VOLCANISM

Eruptions above mantle shear

Why broad fields of volcanism are found in the interior of tectonic plates is hard to explain. Spatial correlations between sheared mantle flow and volcanism suggest that differential motion between surface plates and the mantle generates upwelling and melt.

Scott D. King

Within every significant tectonic plate, volcanic activity has been recorded. These intraplate eruptions are typically less voluminous than the more prominent eruptions at plate boundaries or hotspots. And in contrast to hotspot or plate-boundary volcanism, volcanic activity within a tectonic plate usually spans a broad area, of hundreds to thousands of kilometres. Examples of this distinct type of volcanism include the seamounts that dot the western Pacific Ocean basin[1] and the volcanic fields of southwestern North America[2] and eastern Australia[3]. Writing in *Nature Geoscience*, Conrad and colleagues[4] test the hypothesis that upwelling flow in the mantle that is produced by a shear instability generates the melt responsible for this type of volcanic activity.

The theory of plate tectonics provides a framework for understanding most of the volcanic activity on Earth. The most voluminous eruptions occur at oceanic spreading ridges, where new sea floor is formed in a narrow zone of only a few kilometres in width, as plates are pulled apart and magma seeps in to fill the void. Here, more than three times as much molten rock is erupted as through all volcanoes on land combined. Volcanism also accompanies subduction zones, where one tectonic plate sinks beneath another. The zone of volcanic activity is somewhat broader here, extending to a few hundred kilometres from the ocean trench where the subduction occurs. Volcanic activity can also occur within plates, often far from plate boundaries, where a hotspot in the underlying mantle brings up magma from depth. Hotspot volcanism usually forms a narrow, linear chain of volcanic islands[5] that tracks the movement of the tectonic plate over the hotspot. However, none of these models explains the large volcanic fields found in the interior of many plates.

Conrad and colleagues[4] investigate the possibility that these broad regions of intraplate volcanism are caused by magma upwelling where the surface plates and the mantle move relative to each other. Such relative motion can produce variations in mantle flow at different depths beneath the plate. Where differences in mantle flow interact with variations in material strength or composition, this acts as an obstacle that can lead to rising flow and magma generation[6,7]. This mechanism of magma generation requires relative motion between the lithosphere and the mantle in combination with changes in material strength, either in the weaker mantle beneath the lithosphere or at the base of the lithosphere. In both cases, when the sheared flow encounters the obstacle, a component of the flow veers upwards, towards lower pressure (Fig. 1), and thus closer to temperature–pressure conditions that allow melting. If this mechanism is responsible for most intraplate volcanism, volcanic activity would be expected preferentially in regions where the plate and underlying mantle move at different speeds.

To assess the plausibility of this scenario, Conrad *et al.* use a numerical model of global mantle flow[8] to calculate the shear beneath plates, and correlate it with regions of recent volcanism. They identify regions of continental intraplate volcanism by querying a geochemical database for all known basaltic samples less than ten million years old that are more than 300 km away from a plate boundary and therefore indicative of recent intraplate volcanic activity. And to define the regions of broad intraplate volcanism in the ocean, they use a survey of seamounts less than ten million years old. With a high degree of statistical confidence, Conrad and colleagues find a strong correlation between regions of high shear and intraplate volcanism.

The mantle flow model used by Conrad and colleagues relies on three-dimensional seismic velocity anomalies in the mantle, imaged using a tomographic inversion. There are a number of somewhat uncertain steps involved in constructing flow models using this procedure, resulting in a degree of uncertainty in the results. Nevertheless, the resulting flows are in agreement with independent geophysical observations including gravitational potential, surface topography and plate velocities, providing some confidence in this approach. Furthermore, the large-scale patterns of seismic anomalies in the mantle have been robustly imaged by a number of different groups and the resulting mantle

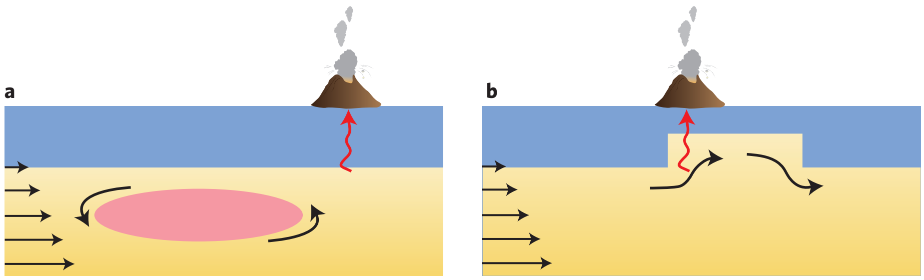

Figure 1 | Melting by shear. **a**, When the weak upper mantle (yellow) moves relative to the lithosphere (blue), and the sheared flow (black arrows) encounters an obstacle in the form of an anomaly in material strength or composition (pink), part of the flow is redirected upwards. **b**, Similarly, topography on the boundary between the strong plate (blue) and weaker upper mantle (yellow) can lead to rising flow into the weak cavity. In both cases, the rising parcel of mantle material moves into a lower-pressure environment, where it can melt and lead to volcanism (red arrow). Conrad and colleagues[4] show that regions of intraplate volcanism are strongly correlated with regions of sheared mantle flow, providing support that this mechanism explains volcanic activity within a tectonic plate. Cartoon adapted from http://www.mantleplumes.org/ShearDrivenUpwelling.html.

flow pattern does not seem to be strongly dependent on the seismic model or density scaling[9], suggesting that the tomographic inversions can be used to identify regions of sheared flow with reasonable confidence.

