

GEODYNAMICS

Surface impact of mantle processes

Dynamic motions in Earth's mantle can be expressed at the surface. Rocks and landscapes beneath the North Atlantic Ocean record surface uplift driven by pulses of hot material upwelling in a mantle plume beneath Iceland.

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The Earth's tectonic make-up is unusual among the terrestrial planets of the Solar System. The martian surface is composed of a single rigid, static and unbroken carapace, whereas the interior of Venus is vigorously convecting beneath a thick viscous lid but the planet has no mobile plates. Earth, however, has a unique combination of a strong outer shell made of a number of discrete, moving plates and a convecting interior. Although plate tectonic motions and the interactions between plates are responsible for the main patterns in surface elevation of the Earth, deep processes can also influence surface topography. The convective circulation that drives upwellings and downwellings in Earth's mantle can cause the surface of the planet to rise up and subside. Writing in *Nature Geoscience*, Poore *et al.*¹ and Hartley *et al.*² demonstrate an intriguing connection between the ascent and lateral spreading of pulses of hot material in the Iceland mantle plume and patterns of uplift of the North Atlantic Ocean floor.

Flow in the mantle is principally driven by the descent of cold tectonic plates during subduction or by the ascent of plumes of hot material derived from deep within the Earth. The Earth's surface subsides above mantle downwellings and rises up above mantle upwellings to form dynamic topography. But linking mantle flow to surface topographic features is challenging. It is extremely difficult to identify and isolate mantle-induced dynamic topography because this requires the removal of topographic effects that do not originate from flow in the mantle, but are instead created by plate tectonic motions, including stretching, thickening or bending of the tectonic plates.

The Iceland mantle plume is upwelling beneath the North Atlantic Ocean at a plate boundary — the Mid-Atlantic Ridge. Prominent undulations in elevation of the sea bed on either side of the mid-ocean ridge close to Iceland are known as V-shaped ridges. The ridges are thought to result from variations in the activity of the Iceland plume, but their exact relationship with mantle convective circulation is uncertain.

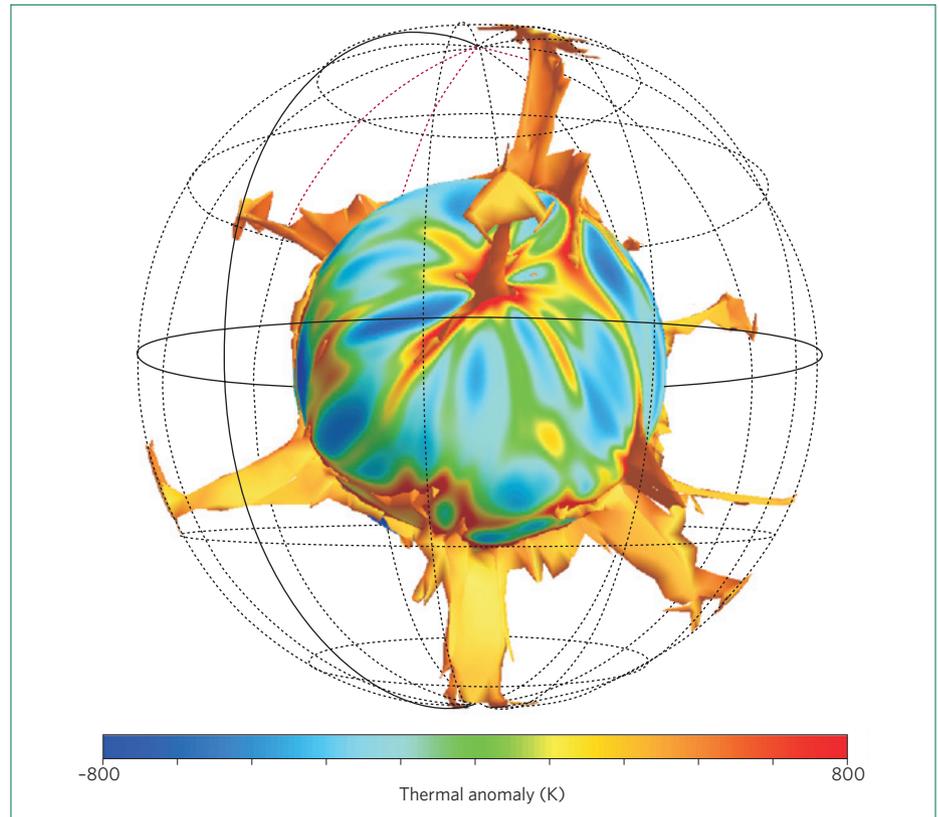


Figure 1 | Numerical model of mantle plumes rising from above the Earth's core-mantle boundary. Convective upwellings deep in the mantle can influence the topography at Earth's surface, causing an increase in surface elevation (warm colours indicate anomalously warm mantle temperatures). Poore *et al.*¹ demonstrate that pulses of hot mantle material rising up in the Iceland mantle plume caused the North Atlantic sea floor to rise up periodically, affecting deep ocean current circulation. Hartley *et al.*² image an ancient landscape that was created when hot material rising up in the Iceland plume caused the sea floor to be lifted above sea level about 56 million years ago. Figure adapted with permission from ref. 10, © 2008 Elsevier.

