Which forces drive North America?

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ABSTRACT

Understanding the mechanism of plate tectonics is one of the most important problems in the geosciences. Are the tectonic plates pulled and pushed from the side, as the Orowan-Elsasser model suggests, or does mantle convection play an active role in driving the plates? This question can be addressed by studying the deformation of deep continental roots. The application to North America shown here indicates that the deeper mantle moves at a higher velocity than the North American plate and that the mantle plays an important role in driving the plates. I suggest that this finding (1) provides a natural explanation for why the motion of North America slowed down dramatically during the past 100 m.y. and (2) predicts that North American motion will eventually come to a halt.

Keywords: plate tectonics, deformation, lithosphere, seismology, mantle, anisotropy.

INTRODUCTION

Although the concept of plates moving on Earth's surface is universally accepted, it is less clear which forces cause that motion. The contrasting views are that the dominant forces might operate either (1) from the side by ''slab pull'' by the subducting plates (slabs) and ''ridge push'' from mid-oceanic ridges (Elsasser, 1969) or (2) from below by mantle convection (Holmes, 1933). Both concepts can explain the general pattern of surface plate motion (Forsyth and Uyeda, 1975); with regard to North America, both views were presented at the fall 2000 American Geophysical Union meeting.

A quantity that is important for distinguishing these models is the degree of mechanical interaction between plates and deeper mantle, as documented by the level of shear stress acting on the base of the plates. This stress is hardly known, but if it is on the order of a few megapascals below stable continental areas, as has been suggested (Melosh, 1977), this estimate would indicate that the force F_b acting on the base of the stable portion of North America is of the same order of magnitude as ridge push F_r from the North Atlantic. This similarity suggests that the plate is neither decoupled (the case of $F_b \ll F_r$) nor fully coupled (the case of $F_b \gg F_r$) to mantle convection. In this case of partial coupling, one should expect considerable internal deformation within the lithosphere-asthenosphere system. An open question, however, is in which direction the stresses operate, i.e., is the deeper mantle driving or resisting plate motion? A technique for resolving this question is illustrated in Figure 1. Assuming that the lithosphere deforms approximately in simple shear due to the interaction between plate and deeper mantle, we expect deformation of the root to lead to a lattice-preferred orientation of minerals (Nicolas and Christensen, 1987), most notably of olivine, which rotates toward the (horizontal) flow plane with increasing strain. Note that the direction into which the lattice-preferred-orientation dips may then be interpreted as the direction in which the basal shear stress acts, relative to an observer at the surface. The question is, of course, whether the dip is different from zero (horizontal) because we would otherwise lose the ability to distinguish the two opposite directions of flow. This we determine using the effective seismic anisotropy experienced by teleseismic waves, and especially by determining the fast direction that is parallel to the lattice-preferred orientation of olivine *a*-axes. The azimuth in which that seismic fast axis dips thus determines the direction in which the shear stress at the base of the lithosphere acts.

Seismic anisotropy has been studied extensively (e.g., Silver, 1996; Savage, 1999; Montagner and Tanimoto, 1991), mostly by analyzing shear-wave splitting and surface waves. Neither of these techniques can determine the dip angle of the fast direction easily, and there are only a few studies that attempted to do that (Hartog and Schwartz, 2000, 2001; Levin et al., 1999). In this paper we use a technique based on angular variations of P-wave delays (Bokelmann, 2002) that determines both the azimuths and the dip angles for a set of stations in North America.