There are some regions of intraplate volcanism in Africa and Asia where the correlation fails. The volcanism in both regions has been previously explained by a mechanism termed edge-driven convection[10,11], where a horizontal temperature gradient resulting from a vertical material boundary such as a continental root drives small-scale convection. It is encouraging that there are alternative explanations for these two volcanic areas with low shear. Some recent volcanism in eastern Europe also occurs over a low-shear region. However, there may not be a specific explanation for each area where the correlation fails: shearing by itself is not sufficient to generate melt, it must be accompanied by variations in material strength or composition, or by some other physical process. All in all, the reported correlation between regions of inferred strong shear and intraplate volcanism is quite impressive.

As Conrad and colleagues discuss, shearing of the global flow beneath plates could result in magma melt through other physical mechanisms than the shear-induced upwelling that they favour. These include fracturing of the lithosphere where the mantle flow shears against its base or weakening of the lithosphere by shear-induced strain. Alternatively, more traditionally considered processes such as active upwelling of mantle material, for example in plumes or small-scale convection cells, can also result in large shear and hence melting.

Whether intraplate volcanism is the result of one of the processes discussed above or another, as yet unidentified mechanism, the findings presented by Conrad and colleagues[4] suggest that melting is nearly ubiquitous in the uppermost mantle. The small change in pressure experienced by a parcel of mantle displaced vertically only slightly by the shear instability mechanism can produce melt only if the shallow upper mantle is nearly at the solidus temperature everywhere. If this were not the case, the locations of melting would more than likely be correlated with warmer regions of the upper mantle rather than shear.

Conrad and colleagues[4] identify a correlation between volcanism and shear between the plate and mantle that provides an important step in understanding volcanism on Earth. ❐

Scott D. King is in the Department of Geosciences, 4044 Derring Hall (0420), Virginia Tech, Blacksburg, Virginia 24061, USA.
e-mail: sdk@vt.edu

References

1. Hillier, J. K. & Watts, A. B. *Geophys. Res. Lett.* **34,** L13304 (2007).
2. Smith, E. I., Keenan, D. L. & Plank, T. *GSA Today* **12,** 4–10 (2002).
3. Johnson, R. W. *Intraplate Volcanism in Eastern Australia and New Zealand* (Cambridge Univ. Press, 1989).
4. Conrad, C. P., Bianco, T. A., Smith, E. I. & Wessel, P. *Nature Geosci.* **4,** 317–321 (2011).
5. Morgan, W. J. *Nature* **230,** 42–43 (1971).
6. King, S. D. & Anderson, D. L. *Earth Planet. Sci. Lett.* **160,** 289–296 (1998).
7. Conrad, C. P., Wu, B., Smith, E. I., Bianco, T. A. & Tibbetts, A. *Phys. Earth Planet. Int.* **178,** 162–175 (2010).
8. Conrad, C. P. & Behn, M. D. *Geochem. Geophy. Geosy.* **11,** Q05W05 (2010).
9. Becker, T. W. & Boschi, L. *Geochem. Geophy. Geosy.* **3,** 1003 (2002).
10. King, S. D. & Ritsema, J. *Science* **290,** 1137–1140 (2000).
11. Zhu, R. X. & Zheng, T. Y. *Chinese Sci. Bull.* **54,** 3354–3366 (2009).

GEODYNAMICS

Mantle-controlled mountains

Mountain-forming systems on Earth occur at present either at the edge of continental plates or in their centre. Isotopic signatures from orogenic rocks worldwide indicate that these two distinct systems have existed for at least 550 million years.

Heinrich Bahlburg

Most of the prominent mountain chains on Earth fall into one of two classes. External mountain belts are located at the margins of continents: the ocean floor sinks into the mantle below the continent and causes uplift at the boundary. Internal mountain belts, by contrast, are now present within continental interiors where two continental plates have collided. These two distinct classes of mountain-forming, or orogenic, systems seem to have been significant features of Earth's crustal evolution for at least the past 550 million years (Myr)[1,2]. Writing in *Nature Geoscience*, Collins *et al.*[3] report that internal and external mountain chains each have a distinct and persistent hafnium isotope signature that allows reconstruction of the provenance of the subducted material over time, and may bear witness to the long-lived mantle convection that drives plate movement.

Both internal and external mountain chains ultimately result from the subduction of oceanic lithosphere. Because the lithosphere — the outer rigid shell of the Earth — is denser beneath the oceans, oceanic lithosphere tends to subduct under the more buoyant continents at convergent plate margins. In this process, some material is scraped off the down-going plate and accreted to the overriding continental plate. The overriding continental crust becomes marked with the geochemical signature of the oceanic lithosphere, which can be identified by its enrichment in the radiogenic isotopes of hafnium[4]. By contrast, the continental lithosphere has a lesser-to-unradiogenic hafnium isotope signature.

The external mountain belts found at present on Earth are located along the Pacific Ocean margins, predominantly oriented in a north–south direction (Fig. 1a). Spanning the margins of the Americas, Asia and Australasia, these external orogens are generated and persist through the continuous subduction of dense Pacific Ocean lithosphere that is constantly created at a far-off mid-ocean ridge; as a consequence of mid-ocean spreading, this new material moves away from the ridge, increases in density through cooling and can finally be subducted beneath a convergent plate margin.

At mountain belts in the interior of continents by contrast, the down-going plate is characterized by a string of fragments of oceanic and continental lithosphere. Initially, a section of dense