It remains unknown whether, for example, temperature or compositional changes in the mantle are responsible.

Poore *et al.*¹ report that the geochemical signature of the basaltic rocks that make up these V-shaped ridges indicate episodicity in the supply of hot material from deep below the surface. They suggest that wave-like pulses of unusually hot mantle rose up within the underlying Iceland plume, causing increased melting of the overlying

tectonic plate that led to voluminous basaltic eruptions and creation of the V-shaped ridges. The ridges formed directly above the Iceland mantle plume at times roughly coincident with changes in ocean circulation in the North Atlantic. Between Greenland and Iceland, episodic increases in the elevation of the sea bed caused the flow of deep, cold water into the North Atlantic to be occasionally restricted. Past studies have shown that mantle material rising up in the

Iceland plume could spread out radially beneath the tectonic plate in a low viscosity 'channel'^{3,4} causing an annulus of uplift to migrate across the sea bed over millions of years, like a ripple travelling away from a pebble thrown into a pond. Poore *et al.* therefore suggest that the pulses of hot mantle responsible for creating the V-shaped ridges may also have caused transient uplift of the sea bed between Iceland and Greenland.

In a related paper, Hartley *et al.*² invoke an identical mechanism to explain the formation of an exquisite ancient landscape about 55–57 million years ago. Located west of the Orkney–Shetland Islands, the landscape is today buried beneath about two kilometres of sedimentary rock on the ocean floor. They suggest that hot pulses in the Iceland mantle plume caused the overlying sea bed to become temporarily elevated above sea level. The surface was exposed, allowing rivers to erode and create channels, for about a million years before it subsided back below the ocean. The landscape was imaged in high resolution by harnessing information from seismic waves. The images clearly show the erosional river pattern that was etched into the rocks and frozen in geological time. By modelling the topographic profiles along individual rivers, Hartley *et al.* show that the landscape was lifted above sea level in a series of discrete steps of 200–400 m each.

Using river profiles to reconstruct the history of surface uplift driven by mantle flow is a challenging task⁵. Rivers strongly interact with each other in complex drainage networks that are sensitive to small changes in surface uplift and subsidence caused by tectonic processes unrelated to deep mantle processes. If these effects can be accounted for, consistent patterns in the magnitude and timing of uplift events in different river drainage networks may provide valuable estimates

of dynamic topography that are difficult to obtain from other methods.

Intriguingly, the timing of formation of the ancient landscape west of the Orkney–Shetland Islands coincides with a global climatic event known as the Palaeocene–Eocene Thermal Maximum⁶ — a period of rapid and extreme global warming. Triggers of this climatic event are unclear, but could be linked to the release of large quantities of methane stored in sediments on the sea bed. Uplift of the sea bed would have caused the methane stored in the ocean floor to become unstable, triggering its release into the atmosphere⁷. Pulses of hot mantle rising up in the Iceland mantle plume therefore provide a viable mechanism to elevate the sea floor at this time. Furthermore, about 33–34 million years ago, the climate suddenly cooled causing the planet to undergo a transition from a greenhouse to an icehouse world. This climatic change has been linked to periods when activity in the Iceland plume was suppressed, causing the sea bed between Iceland and Greenland to subside⁸. The low elevation enhanced the transport of cold ocean bottom water through a gateway from the Norwegian–Greenland Sea into the North Atlantic and may have helped cause planetary cooling.

The topographic features complicating the extraction of the dynamic topography signal are particularly strong at plate boundaries. In contrast, continental interiors provide promising locations to attempt the discrimination between mantle and plate tectonic forcing of topography. Early results are encouraging⁵, but the unmistakable case for the transmission of mantle flow heterogeneities to the surface topography of the continents is far from proved. The rewards are rich, for on the one hand topographic history could be used to inform us about time-dependent mantle flow. On

the other hand, mantle processes could help explain, for example, the much-debated long-term variation of global sea level⁹, and the flooding of the continents that has given rise to the vast, shallow continental seas at times in our geological history.

Poore *et al.*¹ and Hartley *et al.*² show that the geological narrative contained in geomorphological and stratigraphic records provides a powerful tool for the understanding of deep Earth processes taking place well beyond our direct vision. The same narrative brings life to the extraordinary pictures of inner Earth derived from geophysical imaging, helps to constrain numerical models of the dynamics of the spherical shells in which plumes form so spectacularly (Fig. 1)¹⁰, and raises the general prospect that the main stream of geological history, including that of the Earth's surface, has been shaped from very deep below our feet. □

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