Stable North America is a particularly suitable candidate to ad-

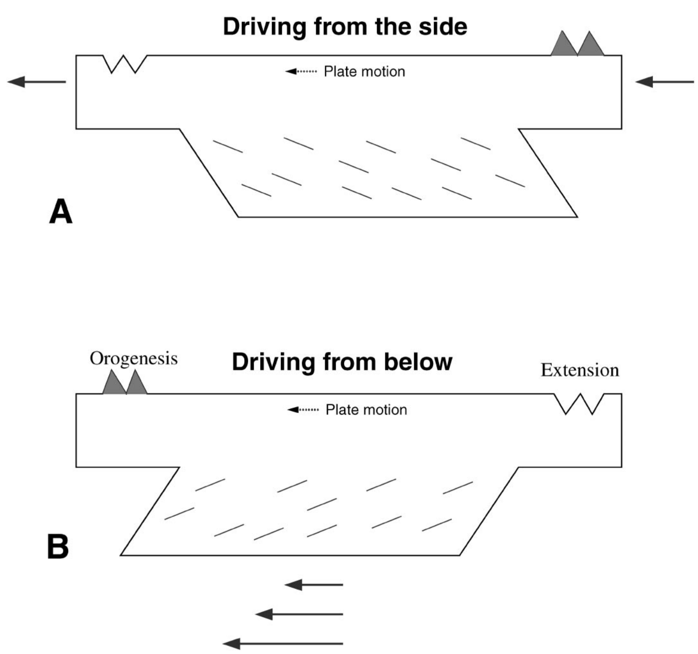

Figure 1. Driving forces (arrows) and sense of shear within tectonic plate (vertically exaggerated). Simple-shear deformation due to plate-mantle interaction leads to preferred mineral orientation in portions of thick lithosphere, and seismic anisotropy. Seismic fast axes are shown schematically by diagonal dashes. Dip direction of fast axes is indicative of driving mechanism. A: If plate is driven from side and mantle resists motion, fast axes dip away from plate-motion direction. B: Conversely, if plate is driven by faster-moving deeper mantle, fast axes dip toward absolute-plate-motion direction. If driving forces are large, diagnostic pattern of orogenesis (mountain building) and extension may develop; orogenesis will occur on side toward which root is moving (see text).

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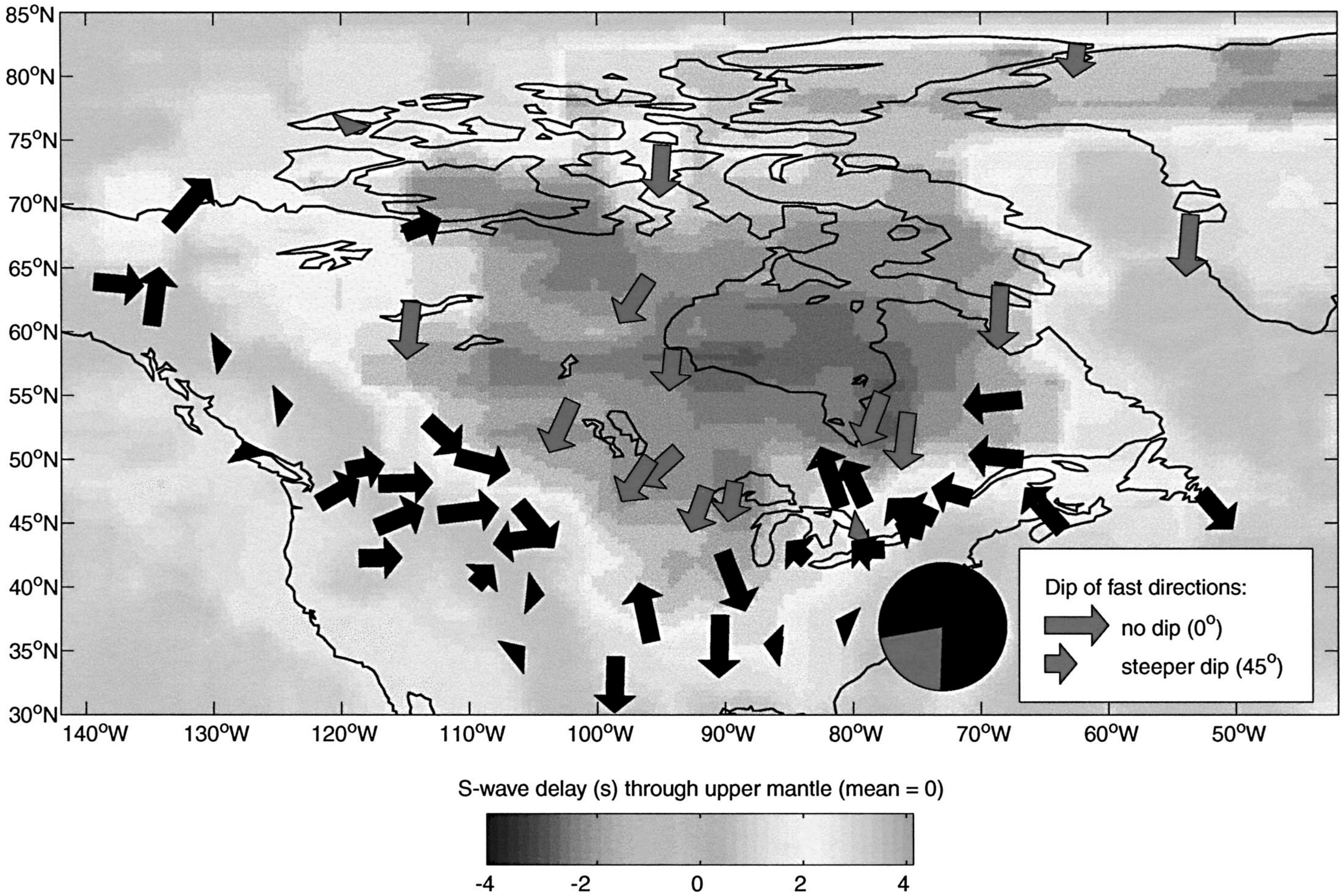

