

INTERACTION OF CONTINENTS WITH THE UNDERLYING MANTLE

Götz Bokelmann

Department of Geophysics, Stanford University, Stanford, CA 94305–2215
goetz@pangea.stanford.edu

1) Mechanical interaction

Are the tectonic plates pulled and/or pushed from the side as the Orowan–Elsasser model (Elsasser, 1969) suggests or does mantle convection play an active role in driving the plates (Holmes, 1933)? Both concepts, driving from the side by "slab pull" from the subducting plates (slabs) and "ridge push" from the midoceanic ridges, or driving from below by mantle convection can explain the general pattern of surface plate motion (Forsythe and Uyeda, 1975). The question of which of the two is more important can be addressed by studying the deformation of deep continental roots. The stress acting on the deep lithosphere is hardly known but it is expected to be on the order of a few MPa below stable continental areas. In this case of partial coupling we should expect considerable internal deformation within the lithosphere, especially for the deep continental roots under the stable portion of North America.

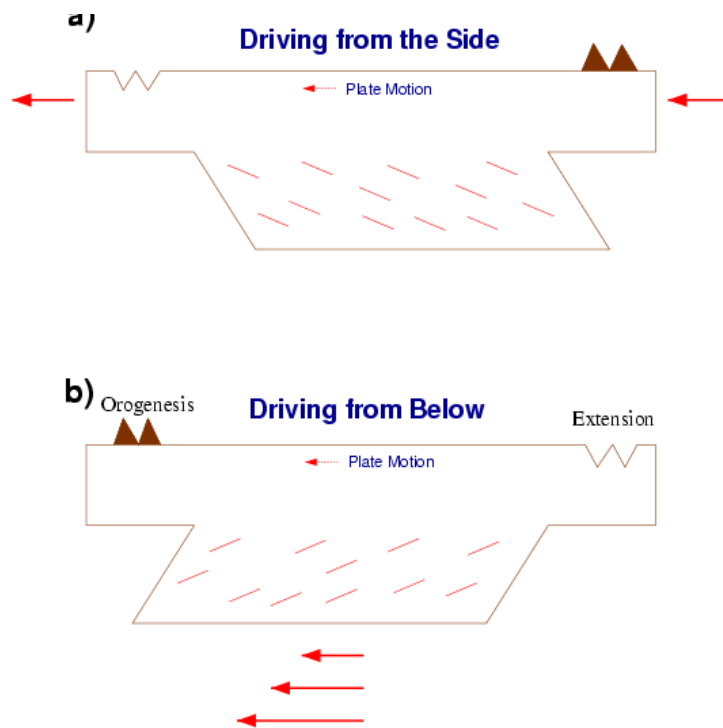


Figure 1: Driving forces and the sense of shear within the tectonic plate. Simple–shear deformation due to plate–mantle interaction leads to a preferred mineral orientation/foliation (and seismic fast axes indicated schematically) in the root zone of the plate. The dip direction of the fast axes is indicative of the driving mechanism. If the plate is driven from the side and the mantle resists the motion (a), they dip away from the plate motion direction. Conversely, if the plate is driven by a faster moving deeper mantle (b), the fast axes dip towards the absolute plate motion direction. If the driving forces are large, we may also have a diagnostic pattern of orogenesis (mountain building) and extension, with orogenesis occurring on the side toward which the root is moving.

2) How can we study the interaction?

Stable North America is a particularly suitable candidate to address this question since it has very thick lithosphere and relatively high absolute plate velocity. It also shows the strongest shear-wave splitting among all shield regions on Earth which confirms the strong deformation in the lithosphere under stable North America and a relatively strong coupling with the deeper mantle. An open question, however, is in which direction the basal stresses operate, that is whether the deeper mantle is rather driving or resisting plate motion. A technique for resolving this question is illustrated in figure 1. Deformation of the root leads to a preferred orientation of minerals, most notably olivine which attains a seismically observable fast direction that dips towards the direction of flow. With increasing strain this fast direction rotates toward the (horizontal) flow plane. Figure 1 shows that the dip direction of fast axes distinguishes the two driving-force models, unless deformation is very large and the rotation toward the horizontal is complete.

In a previous study we found that the Canadian shield lithosphere consists of two anisotropic layers with the shallower one having a subvertical and the deeper having a subhorizontal foliation plane (Bokelmann and Silver, 2000). These foliation plane orientations are indicative of a) a vertically coherent deformation of the shallow lithosphere with the crust and b) a simple-shear deformation in the deep lithosphere due to mechanical interaction with the deeper mantle as shown in figure 1. From the strong shear-wave splitting under the Canadian shield we expect anisotropy to also show up in teleseismic P-wave delay data with a size of about 2 seconds. Inspecting P-wave delays we find systematic variations of that size (figure 2) and interestingly arrivals from southwestern direction are systematically faster than other directions for stations on the stable portion of North America. This is what we would expect if North America were driven from below because olivine a-axes would be dipping into the southwestern Absolute Plate Motion (APM) direction. A current theme of research is to try to also extract such information from shear-wave splitting, which is difficult in the case of realistic (orthorhombic) olivine symmetry.

