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Earthly powers

Plate tectonics can't explain everything, so what else is shaping our planet's surface? Anil Ananthaswamy investigates

"A LOT of people thinks that the devil has come here. Some thinks that this is the beginning of the world coming to a end."

To George Heinrich Crist, who wrote this on 23 January 1812, the series of earthquakes that had just ripped through the Mississippi river valley were as inexplicable as they were deadly. Two centuries on and we are no closer to an understanding. According to our established theory of Earth's tectonic activity, the US Midwest is just not the sort of place such tremors should occur.

That's not the only thing we are struggling to explain. Submerged fossil landscapes off the west coast of Scotland, undersea volcanoes in the south Pacific, the bulging dome of land that is the interior of southern Africa: all over the world we see features that plate tectonics alone is hard pressed to describe.

So what can? If a new body of research is to be believed, the full answer lies far deeper in our planet. If so, it could shake up geology as fundamentally as the acceptance of plate tectonics did half a century ago.

The central idea of plate tectonics is that Earth's uppermost layers – a band of rock between 60 and 250 kilometres thick known as the lithosphere – is divided into a mosaic of rigid pieces that float and move atop the viscous mantle immediately beneath. The theory surfaced in 1912, when German geophysicist Alfred Wegener argued on the basis of fossil distributions that today's continents formed from a single supercontinent, which came to be called Pangaea, that broke up and began drifting apart 200 million years ago.

Wegener lacked a mechanism to make his plates move, and the idea was at first ridiculed.

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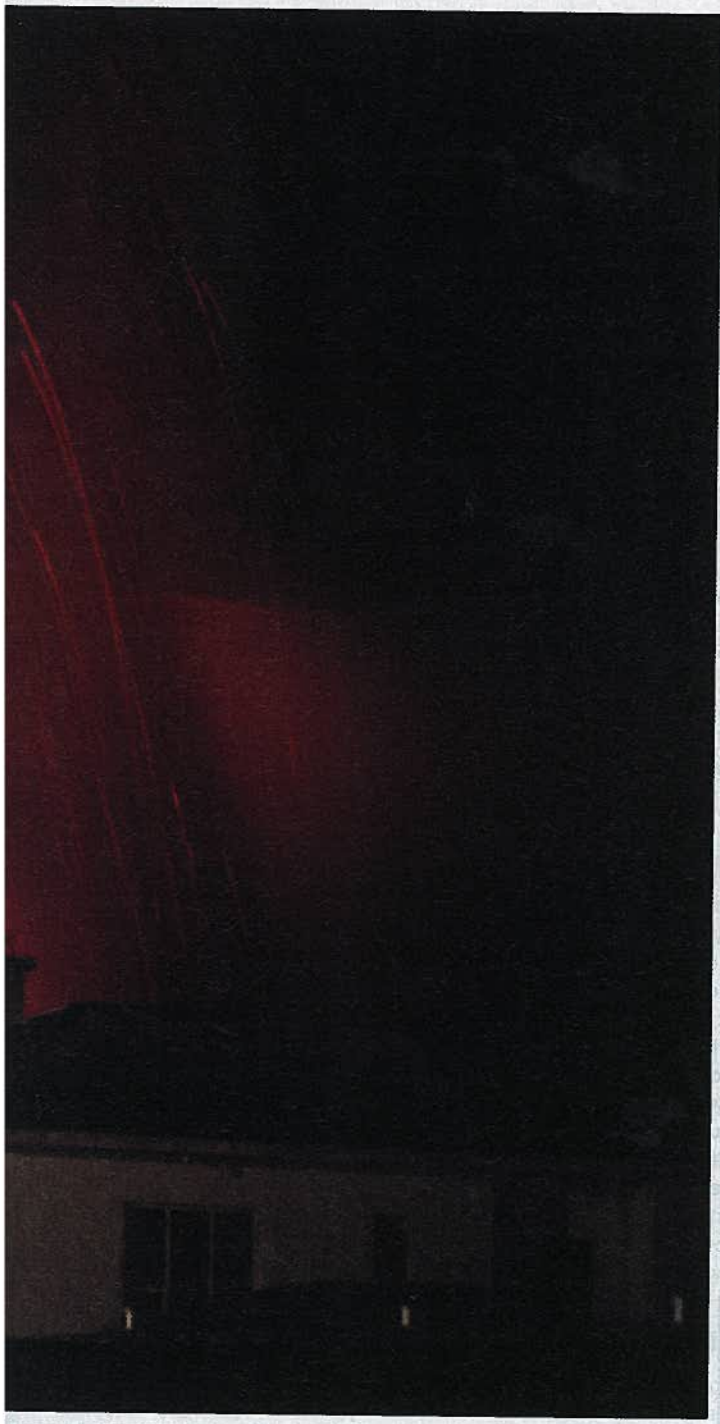


