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# Shear stress at the base of shield lithosphere

Götz H. R. Bokelmann
Department of Geophysics, Stanford University, Stanford, California, USA

Paul G. Silver
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC, USA

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[1] One of the basic unresolved issues regarding plate tectonics is the degree of coupling between surface plates and convecting mantle below. Are the plates effectively decoupled from the mantle flow field by a low viscosity asthenosphere, or are they strongly coupled to mantle flow? While these two views are essentially incompatible, they both do a reasonably good job of predicting the motions of the surface plates, and cannot therefore be distinguished on this basis. The significant distinguishing feature for these models is the magnitude of basal shear stress that is applied to the base of the plate. While it is difficult to measure this stress directly, it is possible, in principle, to measure the corresponding deformation of the plate through observations of seismic anisotropy and to infer stress. Here we focus on the Canadian Shield, for which we expect strong plate-mantle interaction. We show that seismic anisotropy can be used to constrain the magnitude of the stress level applied to the base of the plate, and to document the level of interaction between tectonic plates and the mantle below. *INDEX TERMS:* 7218 Seismology: Lithosphere and upper mantle; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8159 Tectonophysics: Evolution of the Earth: Rheology—crust and lithosphere; 8164 Tectonophysics: Evolution of the Earth: Stresses—crust and lithosphere. **Citation:** Bokelmann, G. H. R., and P. G. Silver, Shear stress at the base of shield lithosphere, *Geophys. Res. Lett.*, *29*(23), 2091, doi:10.1029/2002GL015925, 2002.

## 1. Introduction

[2] It is reasonable to expect that the plate-mantle coupling is strongest where the plate is thickest, such as beneath stable cratonic regions, and where the differential motion between the plate and the deep mantle is particularly high, as indicated by absolute plate motion. The Canadian Shield, which possesses both characteristics, is the object of our study. This region is underlain by very thick lithosphere [*Grand*, 1994] and is the fastest moving shield region of very large thickness (to the right of broken line in Figure 1). The Canadian Shield is also conspicuous by its highly seismically anisotropic mantle. As measured by the size of shear-wave splitting delays [*Silver and Chan*, 1988; *Silver*, 1996; *Savage*, 1999], the anisotropy is among the largest in the world, and is far higher than in any other stable continental region.


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## 2. Canadian Shield

[3] The association of thick lithosphere and large anisotropy in the Canadian shield suggests that the anisotropy is contained within the lithosphere, rather than in an asthenosphere below [*Silver and Chan*, 1988]. In addition to being documented in shear-wave splitting, the anisotropy is also revealed in the dramatic difference in P- and S-wave travel times through the upper mantle, namely that S-wave travel times vary laterally (from the center to the southwestern edge of the Western Superior Province) much more strongly than P-wave travel times (Figure 2). The parameter $\mathrm{dln}v_s/\mathrm{dln}v_p$, which measures the relative variation in S- and P-velocity, is therefore much larger than can be easily explained by lateral variations in composition or temperature including partial melt [*Bokelmann and Silver*, 2000], which give values between 1 and 2.2, or by the effect of heterogeneity [*Duffy and Anderson*, 1989]. On the other hand we will show below that lateral variations in an anisotropic lithosphere, the presence of which is unequivocally demonstrated by shear-wave splitting studies within the Canadian Shield [*Silver and Chan*, 1988], can easily account for the value of $\mathrm{dln}v_s/\mathrm{dln}v_p$. The anisotropy of the lithosphere is most likely dominated by olivine due to its large volume fraction, its strong intrinsic anisotropy, and its tendency to align under finite strain [*Duffy and Anderson*, 1989]. In our simplified model we assume that the anisotropy can be described by a fraction of fully aligned olivine grains embedded within an isotropic matrix. The orientation of such an aggregate can change the P-velocities substantially, while not affecting the S-velocity pattern much [*Bokelmann and Silver*, 2000]. We also find that the presence of anisotropy does not have much of an effect on ‘‘isotropic’’ S-delays [see also *Toomey et al*, 1998].