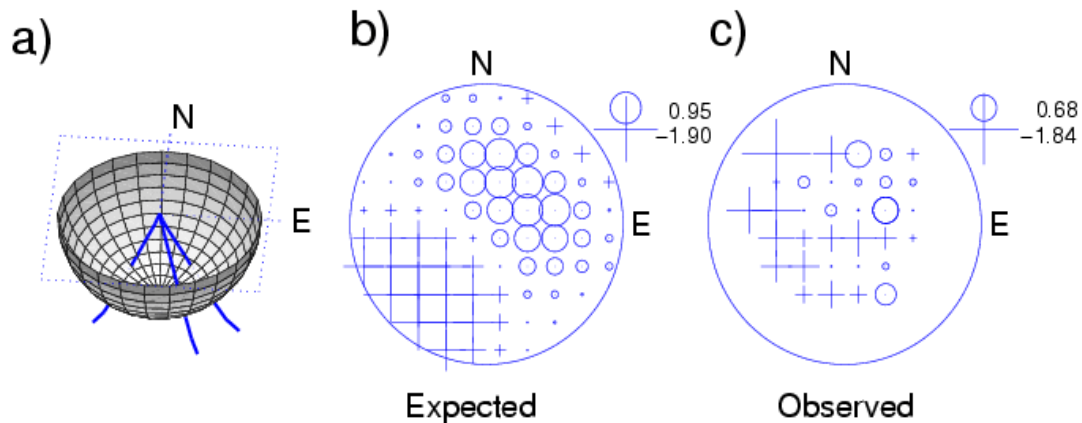


Figure 2: Expected and observed travel time variation for driving from below shown on a lower hemisphere under the station (a). Example ray paths are shown by the thick lines. b) shows the predicted delay variation from aligned olivine in a 100 km thick layer, with the (fast) olivine a-axis dipping 30° to the southwest, in positive APM direction. The (intermediate) c-axis is horizontal. Crosses/spheres show arrivals that are early/late, and the size gives the delay in seconds. c) shows observed P-wave arrival time residuals for a typical station on the Canadian shield (averaged residuals). Note that waves from southern to western direction arrive earlier than waves from the northeast, similar to the prediction from the "driving-from-below" model in b).

We find a consistent pattern for all stations on the stable portion of North America (region of thick lithosphere). Figure 3 shows fast directions resulting from an inversion of the teleseismic delay data (Bokelmann, 2000/2001). Where North America is underlain by fast mantle (blue) indicating a thick lithospheric root (which approximately corresponds to the areal extent of the tectonically stable North America) fast axes dip in southern to western directions. Fast directions from SKS shear-wave splitting are quite similar to the P-wave fast directions in most places, confirming that the P-wave fast directions are in fact due to lithospheric anisotropy.

