shown buried (striped ornamentation) beneath the West Siberian Basin. CAMP: Central Atlantic Magmatic Province, located along the eastern edge of North and South America, and western edge of North Africa and southern Europe. Cretaceous Plateaus include the Hess and Shatsky Rises, and Ontong Java and Manihiki Plateaus.

basaltic, this requires some form of energy source in the mantle. The required energy may be reduced slightly if the mantle source is highly fertile (see glossary). This would be the case if, for example, it contains large amounts of eclogite (see glossary and Anderson this issue) or is volatile rich.

What is the source of this energy? And how much is required? Over time, the world's oceanic ridge system supplies a remarkably constant amount of basaltic magma. The thickness of the ocean crust – ignoring the sediments – is very uniform, at about seven kilometres. There are differences. Very slow-spreading ridges, such as the Southwest Indian Ridge, create anomalously thin crust, to the point where it may even be absent. Similarly, ocean crust near major transform faults may be thin. And, conversely, in some areas (remarkably rare), such as Iceland, the crust is anomalously thick (perhaps as much as 35 km). But the bulk of the ocean crust is broadly uniform in thickness and composition, which is remarkable given that two important variables – source temperature and source composition – can have a dramatic effect on the volume and type of basalt produced. An increase of 100°C in the potential temperature (see glossary) of the mantle source will more than double the amount of melt produced, and hence double the thickness of the ocean crust. The source temperature of normal mid-ocean ridge basalts is unlikely, therefore, to vary significantly.

So how do we generate the high crustal thicknesses found in LIPs (typically 35 km for an oceanic plateau)? There are several ways of doing this. First, we can increase the temperature of the source. A straightforward increase in source potential temperature from 1300°C to 1500°C can produce a 30+ km thick layer of melt. This is at the heart of the plume model (White and McKenzie 1989; Campbell this issue), where heat energy is transferred in a mass of mantle ascending from a thermal boundary layer deep in the Earth (e.g. the core–mantle boundary). Second, we can increase the rate at which source material is processed through the zone of partial melting. Rather than passive upwelling (as is thought to occur at mid-ocean ridges), the mantle rock actively convects into and through the zone of partial melting. Combined with higher temperatures, this provides a potent model for large-volume melt generation, and is again implicit in the plume model. Rapid fluxing may be particularly important during the start-up phase of the mantle plume (Richards et al. 1989; Campbell this issue), when the LIP is created, but it is also a key feature of the 'edge' model, discussed below. The impact model (Jones this issue) also invokes high source temperatures, induced by kinetic energy following meteorite impact. And third, we can increase the fertility and volatile content of the source to create more melt. None of these three factors – temperature, mantle ascent rates, and source composition – are exclusive; indeed there is every reason to believe they may occur together.

What is the evidence for high mantle temperatures during LIP formation? The most direct evidence is the occurrence of highly magnesian melts (preserved in high-Mg basalts, picrites, and komatiites). These are found in several LIPs but, importantly, not all, and this has been used as evidence against an excessively hot mantle source (Anderson this issue). To counter this, it should be remembered that magnesian melts are more dense than normal basalt and may be trapped in magma chambers in the deep crust; in effect, they are filtered out. Thus, absence of evidence for picrites, the products of crystallization of magnesian melts, is not necessarily evidence for the absence of them.

TABLE 1

PREDICTIONS ARISING FROM VARIOUS MODELS OF LIP FORMATION

Prediction / Model	Excess mantle-derived magmatism	Regional uplift/doming	High-T magmas (e.g. picrites and komatiites)	Extraterrestrial material and impact breccias	Hotspot trail leading from LIP	Currently active hotspot
Mantle plume	Yes (unless the plume impinges on the base of thick lithosphere)	Likely (before and/or during magmatism)	Likely (but dense melts may not reach the surface)	No	Likely	Possible
Meteorite impact	Likely	Likely (during magmatism)	Yes (probably abundant)	Yes	Possible	Possible
Edge model, with enhanced mantle convection	Possible (if mantle can ascend sufficiently to decompress and melt)	Likely (during magmatism)	Unlikely	No	Unlikely	Unlikely
Delamination	Possible (if mantle can ascend sufficiently to decompress and melt)	Likely (could be substantial during or after magmatism	Unlikely	No	Unlikely	Unlikely
Melting of fertile mantle without excess heat	Possible	Unlikely	Unlikely	No	Unlikely	Unlikely

Arguments against very high mantle temperatures are supported by limited uplift in the vicinity of some LIPs. A hot mantle source beneath the lithosphere would be expected to cause significant uplift, especially if it were dynamically emplaced by a mantle plume (Campbell this issue), but in some provinces the evidence for such uplift is ambiguous (Anderson this issue). Readers may wish to read the recent work by Burov and Guillou-Frottier (2005), however, which suggests that the amount of uplift above a plume may be small, or absent, in some circumstances.