[4] Lithospheric anisotropy has two possible causes, each associated with one of two foliation plane orientations. The first one is vertically coherent deformation of the plate, which is associated with subvertical foliation planes and a lineation direction parallel to major geologic structures. This is most likely the dominant source of anisotropy in the lithosphere due to the low temperatures and low strain rates [*Silver*, 1996]. The second cause is basal shear deformation of the lower portion of the plate which is predicted to have a more or less horizontal foliation plane, and a lineation direction parallel to the absolute plate motion direction. The corresponding splitting fast polarization directions are parallel to the lineation. A particular feature of the Canadian Shield is that both causes would give approximately the same azimuth of fast polarization, since absolute plate motion is roughly parallel to the orientation of the fabric

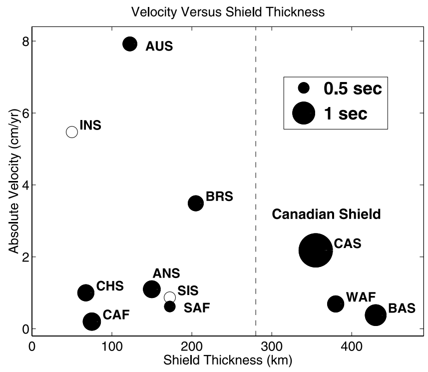


**Figure 1.** Velocity of shield motion (after *Gordon and Gripp*, 1990, taken at geographical centers of shields) versus thickness [*Polet and Anderson*, 1995] for the major shield regions on Earth. The size of the filled circles gives the shear-wave splitting delay averaged from available data [*Silver*, 1996; *Savage*, 1999; empty circles if no data]. The Canadian Shield stands out in that it is very thick, has considerable velocity, and the strongest shear-wave splitting among all shields on Earth. It is an ideal candidate to look for signs of mechanical coupling between plate and mantle (ANS = Antarctic Shield, AUS = Australian S., BAS = Baltic S., BRS = Brazilian S., CAF = Central African S., CAS = Canadian Shield, CHS = Chinese S., INS = Indian S., SAF = South African S., SIS = Siberian S., WAF = West African S.).

in the crust (and shallow lithosphere) of the Canadian Shield. A third possibility which we don't consider in this paper but which may contribute in regions of substantial lithospheric thickness variation is flow around lithospheric keels [*Bormann et al.*, 1993; *Fouch et al.*, 2000].

## 3. Two-Layer Anisotropy

[5] We consider a simple two-layer model of anisotropy, an upper layer that is constant (in thickness and intrinsic anisotropy) across the edge of the shield in Figure 2, and a deeper layer that is present only where lithospheric thickness is large and where large splitting is observed (the latter more or less coincides with the Canadian Shield). We seek to constrain the style of deformation in each layer by determining the thickness and foliation plane orientation that satisfy both the shear-wave splitting delay times and the P- and S- travel-time constraints, including $\mathrm{dln}v_s/\mathrm{dln}v_p$. Since the data in this study cannot constrain the dip angle of foliation we only consider vertical and/or horizontal foliation, but a separate study considers the dip angle of foliation [*Bokelmann*, 2002a, 2002b] using a larger set of P-wave data. The analysis in this paper is also simplified by constraining the fast polarization directions in the two layers to be parallel. Inverting for the contributions of the two layers, we find that the deeper layer needs to be 100 ± 20 km thick and it needs to have a more or less horizontal foliation plane to fit the data [*Bokelmann and Silver*, 2000]. This is the only model we could find that is able to explain the near-constancy of P-wave delays in Figure 2 while also explaining the large variation in S-wave delays and shear-wave splitting. For the shallower layer, a vertical foliation plane orientation provides a slightly better fit.

