THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Tarduno, J.A., and A.A.P. Koppers. 2019. When hotspots move: The new view of mantle dynamics made possible by scientific ocean drilling. *Oceanography* 32(1):150–152, https://doi.org/10.5670/oceanog.2019.137.

DOI

https://doi.org/10.5670/oceanog.2019.137

PERMISSIONS

WHEN HOTSPOTS MOVE

The New View of Mantle Dynamics Made Possible by Scientific Ocean Drilling

By John A. Tarduno and Anthony A.P. Koppers

ABSTRACT. Hotspots tracks—chains of volcanic edifices arising from deep mantle upwellings—were once thought to solely record plate motion. Results of ocean drilling expeditions have led to a transformative change: it is now recognized that these tracks can also reflect the motion of hotspots in Earth's mantle. When hotspots move, their paths can provide insight into the nature of the mantle and the history of convection.

INTRODUCTION

Morgan (1972) surmised that hotspots (Wilson, 1963) were fixed in the deep mantle and hence were suitable as a frame of reference for the motion of tectonic plates. The Hawaiian-Emperor chain was central to this hypothesis. The great 60° bend in the track was the type example of a change in plate motion preserved by a hotspot chain. This simple model was so elegant and powerful that it became a mainstay of introductory textbooks for decades.

Paleomagnetism has inherent capabilities to record paleolatitude and thus can provide critical data to test the fixed hotspot hypothesis. If a hotspot has always been fixed, the volcanic edifices composing an age progressive chain should all record the same latitude, equaling the present-day hotspot location. Yet, to obtain suitable samples requires scientific ocean drilling because the critical volcanic edifices needed for the test have now subsided to great water depths.

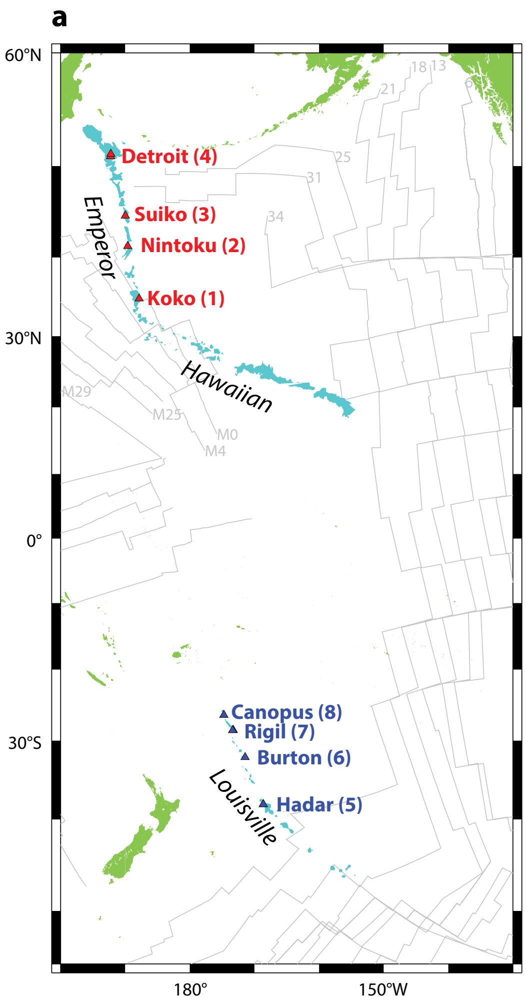
PALEOLATITUDE TESTING OF HAWAII HOTSPOT FIXITY

Ocean Drilling Program Leg 197 in 2001 was the first expedition solely devoted to a paleomagnetic test of hotspot fixity. Through the drilling of seamounts comprising the Emperor track, a trend of decreasing paleolatitude with age was observed (Tarduno et al., 2003). The data are most compatible with southward motion of the hotspot at a rate of ~44 mm yr^{-1} (Figure 1). The Leg 197 results did not just shatter the concept of hotspot fixity. They also suggested that most of the north-south morphology of the Emperor Seamounts was created by hotspot motion (Tarduno et al., 2009). If one subtracts this motion, the great Hawaiian-Emperor bend becomes a minor feature (Figure 2), similar to other wiggles in the chain at times of known plate motion change (Wright et al., 2016). However, based on scientific ocean drilling, we now understand that the bend represents a major change in mantle dynamics, from a rapidly to a more slowly moving hotspot. This realization motivated several additional questions. Had the Pacific hotspots moved as a group? Were local forces involved in driving Hawaiian hotspot motion?