If mantle plumes or impacts are not the main generators, what other mechanisms may be responsible for LIP formation? King and Anderson (1995) noted that many continental flood basalt provinces lie close to the edges of Archaean cratons. They proposed that thermal insulation by the craton raises the temperature of the underlying asthenosphere, which then flows sideways out from beneath the craton and under thinner lithosphere. As it ascends, the mantle decompresses and melts. In this model the mantle need not be as hot as in the plume model. Furthermore, King and Anderson (1998) argued that 'edge-driven convection', where a secondary convection cell is established at the craton margin, could increase magma production rates and volumes. An alternative model, but also involving displacement of upper mantle, is the delamination model, in which dense lower crust and the attached lithospheric mantle sink into the mantle, and upper mantle flows into the ensuing space, decompressing and melting (Elkins-Tanton 2005; Anderson this issue). This model predicts substantial uplift as the lithosphere rebounds, but again does not necessarily produce high-Mg melts. It is also debatable whether the required volumes of magma, and magma of the right composition, could be produced in this way from normal-temperature asthenospheric mantle.

My personal view is that most, if not all, LIPs can be explained by mantle plumes, and that the best evidence – picritic rocks – for the high source temperatures is often hidden in the deeper crust or upper mantle. Variations in source composition doubtless play a role in the composition and amounts of liquid that are generated, but at the heart of the model is a mechanism for the release of thermal energy originating from deep within the Earth. The lithosphere plays a crucial role, capping (even preventing) melting and redirecting the hot mantle towards thin spots. Some LIPs may be entirely driven by lithospheric processes, and some may be impact generated, but the majority of them appear to be plume generated.

ENVIRONMENTAL EFFECTS AND MASS EXTINCTIONS

There are several ways in which a LIP could affect the global environment. One is through the immediate, eruptive release of gas and aerosols. As shown by Self et al. (this issue), a large basaltic lava eruption can release prodigious quantities of SO_2, CO_2 and halogens, the effects of which we are only beginning to appreciate. The initial release of SO_2 and its injection into the stratosphere could trigger a global volcanic winter, akin to the models of nuclear winters, reducing photosynthesis through light occlusion and cooling. Long-term accumulation of CO_2 may lead to subsequent warming – a volcanic summer – especially if the biologically driven carbon-capture mechanisms are compromised by the preceding volcanic winter. However, as pointed out by several workers, including Self et al. (this issue) and Wignall (this issue), the average flux of CO_2 released by a LIP over its entire history is not large – much less than the current annual production of anthropogenic CO_2, for example.

The evidence that there is a link between LIPs and the environment is indicated by the close coincidence between LIPs and mass extinctions (FIG. 2), as noted by Vincent Courtillot in 1994 and subsequently developed in his book *Evolutionary Catastrophes* (1999). But how does a LIP, or flood basalt event, trigger a mass extinction? What other indicators are there of climate change? One is a rapid shift in the carbon isotope record at the time of the extinctions. Such isotopic variations indicate massive changes in seawater and atmospheric composition, requiring the addition of billions of tonnes of carbon to the atmosphere and ocean reservoirs. This carbon, it is argued, as CO_2 in the atmosphere, leads ultimately to powerful global warming, loss of habitat, and mass extinction (Kiehl and Shields 2005). But