Iceland's volcanoes may be the product of rising plumes in the mantle

But evidence slowly mounted that Earth's surface was indeed in flux. In the 1960s people finally came to accept that plate tectonics could not only explain many features of Earth's topography, but also why most of the planet's seismic and volcanic activity is concentrated along particular strips of its surface: the boundaries between plates. At some of these margins plates move apart, creating rift valleys on land or ridges on ocean floors where hotter material wells up from the mantle, cools and forms new crust. Elsewhere, they press up against each other, forcing up mountain chains such as the Himalayas, or dive down beneath each other at seismically vicious subduction zones such as the Sunda trench, the site of the Sumatra-Andaman earthquake in December 2004.

And so plate tectonics became the new orthodoxy. But is it the whole truth? "Because it was so hugely successful as a theory, everybody became a bit obsessed with horizontal motions and took their eye off an interesting ball," says geologist Nicky White at the University of Cambridge.

That ball is what is happening deep within Earth, in regions far beyond the reach of standard plate-tectonic theory. The US geophysicist Jason Morgan was a pioneer of plate tectonics, but in the 1970s he was also one of the first to find fault with the theory's explanation for one particular surface feature, the volcanism of the Hawaiian islands. These islands lie thousands of kilometres away from the boundaries of the Pacific plate on which they sit. The plate-tectonic line is that their volcanism is caused by a weakness in the plate that allows hotter material to well up passively from the mantle. Reviving an earlier idea of the Canadian geophysicist John Tuzo Wilson, Morgan suggested instead that a plume of hot mantle material is actively pushing its way up from many thousands of kilometres below and breaking through to the surface.

Mapping the underworld

That went against the flow, and it wasn't until the mid-1980s that others began to think Morgan might have a point. The turnaround came when seismic waves unleashed by earthquakes began to reveal some of our underworld's structure as they travelled through Earth's interior. Seismic waves travel at different velocities through materials of different densities and temperatures. By timing their arrival at sensors positioned on the surface we could begin to construct a 3D view of what sort of material is where.

The resulting images are rough and fuzzy, but seem to reveal a complex, dynamic mantle. Most dramatically, successive measurements have exposed two massive piles of very hot, dense thermochemical material sitting at the bottom of the mantle near its boundary with Earth's molten core. One is under the southern Pacific Ocean, and one beneath Africa. Each is thousands of kilometres across, and above each a superplume of hotter material seems to be rising towards the surface.

That could explain why the ocean floor in the middle of the southern Pacific lies some 1000 metres above the surrounding undersea topography, another thing plate tectonics has difficulty explaining. Something similar goes for the African plume. "If you go south of the Congo all the way down to southern South Africa, including Madagascar, that whole region is propped up by this superplume," says White.