TESTING INTER-HOTSPOT MOTION

Integrated Ocean Drilling Program Expedition 330 investigated the scale of motion in 2010/2011 by drilling the Louisville chain on the southern Pacific Plate. In contrast to the results from Leg 197, age and paleolatitude data showed limited latitudinal motion of the hotspot (Figure 1), establishing that the Hawaii and Louisville hotspots had moved independently (Koppers, et al., 2012). Because the common motion is minor between ~70 and 50 million years ago, these data support global analyses indicating that true polar wander, the rotation of the entire solid Earth, has also been minor (Tarduno, 2007). Moreover, the limited Louisville motion provided the opportunity for another test.

If the Hawaiian hotspot had moved rapidly in Earth's mantle, while Louisville's motion was more limited, we should see a pattern of decreasing distances between seamounts of the same age on the two hotspot tracks with time, because the Hawaiian hotspot moved south and closer to Louisville. Recent advances in radiometric age dating show exactly this pattern (Konrad et al., 2018). Interestingly,



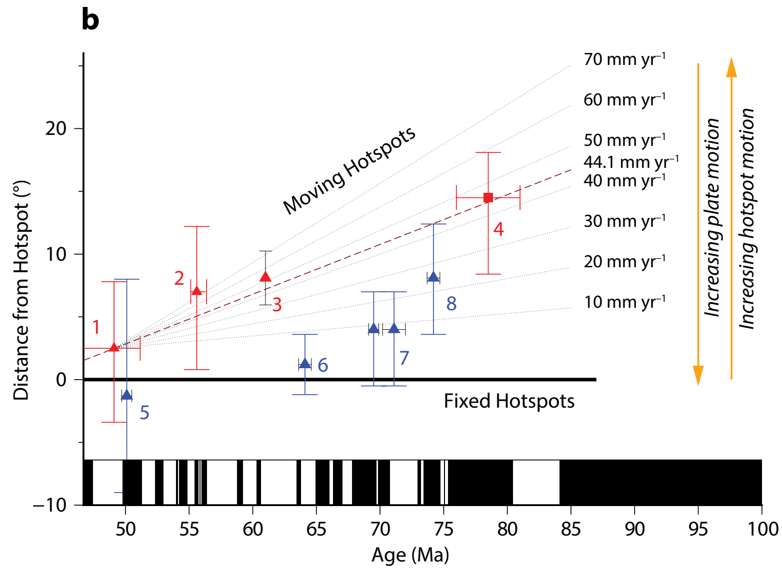


FIGURE 1. Ocean drilling tests of hotspot motion. (a) Hawaiian-Emperor and Louisville Chain seamount and guyot drill sites. (b) Difference between present-day hotspot latitude and paleolatitude determined from paleomagnetic analyses. Results for Hawaiian-Emperor Seamounts from Ocean Drilling Program Leg 197 together with data collected on samples recovered from drilling during Deep Sea Drilling Project Leg 55 and Ocean Drilling Program Leg 145 (in red; see Tarduno et al., 2003, and references therein). Results for Louisville Seamounts from Integrated Ocean Drilling Program Expedition 330 (in blue; Koppers et al., 2012). If hotspots were fixed, paleolatitudes should cluster around the 0° distance line (fixed hotspots). Instead, data indicate rapid movement of the Hawaiian hotspot and more limited motion of the Louisville hotspot.

these data suggest the prior estimate of motion may be conservative. The age-distance data suggest motion rates as high as 60 mm yr^{-1}. We note that this motion also provides a long-sought explanation for geochemical trends seen in the lavas from the Emperor and Hawaiian volcanic chains (Harrison et al., 2017).

GEODYNAMIC IMPLICATIONS

What could have driven this rapid Hawaiian hotspot motion and then led to its cessation? Two mechanisms, which are not mutually exclusive, are current contenders. One explanation invokes “top-down” control. Spreading ridges can migrate across ocean basins and are focused areas of mantle flow that can affect the upwelling pathways of mantle plumes that feed hotspots. Geochemical and paleolatitude data indicate that early in its history the Hawaiian hotspot was situated on a spreading center (Keller et al., 2000; Tarduno et al., 2003, 2009). That spreading waned with time and stopped near the time of the Hawaiian-Emperor bend. The spreading center upwelling could have captured the plume early in its history. As the ridge upwelling diminished, the plume conduit may have returned to a more vertical geometry, resulting in the hotspot motion pattern detected on the surface. Numerical simulations and experimental analogs suggest this is possible (Bunge et al, 1997; Tarduno et al., 2009).

The second explanation invokes a “bottom-up” control. For decades it has been clear that a broad region of deep mantle that is anomalously hot and/or dense underlies the Pacific basin (Tarduno et al., 2009; Garnero et al., 2016). Today, this is called the Pacific Large Low Shear Velocity Province (LLSVP). Could interaction of the Hawaiian plume with the Pacific LLSVP, including deformation of the edges of this province by subducting slabs, have caused the rapid hotspot motion and then a slowdown? Numerical models again suggest this is a viable option (Hassan et al., 2016) and again the geochemical trends support this interpretation (Harrison et al., 2017).