Figure 2. Orientation of fast axes for stations in northern North America. P-wave fast azimuths are shown by arrows in light gray for southwestern direction (between 180° and 260°) and in black for other directions; shades in sphere (lower right) show angular ranges. Length of arrow shows dip angle. Background map shows S-wave traveltimes, δt_S, integrated from 400 km to surface in tomographic model from Grand (1994). Darker gray shades indicate extent of thick lithosphere. Note that this region corresponds to stations that have exclusively southern to western fast directions, whereas other areas have very different fast directions.

dress the question of driving forces because 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 indicates strong and coherent deformation in the lithosphere-asthenosphere system under stable North America.

ANISOTROPY AND DRIVING MECHANISM

A previous study found that the deep Canadian Shield consists of two anisotropic layers; the shallower one has a subvertical foliation plane, and the deeper one has a subhorizontal foliation plane (Bokelmann and Silver, 2000). These foliation-plane orientations are indicative of (1) a vertically coherent deformation of the shallow lithosphere and the crust and (2) a simple-shear deformation in the deep lithosphere and/or asthenosphere due to mechanical interaction with the deeper mantle, as shown in Figure 1. From the strong shear-wave splitting under the Canadian Shield, one would expect anisotropy to also show up in angular variations of teleseismic P-wave delay data with a size of ~2 s. Upon inspection of the global P-wave delay data set (Engdahl et al., 1998), systematic variations in P-wave delays are found, and they are about that size; furthermore, arrivals from southwestern direction are systematically faster than arrivals from other directions for stations on the stable part of North America. This effect is what one would expect if North America were driven from below, because olivine *a*-axes would be dipping into the southwestern absolute plate motion (APM) direction.

In fact, southern to western fast directions are observed for all stations on the portion of North America that has thick lithosphere. Figure 2 shows fast directions resulting from an inversion of the teleseismic delay data (Bokelmann, 2000, 2002). Wherever North America is underlain by fast mantle (darker gray background), indicating a thick lithospheric root (roughly corresponding to stable North America), fast axes dip in southern to western directions. Fast directions from SKS shear-wave splitting are roughly similar to the P-wave fast directions for the majority of stations (e.g., Silver, 1996; Savage, 1999), suggesting that the P-wave delay patterns are due to anisotropy in the lithosphere-asthenosphere system.

Figure 3A shows that the common fast direction of the stations on stable North America is roughly in the range of (positive) absolute plate motion, which would suggest that the thick lithosphere under stable North America is driven from below (case of Fig. 1B). If this is correct, then the azimuth of the fast directions under the region of thick lithosphere gives the direction of basal shear stress relative to the lithosphere, which is due to mantle flow moving with a velocity faster than the North American plate velocity (>2 cm/yr). The direction of mantle motion need not be the same as that of absolute plate motion; i.e., the motion within the mantle is purely poloidal as long as viscosity variations are not large (Bercovici, 1998), and therefore it cannot drive the toroidal (shearing) component of plate motion. To explain the toroidal component, plates and mantle cannot be fully coupled. It is perhaps noteworthy that there is a larger bias with the anisotropic directions for models of absolute plate motion that use a ‘‘no-net-rotation’’