Seismic imaging reveals smaller plume-like features extending upwards in the upper reaches of the mantle beneath Iceland and Hawaii – perhaps explaining both these ›

"Although southern Africa is propped up by a superplume, smaller hot and cold areas at the top seem to correspond with surface topography. Africa has quite an egg-box shape"

islands' existence and their volcanism. Off the coast of Argentina, meanwhile, the sea floor plunges down almost a kilometre, directly above a mantle region that seismic imaging identifies to be cold and downwelling. And although southern Africa is being propped up by its superplume, smaller hot upwellings and cold downwellings at the top of that plume seem to correspond with local surface topography. The Congo basin, for instance, lies on a cold area and is hundreds of metres lower than its surroundings. "Africa has quite an egg-box shape," says White.

Almost everywhere we look, there is evidence of vertical movements within Earth reshaping its surface. "At the time plate tectonics was formed, the deep interior was unknown, so people drew cartoons," says Shun-ichiro Karato, a geophysicist at Yale University. "This is beyond cartoons."

What is less clear is how the mechanisms work. Standard plate-tectonic theory has it that material plunging into the mantle at subduction zones is recycled in the shallow mantle, reappearing through volcanic activity near the subduction zone itself or further afield at boundaries where two plates are being pushed apart. Blurry yet tantalising images, however, show sections of subducted plates at various stages of descent through Earth's interior towards the lower mantle (see diagram, right).

That material clearly can't all stay down. "You need to preserve the mass balance of the mantle," says Dietmar Müller of the University of Sydney, Australia. "As you are stuffing plates down into the mantle, that initiates a return flow of material going up."

But how exactly? Simulations performed last year by Bernhard Steinberger at the GFZ German Research Centre for Geosciences in Potsdam and his colleagues show how a subducted slab, once it arrives at the boundary between the mantle and the core, can bulldoze material along that layer. When this material meets a thermochemical pile, plumes begin to form above. "We can see plumes developing at more or less the right places," says Steinberger. For example, their model shows that slabs being subducted beneath the Aleutian Islands near Alaska could trigger a plume beneath Hawaii, creating a hotspot that fuels the Hawaiian volcanoes (*Geochemistry Geophysics Geosystems*, vol 13, p Q01W09).

Fossil landscape

Meanwhile, Clint Conrad at the University of Hawaii at Manoa and his colleagues have modelled the effect of a tectonic plate moving one way while the mantle beneath is moving in the other direction. They found that if this "shearing" effect occurs in a region where the mantle varies in density or the overlying plate changes in thickness, it can cause mantle material to melt and rise. This model accurately predicts that volcanic seamounts are present on the west but not the east of the East Pacific Rise, a mid-ocean ridge that runs roughly parallel to the western coast of South America. Seismic measurements indicate that the mantle and the plate to the west are moving in opposite directions; to the east they are not. The model also predicts that the shearing effect is largest under the western US, southern Europe, eastern Australia and Antarctica – all areas of volcanic activity away from plate boundaries.

RICHARD A COOKE III/STONE/GETTY

Hawaii's volcanoes pose a problem for traditional theories of plate tectonics

If the dynamics of the deep Earth can change surface topography today, the same must have been true in the past. But while fossil and geological records tell us how drifting plates remapped the planet's surface over eons, seismic imaging only works for the here and now. "It's more difficult to decipher the history of the Earth in deep time, over hundreds of millions of years," says Müller.

White and his colleagues found some clues to a small part of the story off the west coast of Scotland last year. They set off explosions from a ship and recorded the reflected waves, to get a sense of what lies beneath the sea floor. What they saw buried under more recent layers of rock and sediment were fossil landscapes some 55 million years old, replete with hills, valleys and networks of rivers. "They look just like somewhere you could go for an afternoon walk," says White – only they are 2 kilometres beneath the seabed (*Nature Geoscience*, vol 4, p 562).

