speeds along the axis of the helix. To understand this point, imagine that the bacterium's trajectory follows the helical shape of a spring. Pulling on the spring increases its length and decreases its radius, which means that the bacterium travels farther along the stretched spring than it does along the relaxed spring in the same amount of time.

But why do these cells swim on straighter trajectories when they are embedded in complex fluids? Kamdar and colleagues' experiments ruled out the polymer-induced elastic stresses suggested previously, because the team also observed the phenomenon when the fluids contained colloids rather than polymers. The authors showed instead that the trajectories were straighter because of a hydrodynamic phenomenon known as boundary-induced torque, which is experienced by particles in a fluid when they move close to a solid boundary. It results from the difference in drag between the sections of the particle closer and farther away from the wall.

In the case of bacteria moving through a complex fluid, each particle in the suspension – whether it's a polymer or a colloid – acts like a solid surface, inducing a torque on the moving bacteria. This torque bends the flagellar hooks, reducing the misalignment between the flagellar bundle and the cell body. The result is straighter, faster swimming. Together with their experiments, Kamdar and colleagues' mathematical model improves our understanding of bacterial wobbling, which had so far been overlooked despite the fact that it held the key to interpreting decades of observations of bacteria in complex fluids.

Nonetheless, the authors' findings need to be tested further in different experiments. An intriguing direction of study would be to investigate bacterial wobbling as a function of the hook length, which could be achieved by using genetically engineered mutants[7]. Changing the hook length modifies its resistance to bending, which should directly affect the magnitude of the speed increase. Beyond bacterial motion, Kamdar and co-workers' results could contribute to the design of versatile, self-propelled microrobots whose translational speed could be modulated by changing the angle between the propulsion machinery (synthetic flagella) and the body axis.

Raphaël Jeanneret is in the Laboratoire de Physique de l'Ecole Normale Supérieure, Université PSL, CNRS, Sorbonne Université, Université de Paris, F-75005 Paris, France. **Marco Polin** is at the Mediterranean Institute for Advanced Studies (UIB-CSIC), 07190 Esporles, Spain, and in the Department of Physics, University of Warwick, Coventry, UK.
e-mails: raphael.jeanneret@phys.ens.fr; mpolin@imedea.uib-csic.es

1. Kamdar, S. *et al. Nature* **603**, 819–823 (2022).
2. Verdugo, P. *et al. Mar. Chem.* **92**, 67–85 (2004).
3. Shoesmith, J. G. *J. Gen. Microbiol.* **22**, 528–585 (1960).
4. Schneider, W. R. & Doetsch, R. N. *J. Bacteriol.* **117**, 696–701 (1974).
5. Qu, Z. & Breuer, K. S. *Phys. Rev. Fluids* **5**, 073103 (2020).
6. Patteson, A. E., Gopinath, A., Goulian, M. & Arratia, P. E. *Sci. Rep.* **5**, 15761 (2015).
7. Spöring, I. *et al. PLoS Biol.* **16**, e2006989 (2018).

The authors declare no competing interests.

Earth science

Mobile mantle could explain volcanic hotspots

Allen K. McNamara

Ancient records of Earth's magnetic field seem to contradict a conceptual picture of how regions of volcanic activity form. Statistical modelling now reconciles these data with our understanding of mantle fluid dynamics. **See p.846**

The speed of seismic waves can reveal the temperature of structures under Earth's surface, with faster waves indicating cooler temperatures and slower waves, warmer ones. Unusually low wave speeds have been measured[1] beneath the African continent and the Pacific Ocean, and these regions are known as large low-shear-velocity provinces (LLSVPs). Palaeomagnetic data provide an ancient record of Earth's magnetic field, and have been interpreted as evidence that the LLSVPs have remained fixed in their current positions for several hundred million years[2,3]. But this conclusion is at odds with our understanding of how mantle convects[4]. On page 846, Flament and colleagues[5] report simulations showing that palaeomagnetic data cannot distinguish between fixed and mobile LLSVPs – a finding that reconciles these observations with mantle fluid dynamics.

"As a tectonic plate moves over a hotspot, a chain of volcanoes is created, such as those on the Hawaiian Islands."

When tectonic plates collide, one plate sinks into the deep interior, forming a region known as a subduction zone. Perhaps unsurprisingly, the regions of Earth's mantle that experience higher-than-average seismic-wave speeds lie beneath these boundaries. The LLSVPs are found in the deepest parts of Earth's lower mantle, nested between these regions of sinking tectonic plates. Seismic data suggest that LLSVPs have well-defined, sharp boundaries, providing evidence that their composition might be distinct from that of the surrounding mantle[1].