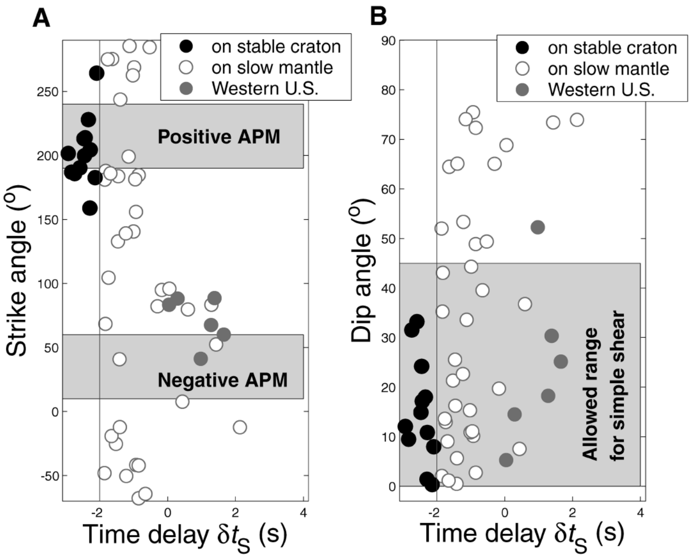

Figure 3. Strike and dip angles of fast axes. A: Strike angles and range of absolute plate motion (APM) direction for North America as function of upper-mantle S-wave delay δt_S (i.e., value in background map of Fig. 2). Note that stations on fast mantle and thick lithosphere locations (black symbols) have dips approximately in range of directions of (positive) APM movement. B: Dip angles of fast axes (from horizontal). Simple-shear deformation mechanism for lithospheric root (fast mantle) as shown in Figure 1 requires dip angles shallower than 45° (Wenk et al., 1991). All stations on fast mantle (except one station near edge) satisfy this test. However, stations in western United States (gray symbols) have northeast-trending fast directions (nearly opposite to those on stable part of continent), and most of their incidence angles are also in range 0°–45°.

reference frame, e.g., NNR-NUVEL-1A (DeMets et al., 1994), rather than a hotspot reference frame.

The underlying assumption was that deformation in the lithosphere occurs approximately by simple shear. We can actually test this assumption, because it requires that fast axes must have a dip angle shallower than 45° from the horizontal (Wenk et al., 1991). Figure 3B shows that all stations on stable North America produce fast axis dip angles that satisfy this test to within the error, whereas 35% of the stations off stable North America don't satisfy this test and require an explanation different from simple-shear deformation from plate-mantle interaction. Fouch et al. (2000) suggested lateral perturbations of mantle flow around the thick lithospheric root as an explanation for perturbed fast shear-wave splitting azimuths off stable North America. Other regions in North America have very different fast directions. The differing thickness of the lithosphere may be important to explain this because it controls the degree of coupling with the deeper mantle; i.e., the coupling is much stronger under the portion with thick lithosphere than in the western United States.

TECTONIC STYLE

It is interesting to consider whether the basal force is also documented in the continental stress field and the tectonic style in different parts of North America. In principle, measurements of stress, and especially of absolute stress, would be important constraints. 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 that cannot be ignored. One such factor appears to be buoyancy (Jones et al., 1996; Zoback and Mooney, 1998).

Considering the North American plate alone, one might expect a tendency for increased northeast-southwest compression in the southwest and more northeast-southwest extension in the northeast (Fig. 1), if the plate is driven from below. This change in stress might lead to orogenesis in southwestern North America and extension in the northeast. Conversely, if the continent were driven exclusively by North Atlantic ridge push, one would expect the opposite (stronger compression in the northeast than in the southwest). In fact, the tectonic history of western North America throughout most the opening of the Atlantic is marked by compressional tectonics (Burchfiel et al., 1992). The stress field at the western edge of the stable continent is currently compressional to the north of Montana up to Alaska, but the extensional Basin and Range in the western United States represents an exception in this large-scale pattern. This exception may be explained as an effect of internal gravitational forces (Jones et al., 1996), and it may occur even if there is a compressional stress field acting from outside. However, the northeastern United States shows evidence for extension in the Baffin Bay area and the Labrador Sea during much of the Atlantic opening (Keen et al., 1990). Such extension occurring in the wake of a thick continent would be naturally explained by driving from below. Similarly, the east-west difference in orogenic behavior of South America led to the suggestion of a driving-from-below mechanism driving the motion of South America (Alvarez, 1982).