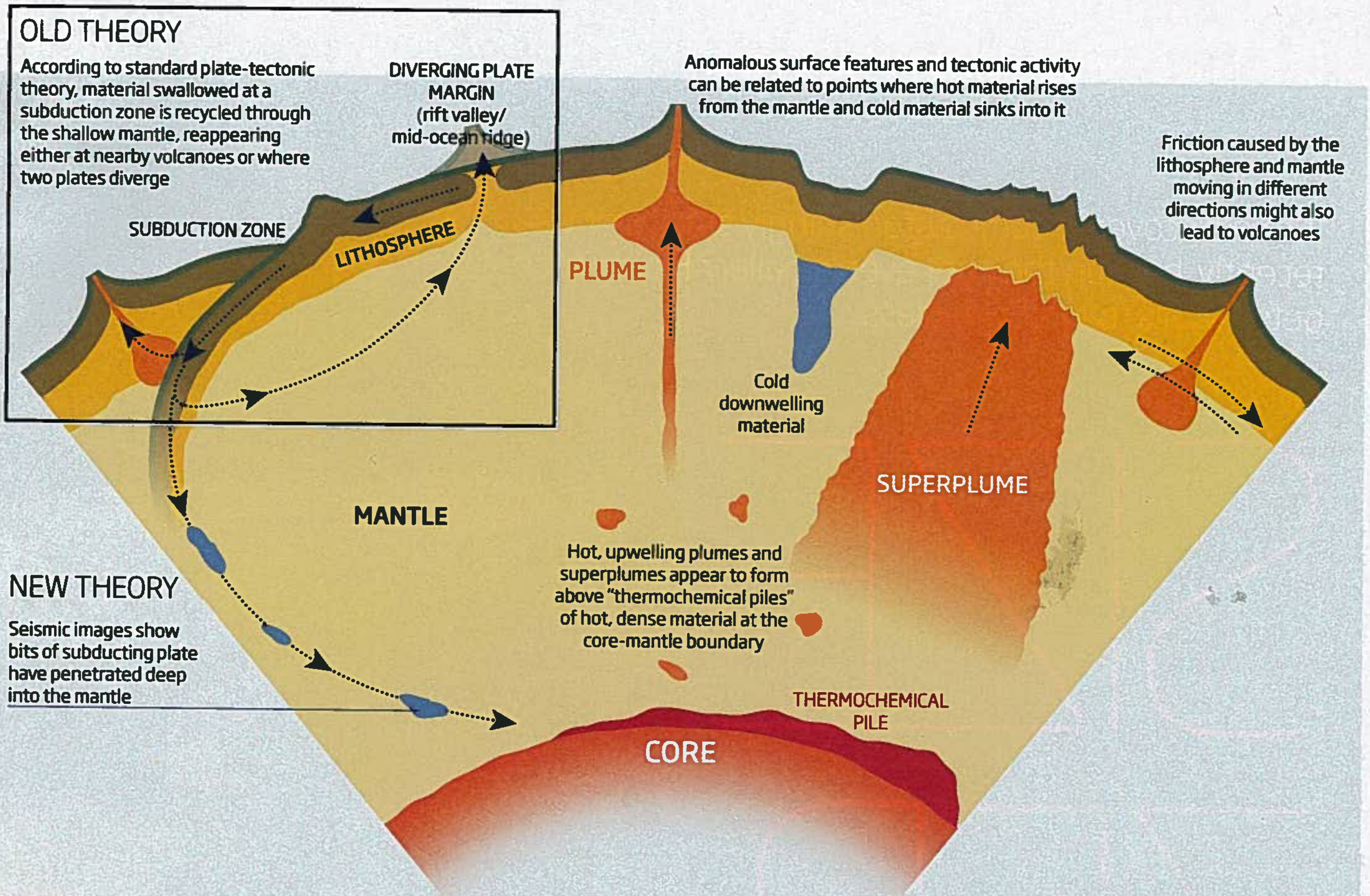
By analysing the way these rivers had changed course over time, the team showed that the region was once pushed almost a kilometre above sea level before being buried again, all in the space of a million years. That is far too quick for plate tectonics to throw up a mountain range and have erosion wear it down again. Instead, White points his finger at a blob of hot, mantle material that he says travelled radially outwards from the mantle plume that is possibly fuelling the volcanoes in nearby Iceland. "If the plate is like a carpet, rats running underneath the carpet would make it go up and down," he says.