[6] One consequence of the horizontal-foliation plane model is that it predicts low P-velocities for near-vertical paths and hence a decrease of $v_p/v_s$ (by 2.8%) for the root zone. We note that this reduction is consistent with an inferred decrease near the base of the lithosphere in a previous comparison of P- and S-velocity models for the Canadian shield [*Anderson and Bass*, 1984]. This horizontal

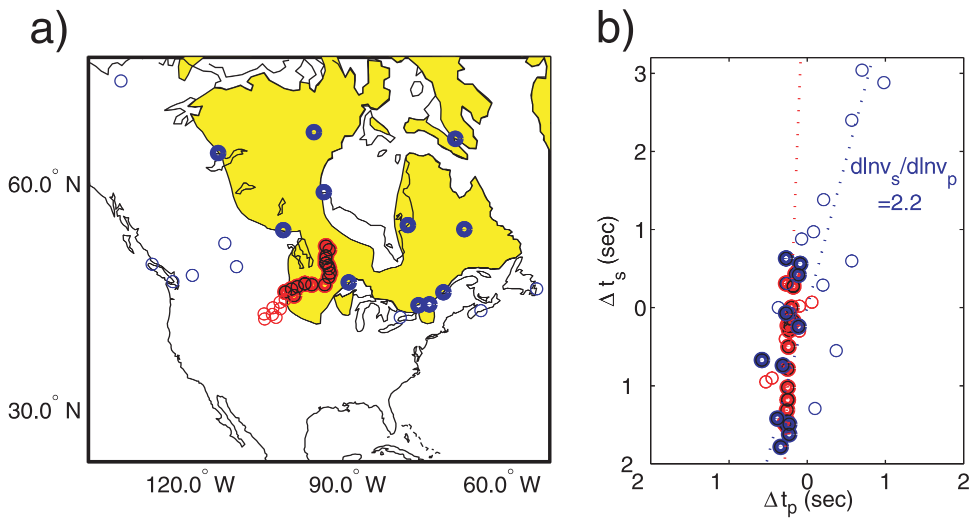


**Figure 2.** a) Locations of stations in Northern North America, the relative P and S station delay variations of which are shown in b). From thermal or compositional variation in the subsurface we expect moderate slopes $Dt_s/Dt_p \sim \mathrm{dln}v_s/\mathrm{dln}v_p$ *1.7 consistent with $\mathrm{dln}v_s/\mathrm{dln}v_p$ between 1 and 2.2 [*Hales and Roberts*, 1970]. We obtain the higher value for the total dataset, but data from stations on or near the shield (filled spheres, otherwise empty spheres) give rise to almost infinite values both for the stations of the APT89 experiment [gray, *Bokelmann and Silver*, 2000] and the permanent stations [black, *Wickens and Buchbinder*, 1980]. Values of $\mathrm{dln}v_s/\mathrm{dln}v_p$ higher than 2.2 are incompatible with purely thermal or compositional variation [*Bokelmann and Silver*, 2000]. We suggest that these large values can be explained by accounting for anisotropy in the lithosphere. The outline of the shield [*Bally et al.*, 1989] is modified to include results from drilling [*Klasner and King*, 1986].

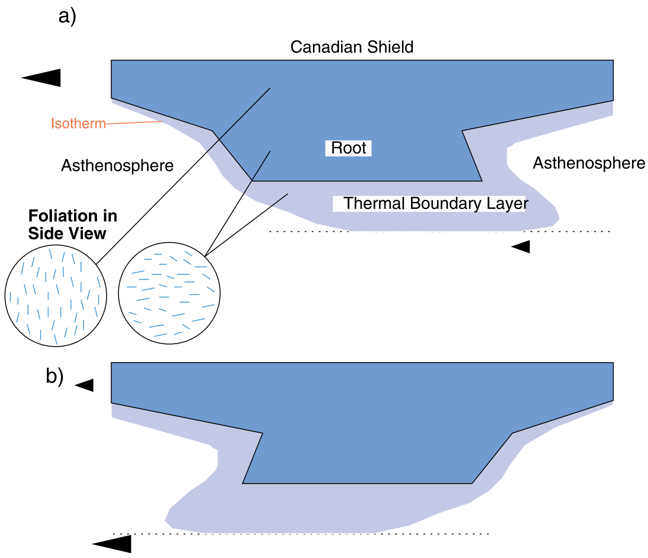


**Figure 3.** Conceptual models of deformed continental lithosphere with the deeper part composed of a thermal boundary layer and a chemically distinct root zone. Relative plate motion between shield and mantle may cause simple shear in the deeper root and subhorizontal foliation planes. Shallower anisotropy in the lithosphere may be characterized by a different kind of anisotropy reflecting the fossil deformation history of the assembly of the shield (vertical foliation). (a) shows the case of plates driving mantle flow and (b) shows mantle flow driving the plate.