SLOWING DOWN OF NORTH AMERICA

Seismic fast directions in the western United States (Fig. 2) are nearly opposite to those on the stable part of the continent, and the dips are generally near 45° or below, indicating that these data are consistent with a simple-shear mechanism. One way of explaining these opposite fast directions is to postulate that the western United States is pushed from the northeast by the bottom-driven thick lithosphere, but this explanation requires a northeastern counterflow in the asthenosphere under western North America. A more natural explanation stems from the well-known tabular high-velocity anomaly in the lower mantle under North and South America (Fig. 4). This anomaly is generally interpreted as a downwelling (Grand, 1994) that may be seen as the edge separating two convection cells to the west and the east. These two convection cells would produce the observed opposite senses of drag under the lithosphere in the eastern and western United States, as predicted by geodynamic modeling studies with the mantle density structure as input model (B. Steinberger and T. Becker, 2001, personal commun.). This view is consistent with the direction of mantle flow under the western United States as determined by combining geodesy and shear-wave splitting (Silver and Holt, 2001).

The downwelling is generally interpreted as subduction of the Farallon slab, and it appears that westernmost North America was originally located over this downwelling. Figure 4 shows that the southwestern motion of North America currently places the western part of the stable continent over the downwelling. If the motion continues and the stable continent centers itself over the downwelling, the lateral force acting on it will be zero, and the motion will stop. This argument predicts that North America should slow down and finally come to rest over the downwelling, if the plate's motion is indeed driven from below. This prediction explains why North America has slowed dramatically throughout the past 100 m.y. (Fig. 4). 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.

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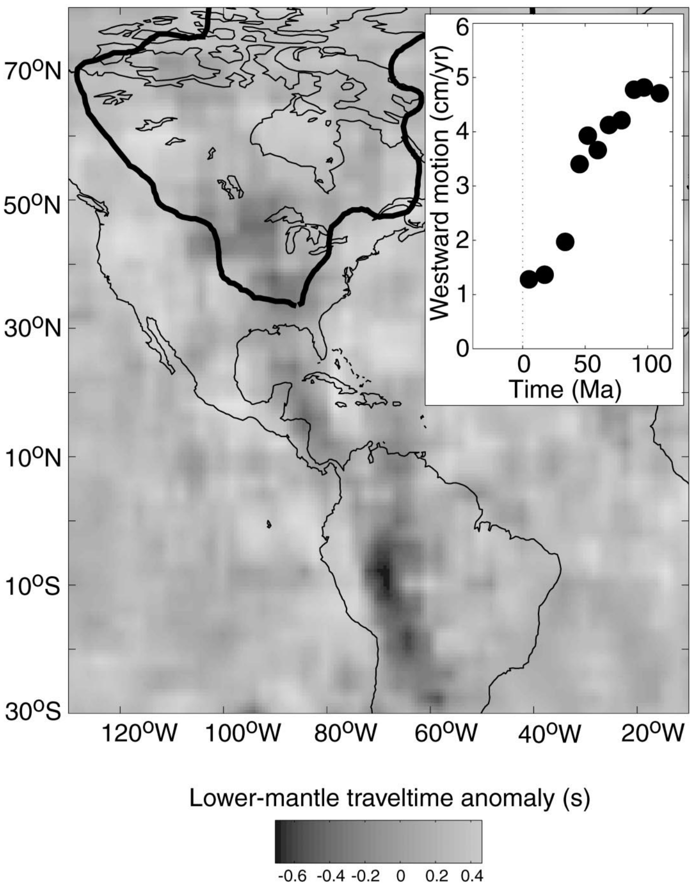

Figure 4. Lower-mantle downwelling and North American motion. Seismic velocities in lower mantle (here shown as traveltimes through 100-km-thick layer at 800 km depth) show tabular fast anomaly under North America and South America (Grand, 1994). Outline of thick lithosphere (taken from Fig. 2) is shown by thick line. Inset shows western component of plate-motion velocity of North America over past 100 m.y. (Gordon and Jurdy, 1986; Lithgow-Bertelloni and Richards, 1998). There is dramatic slowing of North America throughout this time period. I argue that this is due to settling of continent over downwelling, which is predicted to occur if North American continent is driven from below. Region of thick lithosphere has reached downwelling, but it has not yet centered itself over it.

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