Müller's team have identified similarly precipitous vertical movements of the land that is now in eastern Australia, during the Cretaceous period between 145 and 65 million years ago. Again, the timescales involved more or less discount simple plate tectonics. "We are pretty sure this has something to do with a convecting mantle," says Müller.

Even iconic events of Earth's tectonic past might not be all they seem. The Himalayas had formed by 35 million years ago, after the Indian plate separated from the supercontinent Gondwana, sped north and slammed into the Eurasian plate. That is still the broad picture, but plate tectonics fails to explain why India zoomed towards its target at speeds of up to 18 centimetres per year. Today, plates only reach speeds of about 8 centimetres per year, a limit set by how fast

Digging deep

Seismographic images suggest that the workings of the deep Earth have an important effect on surface features



subducting slabs can sink into the mantle.

Steven Cande and Dave Stegman of the Scripps Institution of Oceanography in La Jolla, California, think they have the answer. Last year they used computer models to argue controversially that the horizontal force exerted by the mushrooming head of the Reunion plume, thought to be the source of the massive outpouring of lava that formed the Deccan Traps in western India about 67 million years ago, sent India on its headlong path (*Nature*, vol 475, p 47).

The anomalous and periodically devastating seismicity of the US Midwest, meanwhile, might be explained by plate tectonics and the propagation of surface stresses (*New Scientist*, 14 January, p 34) – or the root causes might go deeper. In 2007, Alessandro Forte of the University of Quebec at Montreal, Canada, and his colleagues implicated the ancient Farallon plate, which started slipping into the mantle along the west coast of North America during the Cretaceous. Their model suggests that the plate has now burrowed deep enough to cause a downwelling below the mid-Mississippi river valley, deforming the overlying lithosphere sufficiently to trigger the disastrous events of two centuries ago (*Geophysical Research Letters*, vol 34, p L04308).

It all adds up to a picture where more than plate tectonics is at work in shaping our planet's past, present and future. "It's just amazing to think that Earth's surface is rather less stable than plate tectonics in its simplest form would have it," says White.

Iceland's anomalies

Not everyone is convinced. Gillian Foulger of the University of Durham, UK, argues that the region around Iceland, for example, is no hotter than the rest of the mid-Atlantic ridge, a diverging plate margin on which the island also sits. Iceland's topography and volcanic activity can be adequately explained by the tectonic activity at such a plate boundary without invoking a plume-driven hotspot (*Science*, vol 300, p 921). She and fellow "aplumatics" also point out that, while seismic waves do travel slower in the shallow mantle beneath Iceland, Hawaii and other supposed hotspots, these velocity anomalies don't extend all the way down to the bottom of the mantle where according to the theories that have been advanced the plumes supposedly begin their journey. "That's never been seen, not one single time, in a reliable way," she says.

Enthusiasts for a deeper explanation of Earth's surface activity think it is only a matter of time and better seismic imaging before these objections are also countered. Efforts to improve imaging are already under way in the form of Earthscope, an ongoing project to blanket the US with seismographs, giving geologists a fine-grained look at the mantle underneath (*New Scientist*, 11 April 2009, p 26). What is needed, however, are similar projects to understand crucial regions of the mantle such as those below Africa and the Pacific Ocean. "If you can design a grand whole-Earth experiment, where you have seismometers scattered evenly all over Earth's surface, at sea and on land, you can do a brilliant job in making better sharp tomographic images," says White.

If we can do that, will history repeat itself, the doubters be won over, and another hotly disputed model become the new orthodoxy? Müller certainly thinks so: "Geology is on the cusp of another revolution like plate tectonics." ■

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