The area above the LLSVPs hosts the majority of Earth's volcanic hotspots; these are localized regions of volcanic activity seemingly unrelated to plate tectonics. And many of these hotspots lie directly over the LLSVP boundaries[2,6–8] (Fig. 1a). Hawaii's Big Island is an example of an active hotspot. Compared with the speed of tectonic plates, hotspot locations are relatively slow-moving. As a tectonic plate moves over a hotspot, a chain of volcanoes is created, such as those on the Hawaiian Islands. The volcano directly above a hotspot is active, whereas the older volcanoes along the chain have become extinct, which means that they are considered unlikely to erupt again.

Hotspot lavas have a different trace-element chemistry from other lavas, such as those generated at divergent plate boundaries, where new plates are formed. This observation has led to the hypothesis that hotspots are caused by hot plumes rising from Earth's lower mantle, probably from regions of the deep mantle that have a different, perhaps more primitive chemistry compared with that of their surroundings[9]. The fact that the LLSVPs are compositionally distinct from their surroundings in the lowermost mantle has implicated them in this hypothesis: one popular conceptual model of Earth's interior has LLSVPs as the source of this anomalous hotspot chemistry, delivered to the surface by rising mantle plumes[10] (Fig. 1b).

It's straightforward to connect the location of active hotspots with the LLSVPs, but what do we know about extinct volcanoes caused by hotspots that existed in the geological past? This is where palaeomagnetism comes into play. Volcanic rocks typically contain a small amount of the iron oxide mineral magnetite, which has a magnetic field that aligns itself with Earth's magnetic field. After a

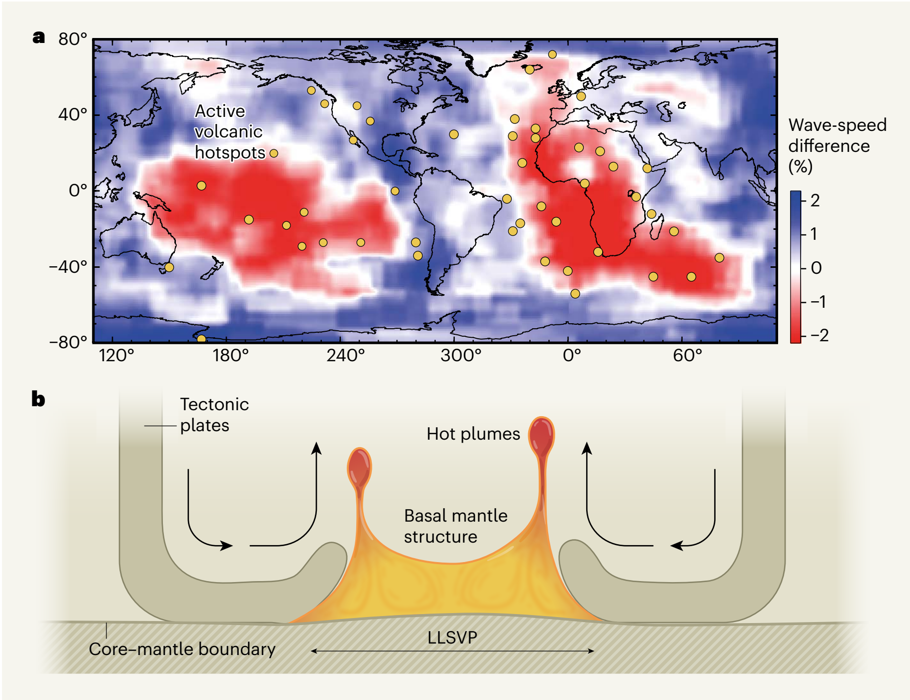

Figure 1 | Slow-moving regions in Earth's mantle coincide with volcanic activity. a, A map of seismic tomography shows how seismic-wave speeds differ from the global average. Higher-than-average speeds correspond to cool regions, where tectonic plates have sunk into Earth's mantle. Regions beneath Africa and the Pacific Ocean, known as large low-shear-velocity provinces (LLSVPs), are warmer mantle areas that have lower-than-average wave speeds. Most active volcanic hotspots on Earth's surface are located above the LLSVPs, and many of these are at the LLSVP boundaries. (Adapted from Fig. 1a of ref. 11.) **b**, Flament *et al.*[5] performed fluid-dynamics simulations that are consistent with a conceptual model for LLSVPs, in which mantle material that is chemically distinct from and denser than its surroundings is shaped into basal mantle structures, which are passively swept around in the lower mantle by sinking tectonic plates. Hot mantle plumes rise from the tops of the basal mantle structures to Earth's surface, where they appear as hotspots. Arrows represent mantle convection currents. (Adapted from Fig. 2d of ref. 11.)

lava solidifies to form rock, the crystallized magnetite retains the orientation of Earth's magnetic field as it cools – recording the direction to the magnetic north and south poles, as well as the field's vertical inclination.