foliation plane orientation in the deeper layer is what we would expect for the presence of basal shear deformation resulting from a mechanical coupling between the plate and underlying mantle (Figure 3). This is probably the best evidence we have to date about this coupling and it gives us an opportunity to address several important questions: Is there a mechanical asthenosphere under the continents? And which deformation mode dominates deformation in the upper mantle: dislocation creep which may give rise to preferred mineral orientation and hence seismic anisotropy, or diffusion creep which is predicted to produce a seismically isotropic mantle [*Karato*, 1992]. And is the dominant deformation mode different in different regions?

## 4. Shear Stress

[7] The existence of a deformed root (inferred from anisotropy) suggests that the shield is at least partially coupled to the convecting mantle. It is possible to quantify this coupling by estimating the level of shear stress from the anisotropy. Assuming that there is no relative motion between the shield and adjacent stable continent, and that the velocity of mantle flow is spatially uniform beneath this region of the plate, the vertically integrated strain-rate of the root and adjacent mantle should be equal and comparable in size to the absolute plate velocity

$$\int \dot{\varepsilon}(z)dz = v_{abs}, \tag{1}$$

which we take as 2.3 cm/yr for the interior of the North American plate. We use (1) as a constraint on the depth profile of strain-rate $\dot{\varepsilon}(z)$, assuming that the deformation occurs between the Moho and 600km depth and is dominated by dislocation-creep $\dot{\varepsilon}_1(z)$ and diffusion-creep $\dot{\varepsilon}_2(z)$ which can be written, based on laboratory data, as

$$\begin{aligned}\dot{\varepsilon}(z) &= \dot{\varepsilon}_1(z) + \dot{\varepsilon}_2(z)\\ &= A_1\sigma^{3.5}e^{-\left[E_1^*+P(z)V_1^*\right]/RT(z)} + A_2\sigma^1 e^{-\left[E_2^*+P(z)V_2^*\right]/RT(z)},\end{aligned} \tag{2}$$

with known activation energies $E_1^*$, $E_2^*$, activation volumes $V_1^*$, $V_2^*$, and constants $A_1$, $A_2$ depending on the grain size