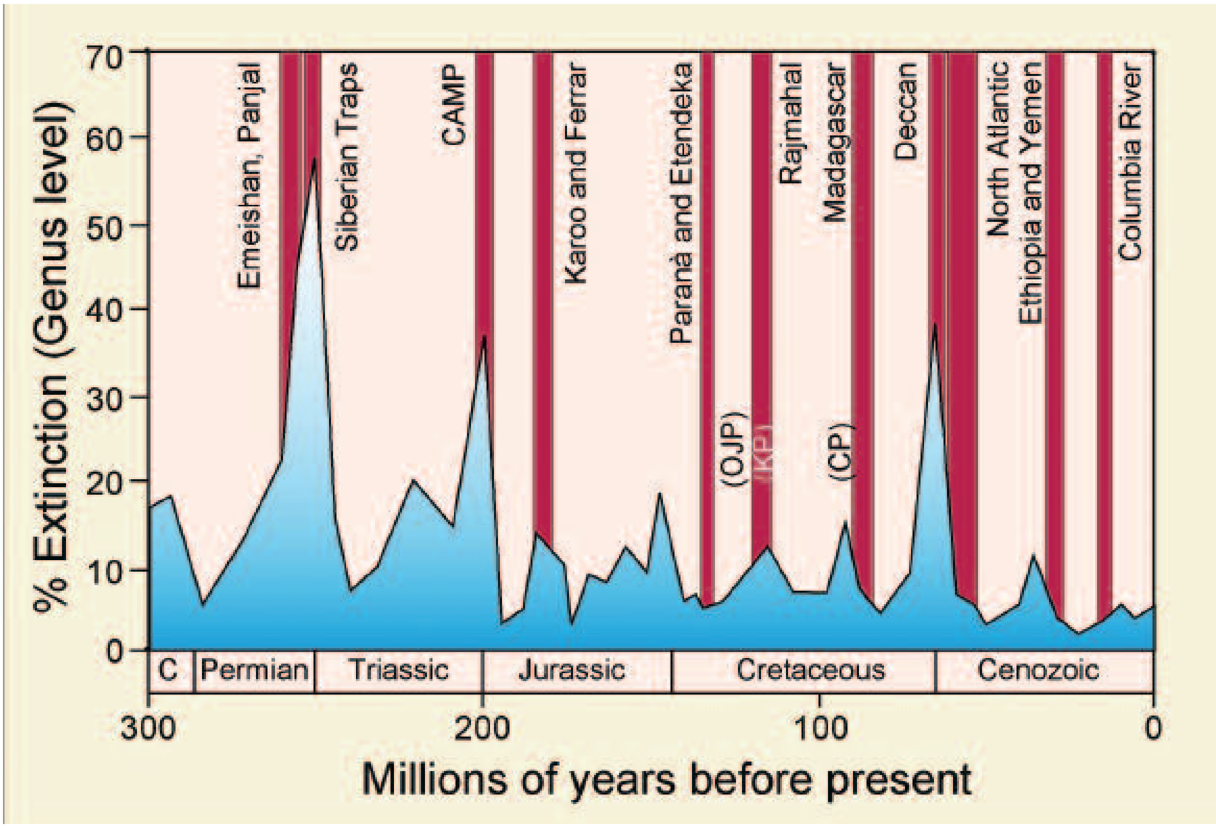

FIGURE 2 Extinction rate versus time (continuous line, blue field) (multiple-interval marine genera, modified from Sepkoski 1996) compared with eruption ages of continental flood basalts (red bands). Three of the largest mass extinctions, the Permo-Triassic, Triassic–Jurassic and the Cretaceous–Tertiary, correspond to eruptions of the Siberian Traps, the Central Atlantic Magmatic Province (CAMP), and the Deccan Traps, respectively. Three oceanic plateaus, the Caribbean (CP), Kerguelen (KP), and Ontong Java (OJP), are shown. Modified after White and Saunders (2005).

where does this carbon come from? Some undoubtedly comes from the basalts themselves but, given the low average rates of CO_2 production, this is unlikely to be the entire story. An alternative, mentioned by both Wignall and Kerr in this issue, is that the greenhouse effects of CO_2 from the LIPs slowly raise the atmospheric and oceanic temperatures, and this triggers release of methane previously trapped in permafrost and methane hydrates on the seafloor. In effect, a threshold is reached, potentially leading to a runaway greenhouse. (Intriguingly, it has recently been reported that Siberian permafrost is melting due to anthropogenically driven global warming; perhaps the flood basalts offer a model for current climate change.) An alternative explanation is that near-surface intrusions that accompany LIP formation are injected into carbon-rich sedimentary layers (methane- or coal-bearing) and that these then release their carbon into the ocean and atmosphere (Svensen et al. 2004; McElwain et al. 2005).

The key to understanding these processes is knowing the duration and flux rates of LIP magmatism, because from these we can calculate the flux rates of the climate-modifying gases and aerosols. $^{40}Ar/^{39}Ar$ and zircon U/Pb dating offer increasingly precise methods for improving this knowledge, but even a precision of better than 0.1% still leaves a lot to be desired. Mass extinction events may occur in periods of 100,000 years or less, which is still outside the precision offered by the best radiometric techniques for dating events that occurred during the mass extinctions at the Permo-Triassic, Triassic–Jurassic, and Cretaceous–Tertiary boundaries.

FURTHER READING

The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) has established the LIPs Subcommision, which maintains a webpage with up-to-date information about studies on large igneous provinces. See http://www.largeigneousprovinces.org

For information on specific provinces, see Mahoney JJ, Coffin MF (1997) Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism. American Geophysical Union Monograph 100, 438 pp.