The inclination provides a direct measurement of the latitude of past hotspots because of the dipolar nature of Earth's magnetic field. The hotspots' longitude is more difficult to ascertain, but it can be constrained by plate reconstructions and other geological information. Therefore, by measuring the magnetic properties of volcanic rocks at extinct hotspot volcanoes, we can determine the locations of those hotspots when they were actively erupting[2].

Palaeomagnetic studies have shown that the locations of numerous hotspots that were active over the past several hundred million years lie above the present-day LLSVP boundaries[2,3]. If hotspots are the result of plumes arising from LLSVPs, then this evidence could imply that the LLSVPs have remained fixed in their current positions over this long time frame.

But the possibility that LLSVPs are spatially fixed features in the mantle is inconsistent with numerical fluid-dynamics modelling of mantle convection, which predicts that LLSVPs are mobile structures that are easily swept around the lower mantle by the ever-changing positions of sinking tectonic plates[4]. In such models, LLSVPs cannot resist the forces exerted by shifting subduction zones sufficiently to be stationary. But if LLSVPs are relatively fixed and stable, then clearly we are missing something fundamental in our understanding of the properties of mantle convection.

Flament and colleagues performed extensive numerical experiments on the fluid dynamics of mantle convection to challenge the implication that ancient hotspots have remained fixed for the past several hundred million years, and thus that the hotspots' locations coincide with those of LLSVPs today. The team considered a range of parameters for the material properties of the mantle to mitigate uncertainty in their results. They also incorporated reconstructed histories of plate motion at the surface – some corresponding to up to one billion years – to help them understand where the tectonic plates had sunk into the mantle.

The modelling reveals a volume of material in the lower mantle that is intrinsically denser than its surroundings, and that is shaped by mantle convection currents – most notably, those arising from the sinking of tectonic plates. The denser structures are known as basal mantle structures, and Flament *et al.* assume that they are the cause of the LLSVPs. The reconstructed history of sinking plates suggests that mantle convection currents change over time, resulting in highly mobile basal mantle structures whose shapes also evolve with time. The authors calculated the probabilities associated with different positions of these structures during their numerical experiments, and compared these statistics with the location of each hotspot at the time of its eruption. A significant fraction of their calculations positioned these mobile basal mantle structures beneath the inferred past locations of active hotspots associated with now-extinct volcanoes.

These results show that palaeomagnetic data cannot distinguish between fixed and mobile LLSVPs. However, the findings do not prove that these compositionally distinct reservoirs are mobile; they simply provide a more feasible dynamical mechanism to explain the palaeomagnetic data. Furthermore, this conclusion relies on a conceptual model in which LLSVPs are reservoirs that are intrinsically denser than their surroundings and remain in the lowermost mantle. But seismic tomography results suggest that alternative conceptual models can exist, and several equally viable possibilities for the cause of LLSVPs are currently being debated in the geophysics community[1]. Nevertheless, Flament and colleagues' study is a breakthrough because it shows that our understanding of how mantle convects and constantly reshapes LLSVPs is consistent with the locations of past hotspots determined by palaeomagnetic data.

Allen K. McNamara is in the Department of Earth and Environmental Sciences, Michigan State University, East Lansing, Michigan 48824, USA.
e-mail: allenmc@msu.edu

1. McNamara, A. K. *Tectonophysics* **760**, 199–220 (2019).
2. Torsvik, T. H., Burke, K., Steinberger, B., Webb, S. J. & Ashwal, L. D. *Nature* **466**, 352–355 (2010).
3. Torsvik, T. H., Smethurst, M. A., Burke, K. & Steinberger, B. *Earth Planet. Sci. Lett.* **267**, 444–452 (2008).
4. Bower, D. J., Gurnis, M. & Seton, M. *Geochem. Geophys. Geosyst.* **14**, 44–63 (2013).
5. Flament, N., Bodur, Ö. F., Williams, S. E. & Merdith, A. S. *Nature* **603**, 846–851 (2022).
6. Thorne, M. S., Garnero, E. J. & Grand, S. P. *Phys. Earth Planet. Inter.* **146**, 47–63 (2004).
7. Burke, K. & Torsvik, T. H. *Earth Planet. Sci. Lett.* **227**, 531–538 (2004).
8. Burke, K., Steinberger, B., Torsvik, T. H. & Smethurst, M. A. *Earth Planet. Sci. Lett.* **265**, 49–60 (2008).
9. Hofmann, A. W. & White, W. M. *Earth Planet. Sci. Lett.* **57**, 421–436 (1982).
10. Tackley, P. J. *Science* **288**, 2002–2007 (2000).
11. Zhao, C., Garnero, E. J., McNamara, A. K., Schmerr, N. & Carlson, R. W. *Earth Planet. Sci. Lett.* **426**, 143–153 (2015).

The author declares no competing interests.