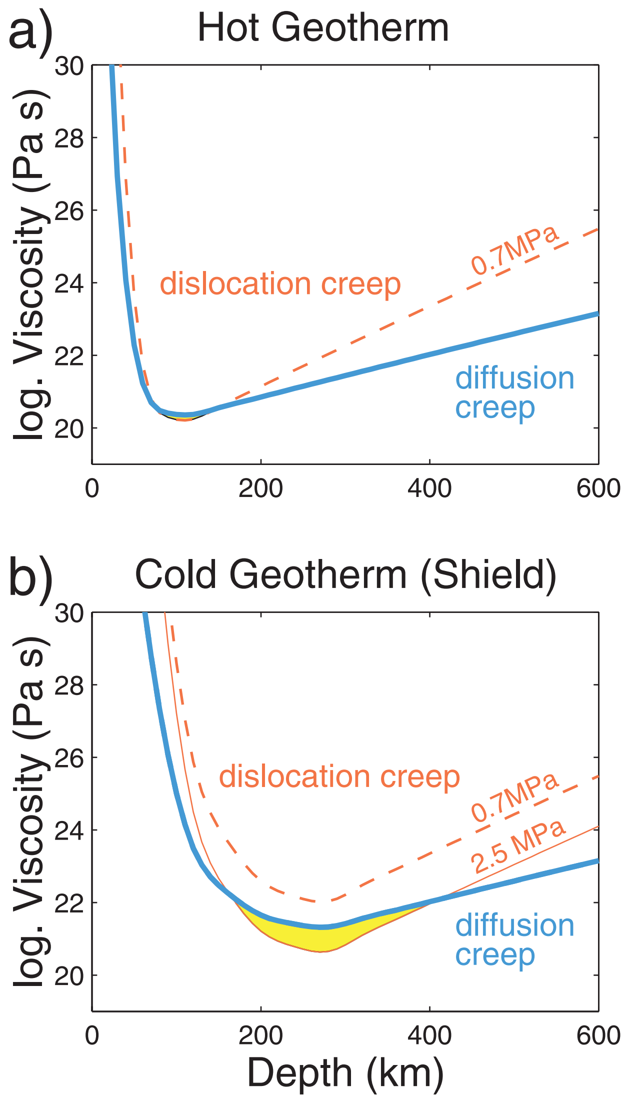


**Figure 4.** Effective viscosity for dislocation creep (broken line) and diffusion creep (thick line), (a) for a hot geotherm, (b) for a cold geotherm (shield). Diffusion creep has lower effective viscosity and dominates deformation in the shallow and deep mantle. Which mechanism dominates at intermediate depths depends on temperature and stress. An increase of stress from 0.7 MPa to 2.5 MPa in the lithospheric root zone (cold geotherm) favors dislocation creep over diffusion creep. This calculation assumes a uniform grain size of 0.4 mm, a dry rheology, and an activation volume of 15 $cm^3$ $mole^{-1}$ for dislocation creep and 8 $cm^3$ $mole^{-1}$ for diffusion creep. Other parameters are as in *Karato and Wu* [1993]. Thermal differences between shield and average mantle persist down to 300 km in this model.

[*Karato and Wu*, 1993]. The level of stress has a significant effect on deformation mode [*Karato and Wu*, 1993], with dislocation creep depending more strongly on stress ($\sim s^{3.5}$) than diffusion creep ($\sim s^1$). We use (1) and (2) to solve for the level of stress $\sigma$ which is assumed to be independent of depth below the Moho, using typical temperature profiles for a ''cold'' and a ''hot'' geotherm [after *Karato and Wu*, 1993] that are representative for the shield and a more typical hot mantle respectively. The resulting stresses are 2.5 and 0.7 MPa. This renders dislocation creep the dominant deformation mechanism under the shield, and it provides a simple explanation as to why there appears to be strong anisotropy in the root zone compared to the adjacent mantle since it predicts stronger anisotropy there between 150 and 400 km depth. (2) provides the strain-rate profile as a function of depth as well as effective viscosity (Figure 4) under both regions. Under the shield, the main deformation occurs much deeper than for a more typical geotherm, which helps to explain the long-term stability of shield regions. The deformation is also widely distributed between 170 and 400 km suggesting that there is no well-defined asthenosphere under the Canadian Shield.

## 5. Conclusions

[8] The inferred stresses acting on the base of the shield lithosphere (2.5 MPa) are quite high. For comparison, the ridge-push ''stress'' acting on the eastern edge of the North American continent is probably about 20 MPa [*Richardson*, 1992]. Integrated over the stable continental portion of the plate the basal forces are of the same order as ridge-push, and they should clearly not be ignored. The direction of the basal shear stress (drag or driving) is under debate [*Forsyth and Uyeda*, 1975; *Alvarez*, 1982; *Zoback and Zoback*, 1989; *Lithgow-Bertelloni and Richards*, 1998; *Bird*, 1998] and the most recent pieces of evidence suggest basal driving [*Bokelmann*, 2000; *Bird*, 2001; *Bokelmann*, 2002a, 2002b]. Shear stresses under (hot) Western North America are probably considerably lower. So no matter whether the mantle is driving or resisting the motion, the plate-mantle interaction is dominated by the (cold) Eastern North America due to the higher level of shear stress and the larger spatial extent. Thus the mantle under Western North America may move in a different direction without affecting the motion of North America much [*Silver and Holt*, 2002]. On the other hand, the motion of deep lithospheric roots is probably to some degree correlated with the motion of the mantle below. The present analysis suggests that the existence of deep anisotropy can be used to constrain the magnitude of stress being applied to the base of the plate, and therefore to document the level of interaction between the tectonic plates and deeper mantle.

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G. Bokelmann, Department of Geophysics, Stanford University, Stanford, CA 94305-2215, USA. (goetz@pangea.stanford.edu)

P. Silver, Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd., Washington, DC 20015, USA. (silver@dtm.ciw.edu)