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Glossary

$\delta^{13}C$ – Carbon isotope values (and other stable isotopes such as oxygen and hydrogen) are expressed relative to a reference standard. The standard used for carbon is a Peedee Formation belemnite (PDB). The difference from the standard is expressed as the delta function, which may be positive (i.e. the carbon has a relatively higher abundance of heavy ^{13}C than the standard), the same, or negative (a higher proportion of light ^{12}C). Results are expressed in parts per thousand. A shift or spike in the seawater isotope curve indicates a geologically rapid change in the relative amounts of light and heavy carbon. Organic carbon, especially biogenic methane, has low $\delta^{13}C$ values; the $\delta^{13}C$ of marine carbonate is about zero.

Basalt – A basic igneous rock of volcanic origin with between 45 and 52 wt% SiO_2 and less than 5 wt% total alkalis. The mineralogy typically comprises clinopyroxene (augite) and plagioclase feldspar. Olivine, and an opaque mineral such as magnetite may also be present. The plutonic equivalent of basalt is **gabbro**.

Delamination – The collapse and peeling of large layers of dense material from the base of the lithosphere or crust. The delamination process allows the asthenosphere to ascend into the resulting space, triggering decompression melting and magmatism.

Eclogite – A high-pressure, high-density metamorphic rock composed mainly of garnet and clinopyroxene. It is the high-pressure equivalent of basalt or gabbro. Emplacement of basaltic magma into the lower crust may lead to the formation of dense eclogite, which may become buoyantly unstable and collapse into the underlying mantle (delamination). Subducted ocean crust is thought to convert to eclogite and be entrained in the mantle, eventually returning to the near-surface by convection processes.

Flow field – The total lava products of one effusive eruption, however long-lasting.

Mantle fertility – The relationship between mantle composition and its ability to produce melt. During partial melting, peridotite (the main mantle rock) can produce only so much melt before it exhausts its supply of 'basalt producing' elements, such as Ca and Al. The more of these elements present in the original rock, the more melt can be produced – it may be said to have an increased fertility. The presence of eclogite, which is chemically equivalent to basalt, substantially increases the fertility of the source. Note, however, that energy, in the form of latent heat of melting, is still required to generate melt. Increasing source fertility will not substantially increase the volume of melt unless that energy is also present.

Optical depth – A measure of how opaque a medium – such as air – is to the radiation passing through it. Solar radiation is partially scattered and absorbed by fine particles in the atmosphere, and so the amount of incident light is always greater than the amount of transmitted light. A completely transparent medium has an OD of zero. An OD of 1 results in ~40% of light reaching the ground.

Peridotite – An ultrabasic rock, with a mineralogy dominated by olivine and with variable amounts of clinopyroxene (e.g. diopside) and orthopyroxene (e.g. enstatite). Garnet or spinel may also be present. It is the predominant rock in the Earth's mantle. Peridotite comprising mostly olivine and orthopyroxene is termed **harzburgite**. Peridotite with olivine, orthopyroxene and clinopyroxene is termed **lherzolite**.

Picrite – A rock of volcanic origin with between 12 and 18 wt% MgO, less than 3 wt% total alkalis ($K_2O + Na_2O$), and an SiO_2 content between 30 and 52 wt%. Picrites are more magnesian – and more primitive – than basalts and may be indicative of a high-temperature parental magma.

Plume buoyancy flux – A measure of the strength of a plume, given by the difference in density between the plume mantle and the surrounding mantle, multiplied by the buoyancy-driven volume flux of the plume.

Potential temperature – Rising, convecting material (plastic mantle rock, or melt, or air) cools slightly by adiabatic decompression. This defines an adiabatic cooling line (or, conversely, a heating line if the material descends) – part of the Earth's geotherm. For rock, the adiabatic gradient is about 0.5°C km^{-1}. The theoretical intersection of this line with the Earth's surface is called the potential temperature. Thus, mantle with an actual temperature of 1400°C at 100 km depth will have a potential temperature of $1400 - (0.5 \times 100) = 1350$°C, assuming that the adiabatic gradient is linear. Potential temperature, or Tp, is a convenient shorthand to describe how hot the mantle is regardless of depth or, put another way, how much energy it contains. Unfortunately we can only approximate the actual Tp of the upper mantle. Some workers (e.g. Anderson this issue) argue that the normal upper mantle has a large temperature range, varying from place to place by ±100°C, whereas others argue that the normal mantle is much more restricted in temperature, with a Tp of about 1300°C, and with localised hotspots (plumes) where the Tp may exceed 1500°C.

Viscosity – The resistance to flow within a liquid (alternatively, a measure of the internal friction of a liquid, or dynamic viscosity). **Kinematic viscosity** is the dynamic viscosity of a liquid divided by its density.

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