SUMMARY AND FUTURE OBJECTIVES

These new ideas on both top-down and bottom-up geodynamics could not have been possible without evidence collected by scientific ocean drilling. The new data have been transformative, allowing us to see beyond the limited view of fixed hotspots to the actual complexity of mantle convection. Hotspots can move, and when they do, they can move as fast as tectonic plates. Studies using

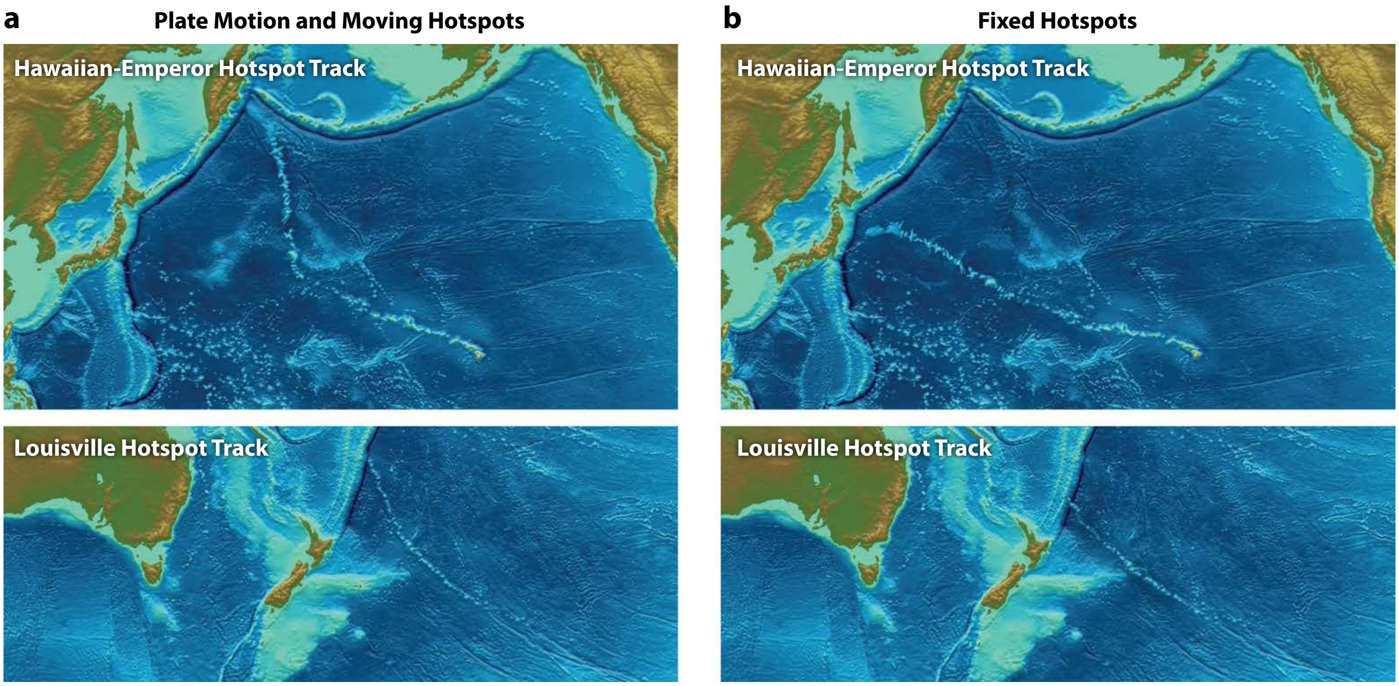


FIGURE 2. Moving versus fixed hotspot tracks. (a) Present-day Hawaiian-Emperor and Louisville hotspot tracks produced by plate motion and moving hotspots. (b) Hotspots tracks that would have been created had the hotspots remained fixed in Earth's mantle, compatible with ocean drilling paleomagnetic data (see Tarduno et al., 2003, and Koppers et al., 2012).

data collected by scientific ocean drilling remain the best means of reconstructing processes that have shaped the oceanic deep mantle over the last 200 million years. The next challenge will be to recover long sequences of lavas in order to construct high-resolution paleolatitude histories (Tarduno et al., 2003) for select sites in other global seamount chains, as well as for submarine volcanic plateaus. These samples are required to further increase the precision of paleolatitude constraints that will allow us to learn even more about Earth's deep interior and overriding lithospheric plates.

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ARTICLE CITATION

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