GEODYNAMICS

Go with the flow

Plate tectonics is the surface expression of mantle convection. Seismic observations at the Cascadia subduction zone show that coupling between tectonic plate motion and mantle flow may depend on the size of the plate.

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Plate tectonics has revolutionized our understanding of the geological evolution of the Earth. This theory states that the Earth's surface is a jigsaw puzzle of rigid lithospheric plates, and it is the movement of these plates relative to one another that is responsible for events such as mountain building, earthquakes and volcanism. The tectonic plates are the top boundary layer of the mantle convection system[1]. This implies that there should be a strong alignment between present-day plate movement at the Earth's surface and flow direction in the Earth's outermost mantle. Writing in *Nature Geoscience*, Martin-Short *et al.*[2] present seismic observations that suggest that only the motion of large tectonic plates is coupled to the underlying mantle.

At the Cascadia subduction zone, the Juan de Fuca oceanic plate and two smaller oceanic plates — the Explorer and Gorda plates — descend below the North American continent at a rate of 2.5 to 4.5 cm per year (Fig. 1). These plates are created at mid-ocean ridges located a few hundred kilometres offshore. Beneath the Cascades onshore, flow in the asthenosphere (the layer of weak mantle under the tectonic plates) seems to be aligned parallel with the direction of plate subduction[3]. The young age of the Juan de Fuca Plate, at less than 10 million years old, implies that it is warm and thin, and may therefore strongly couple with the underlying mantle[3]. As a result, it entrains a thick layer of the mantle as it descends beneath the Cascades. In contrast, at subduction zones with older, cooler and thicker plates, it is proposed that factors such as shear heating may reduce any coupling, so that only a thin layer of mantle is entrained[3].

The direction of mantle flow can be inferred using observations of seismic anisotropy — the directional dependence of seismic wave speed. When the mantle deforms, olivine crystals become aligned with the direction of flow and seismic waves generally travel fastest in this flow direction[4]. The majority of observations of anisotropy, including those at Cascadia, have been made over continental regions. However, below a continent, there are many possible sources of anisotropy, including cracks and faults in the tectonic plates created by past episodes of deformation[5]. Isolating the seismic fingerprint of the asthenosphere beneath the continents is therefore challenging. Oceanic plates are typically thinner and less complex than continental plates, and so offer a simpler system for isolating anisotropy in the asthenospheric layer[6]. To complement the abundant land-based seismometers in the Cascades, seismic instruments have been placed on the adjacent Pacific Ocean floor as part of the Cascadia Initiative project[7].

Martin-Short and colleagues[2] use measurements of seismic anisotropy recorded at 160 seismic stations both

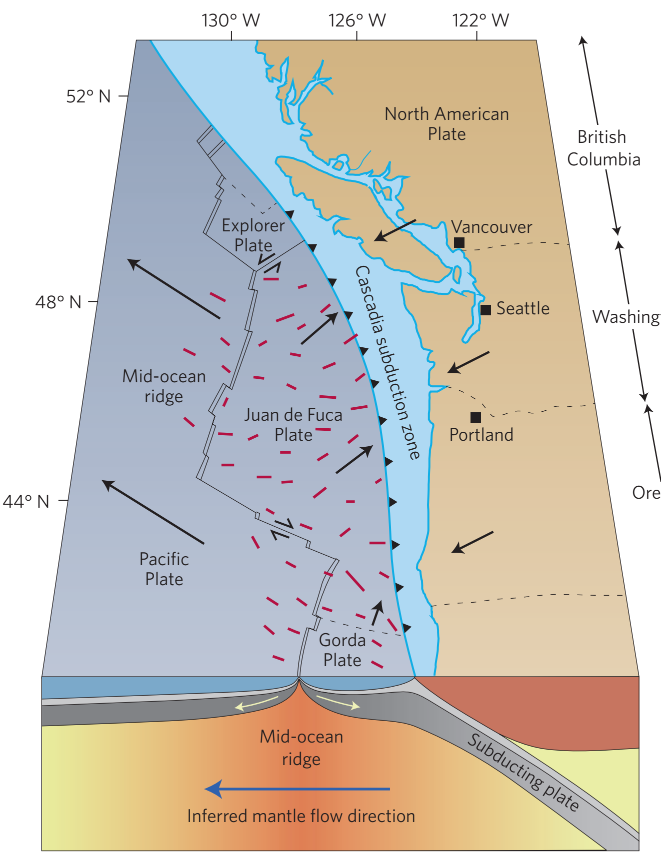

Figure 1 | The Cascadia subduction zone. The Explorer, Juan de Fuca and Gorda oceanic plates subduct below the North American continent. Martin-Short and colleagues[2] report observations of seismic anisotropy (pink lines) that show that mantle flow below the Juan de Fuca Plate is parallel to plate motion (black arrows). Yet, below the small Gorda Plate, the mantle seems to flow to the northwest, possibly due to entrainment of mantle by the large, fast-moving Pacific Plate.

on land and offshore at the Cascadia subduction zone to infer and map small-scale lateral variations in mantle flow. Beneath the Juan de Fuca Plate, they infer mantle flow generally aligned with the plate's direction of motion. Closer to the Cascadia subduction trench and onshore, mantle flow aligns with the subduction direction. Together, these observations are consistent with the idea that asthenospheric mantle below the Juan de Fuca Plate flows in line with plate motion.

However, the researchers find that mantle flow beneath the smaller, slow-moving Gorda Plate exhibits a very different pattern of anisotropy, even though it is just as young as the Juan de Fuca Plate. Here, the inferred mantle flow direction is not parallel to the direction of plate motion. Instead, seismic anisotropy aligns with the northwesterly direction of motion of the adjacent Pacific Plate. Using a simplified numerical model, Martin-Short and colleagues show that the rapid motion of about 6 cm per year of the large Pacific Plate can entrain mantle within a layer roughly 100 km thick below the Gorda Plate. This means that movement of the Gorda Plate is decoupled from the asthenosphere, perhaps because the plate is so small and slow moving.

The offshore measurements presented by Martin-Short and colleagues[2] also reveal northwesterly mantle flow at the southern end of the Cascadia subduction zone, which is interpreted to be induced by the Pacific Plate. Yet, previous onshore measurements were interpreted as southeasterly mantle flow around the edge of the subducted Gorda Plate[8]. Discriminating between these competing interpretations at Cascadia will require geodynamic models that incorporate the effects of mantle entrainment by plate motions and subduction-induced flow. In addition, more work is needed to quantify how the age, size and speed of an oceanic plate affect its coupling to the underlying mantle. A recent global study[9] suggests that coupling is strongest for plates that are moving at more than 4 cm per year. At Cascadia, the Juan de Fuca and Gorda plates are both relatively slow-moving, yet only the mantle below the Juan de Fuca Plate seems to flow in the direction of plate motion. The measurements by Martin-Short and colleagues indicate that plate size may also be a key factor that controls coupling. Geodynamic models, as well as observations of anisotropy over other small oceanic plates, are needed to resolve these questions.

Martin-Short *et al.*[2] provide a high-resolution view of mantle deformation over an entire tectonic plate system, from mid-oceanic ridge to subduction zone. They demonstrate that mantle deformation cannot simply be inferred from present-day plate motions. ❒

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