PLATE TECTONICS

Delayed response to mantle pull

At mid-ocean ridges, the directions in which plates spread and the underlying mantle flows were thought to broadly align. A synthesis of results from ridges that spread at a variety of rates reveals that instead there may be a systematic skew.

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The tectonic plates that floor the world's oceans spread apart along mid-ocean ridges. The ridges are broken into large segments by transform faults. Finer-scale ridge segmentation at all spreading rates is developed by non-transform, second-order offsets (Fig. 1). Given that the mantle beneath the oceanic plates was often assumed to flow passively in response to the plate movements, this finer ridge segmentation was thought to be caused by variations in magma supply[1,2]. However, seismic observations from the fast-spreading East Pacific Rise[3] and slow-spreading Mid-Atlantic Ridge[4] show that the mantle flows obliquely beneath parts of these ridges, implying that mantle flow may not be passive after all. Writing in *Nature Geoscience*, VanderBeek *et al.*[5] use a combination of these existing seismic data[3,4] and measurements from the intermediate-spreading Juan de Fuca Ridge in the Pacific Ocean, to propose that the mantle beneath all of the ridges flows at an oblique angle to the direction of plate spreading.

Seismic data can be used to probe large swaths of seabed and create models of seismic wave velocities in the topmost mantle. At mid-ocean ridges, variations in the velocity of seismic waves that are independent of the direction that waves travel are related to the thermal structure and the amount of partial melt or magma in the mantle. In contrast, variations in the seismic velocities that are dependent on the direction that waves travel constrain the direction of mantle flow.

VanderBeek and colleagues[5] use such seismic data to infer the directions of mantle flow beneath sections of slow-[4], intermediate-[5] and fast-spreading[3] ridges and compare these directions with the known plate-spreading directions. They find that the misalignment between the mantle flow and plate-spreading directions across mid-ocean ridges is the norm rather than the exception. Furthermore, the degree of skew between the two motions increases as the rate of plate spreading decreases. Additionally, the researchers note that recent ridge reorganizations at investigated sites indicate that the plate-spreading direction follows the mantle's lead, with faster moving plates responding more rapidly, although still with some delay, to the pull from the mantle. In other words, the mantle flow is not a passive player, but may instead drag and induce stress within the overriding plates, providing a common source for the second-order segmentation of mid-ocean ridge plate boundaries.

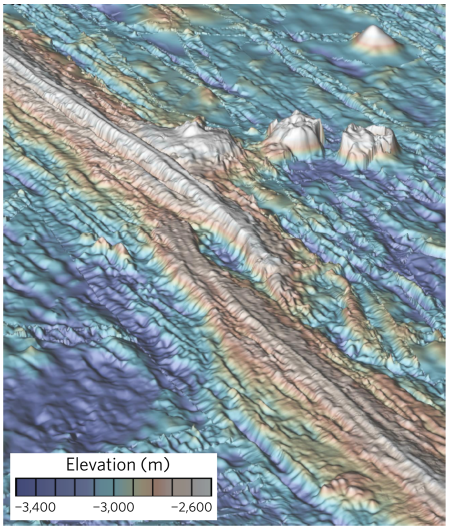

Figure 1 | An overlapping spreading centre from the East Pacific Rise (at 11° 45′ N). This overlapping ridge section marks a typical second-order ridge offset observed at fast- and intermediate-spreading ridges. The distance between the peaks of the disjointed and nearly parallel spreading limbs, expressed in light colours as linear highs, reaches about 7 km. VanderBeek *et al.*[5] use a combination of new and existing seismic data from fast-, intermediate- and slow-spreading mid-ocean ridges in the Pacific and Atlantic oceans to propose that such offsets are formed when the plate is dragged obliquely from its spreading direction by the underlying mantle flow. Figure produced using GeoMapApp (http://www.geomapapp.org) of the Marine Geoscience Data System (MGDS; www.marine-geo.org)[12].

Along the intermediate-[5] and fast-spreading[3] ridges, the second-order ridge offsets are observed to coincide with regions where passing seismic waves travel anomalously slowly. VanderBeek and colleagues argue that these zones with overlapping ridge segments may have higher retention of mantle-derived magma, rather than, for example, greater melt production. They suggest that the delivery of magma from the mantle to mid-crustal reservoirs may be less efficient as rifting becomes distributed between overlapping limbs of the spreading ridge. The inability of melt to efficiently reach shallow crustal depths should lead to greater fractional crystallization, denser crustal rocks and, possibly, a thinner crust — phenomena that have been observed at the Juan de Fuca Ridge and East Pacific Rise[6,7].

The fast-spreading ridges are further partitioned into shorter segments by more ephemeral third-order offsets, which display similar disjointed and overlapping ridge limbs as second-order offsets but at a smaller scale. Seismic images from the East Pacific Rise[8,9] show that these third-order offsets may also be sites of less efficient mantle melt extraction and thinner crust, with magma lenses forming a thick crust–mantle transition zone. However, ruling out greater melt production in the mantle beneath overlapping spreading centres may prove challenging due to interactions between ridges and local seamounts. The two largest melt anomalies in the mantle detected beneath the Juan de Fuca Ridge in this work[5] not only coincide with the second-order offsets, but also seem to directly underlie the Split and Endeavour seamounts. An excess of melt erupting at these locations forms these seamounts, and this could be indicative of greater melt production in the mantle.

Although the researchers maintain that the oblique mantle flow beneath mid-ocean ridges is ubiquitous and that there is an inverse correlation between the skew of mantle-flow and mid-ocean-ridge spreading rate, only three data points are currently available. The surveyed areas may also be affected by transform faults that potentially limit the rate at which spreading centres adjust to changing mantle flow. Moreover, the analysed data describe only a small fraction of the vast system of mid-ocean ridges and some[10] suggest that the datasets used cannot constrain all the details of the computed mantle velocity structure. Finally, seismic data from oceanic plate interiors seem to show strong correspondence between the fossil indicators of plate spreading and the inferred mantle flow directions[11]. If the mantle flow below ridges is indeed skewed, a mechanism may be needed to explain how this realignment takes place as the plate ages and ductile mantle rocks cool and accrete to form oceanic lithosphere.

For the ideas of VanderBeek and colleagues[5] to gain broader acceptance, new data may be needed. Preferably, these data would be collected in areas that have not experienced recent changes in spreading direction and that are away from the bounding transform faults. But this is easier said than done. Such experiments require specialized equipment and major funding, something only a handful of countries can afford, and even then perhaps only once in several years.

VanderBeek *et al.*[5] propose a universal origin for second-order ridge segmentation caused by oblique mantle flow beneath the spreading centres. While we wait for new data, it is important to remember that it is only 60 years since we discovered the vast and continuous mid-ocean ridge system and, therefore, where the largest mountain chains on Earth reside. The remarkable ideas reported here on how mid-ocean ridges are formed and shaped highlight the extraordinary collective achievements that have materialized in a short amount of time, well, geologically speaking. Moreover, they show that understanding a phenomenon can hold as much excitement as its original discovery. ❐

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