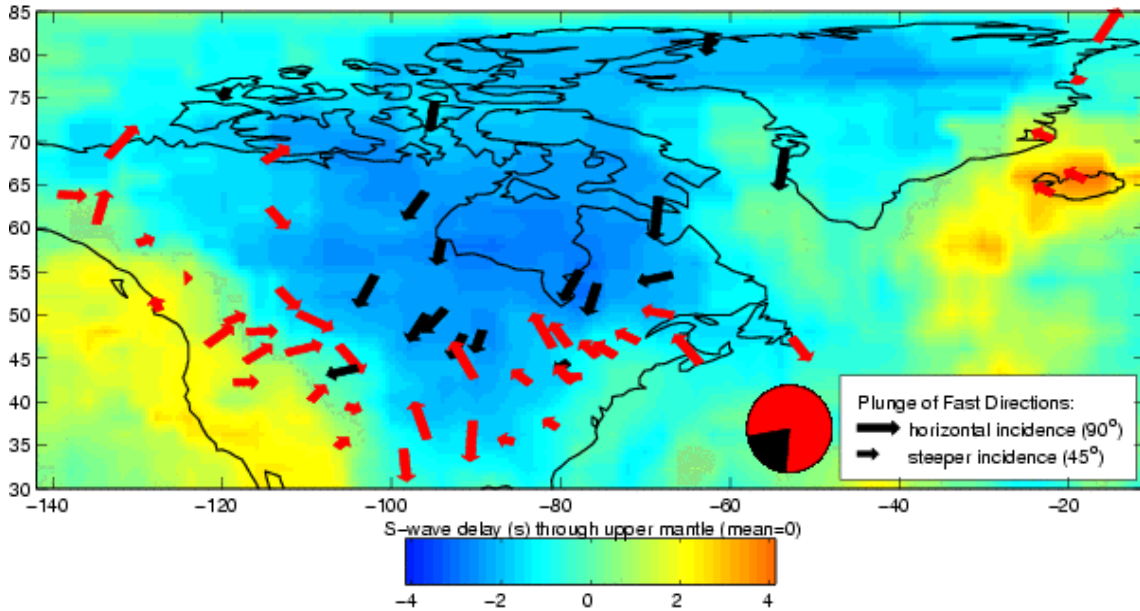


Figure 3: Orientation of fast axes for stations in northern North America. P-wave fast azimuths are shown by black bars for southwestern direction (between 165° and 200°) and red bars for other directions. The length shows the dip angle. The background map shows S-wave travel times integrated from 400 km to the surface in the tomographic model from Grand (1994). Blue colors indicate the extent of thick lithosphere. Note that this region corresponds to stations which have exclusively southern to western fast directions, while other areas have very different fast directions.

The fast directions of stations on stable North America are roughly parallel to (positive) absolute plate motion. This suggests that the thick lithosphere under stable North America is driven from below (case of figure 1b). Other regions in North America have very different fast directions. The distinguishing feature is apparently the thickness of the lithosphere, which may be controlling the degree of coupling with the deeper mantle. We can actually test the underlying simple-shear deformation model, since it requires that fast axes must have a dip angle shallower than 45° from the horizontal. All stations on stable North America show dip angles that satisfy this test to within the error.

The driving-from-below mechanism inferred for the stable portion of North America implies that the deeper mantle under North America moves faster than the North American plate, and that it moves in southwestern direction. Interestingly, the fast directions also correlate well with relative plate motion of the North American plate relative to Eurasia which may suggest a larger-scale mechanism relating the deeper mantle motion (driving North America) to the opening of the Atlantic plate. A single-layer mantle convection pattern under the Atlantic (Alvarez, 1982) would cause correlations of tectonic events over large distances. A mechanism of this kind was invoked to explain the simultaneous motion changes of South America and Africa, which required a coupling of both continents to mantle flow (Silver et al., 1998).

3) Tectonic Style

It is interesting to consider whether the basal force is also documented in the continental stress field. Measurements of absolute stress would be important constraints for resolving the nature of the driving forces, but we don't have many. The existing stress data have been used to support both the side-driven and the bottom-driven mechanism for North America (Bird, 1998; Zoback and Zoback, 1989) suggesting that the resolving power is not yet very large or, more likely, that there are additional effects on the stress field which can not be ignored. An important effect is that of buoyancy (Jones et al., 1996; Zoback and Mooney, 1998).

4) Slowing–Down of North America

Interestingly, seismic fast directions in the western US and especially in the Basin & Range (figure 3) are nearly opposite to those on the stable part of the continent, while the dips are generally near 45° or below, suggesting that also these data are consistent with a simple–shear mechanism. One way of explaining these opposite fast direction is to postulate that western US is pushed from the northeast by the bottom–driven thick lithosphere, but this requires a northeastern counterflow in the asthenosphere under Western North America, and especially the Basin & Range. A more natural explanation stems from the well–known tabular high–velocity anomaly in the lower mantle under North and South America. This anomaly is generally interpreted as a downwelling that may be seen as the edge separating two convection cells to the west and the east. The two convection cells would produce the observed opposite senses of drag under the lithosphere in Eastern and western US (Bokelmann, 2001). The downwelling is generally interpreted as subduction of the Farallon slab, and western North America was originally located over this downwelling. The southwestern motion of North America currently places the western part of the stable continent over the downwelling. Once the region of thick continental lithosphere is centered over the downwelling the net lateral force is zero because there is only vertical motion in the mantle. This predicts that North America should slow down and finally come to rest over the downwelling, if it is indeed driven from below. This would in fact explain why North America has slowed down dramatically throughout the past 100 million years. The process is apparently not complete yet. The stable continent, which is coupled to the mantle, is not yet centered on the downwelling, but it will probably take just a few tens of millions of years, until the motion of North America will come to a halt (Bokelmann, 2001).

5) Important Questions in the Context of Plate–Mantle Interaction:

- Which forces drive the motion of North America?
- What is the future of the North American motion? Will it stop as predicted by basal driving?
- Is the interaction documented in surface features, e.g. in tectonics and the surface stress field?
- Is it manifest in other geophysical observations?
- Is there a mechanical asthenosphere under the craton?
- Can we determine the absolute stress level acting within the Earth?
- How should we model the basal forces?
- How strong is the mechanical coupling between plate and mantle in different parts of North America?
- Which role does the Earth's mantle play in mountain building? Why is there such an asymmetry of mountain building in North America? To which degree is it due to rheological differences and to which degree to the driving forces?
- To which degree is continental tectonics influenced or perhaps even controlled by the mantle?
- Does the interaction between plates and mantle also play a role in the initiation of basin subsidence?

For more information see <http://pangea.stanford.edu/~goetz/home.html> or contact the author under goetz@pangea.stanford.edu .

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