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Olivine anisotropy suggests Gutenberg discontinuity is not the base of the lithosphere

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Abstract

Tectonic plates are a key feature of Earth's structure, and their behavior and dynamics are fundamental drivers in a wide range of large-scale processes. The operation of plate tectonics in general depends intimately on the manner in which lithospheric plates couple to the convecting interior. Current debate centers on whether the transition from rigid lithosphere to flowing asthenosphere relates to increases in temperature or to changes in composition such as the presence of a small amount of melt or an increase in water content below a specified depth. Thus, the manner in which the rigid lithosphere couples to the flowing asthenosphere is currently unclear. Here we present results from laboratory-based torsion experiments on olivine aggregates with and without melt, yielding an improved database describing the crystallographic alignment of olivine grains. We combine this database with a flow model for oceanic upper mantle to predict the structure of the seismic anisotropy beneath ocean basins. Agreement between our model and seismological observations supports the view that the base of the lithosphere is thermally controlled. This model additionally supports the idea that discontinuities in velocity and anisotropy, often assumed to be the base of the lithosphere, are instead intra-lithospheric features reflecting a compositional boundary established at mid-ocean ridges, not a rheological boundary.

Significance statement

Although plate tectonics has seen broad acceptance for Earth, the manner in which lithospheric plates are coupled to Earth's deeper interior is still heavily debated. In particular, recent seismological observations suggest a sharp, flat base of the lithosphere, whereas thermal models suggest a gradational boundary that deepens with age. Based on laboratory experiments, we suggest that thermal models are most appropriate and that seismic studies are detecting features frozen

into the lithosphere after melting at mid-ocean ridges. Experiments on olivine aggregates demonstrate that the seismic characteristics of deforming upper mantle are dramatically different between melt-free and low-melt-fraction aggregates. A model of upper-mantle flow incorporating these results predicts seismological features in excellent agreement with observations beneath the Pacific ocean basin.

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Main text

Although plate tectonics is the unifying paradigm in the earth sciences, important questions remain regarding the physical nature of a tectonic plate. A cornerstone of plate tectonic theory states that plates translate across Earth's surface in a relatively rigid and coherent fashion, with deformation largely concentrated at plate boundaries. Restated, the plates are taken to have a high viscosity with a relatively sharp transition to the less viscous convecting mantle beneath. Referring to plates as the lithosphere and to the underlying rock as the asthenosphere (terminology which predates plate tectonic theory (1)) is now common. Partial decoupling of the asthenosphere from the lithosphere appears essential to plate-tectonic-like behavior (2), but whether a change in material properties at the base of the lithosphere arises from increasing temperature (3) or from transitions in melt (4–7) or water content (8, 9) remains unclear, even in the tectonically simple ocean basins.

Recent seismological investigations of oceanic upper mantle indicate a change in composition at depths often associated with the lithosphere-asthenosphere boundary (LAB). Receiver-function studies and underside reflections of SS precursors detect a sharp velocity discontinuity (the Gutenberg discontinuity) at a depth of 40 to 150 km (4, 6, 10–12). The sharpness of this discontinuity may indicate the presence of a small amount of melt (4), and the lack of a strong dependence of

the discontinuity depth on plate age (6, 10, 13) is roughly consistent with a carbonated peridotite fluid (7, 14). Alternatively, a transition from water-poor to water-rich conditions could establish a sharp reduction in seismic velocity. Extrapolations from laboratory experiments (9) suggest that a dehydration front established by melting near the ridge axis can produce a water-poor layer whose thickness would not depend on plate age (8). In both interpretations, the sharp drop in velocity is often taken to indicate a change in viscosity structure and therefore the base of the lithosphere.

Instead of compositional variations, recent investigations of seismic anisotropy (13, 15, 16) provide evidence for a lithospheric base that is thermally controlled and measurably deeper than the sharp seismic discontinuities. Beghein et al. (13) highlighted two observations. First, the azimuth of the seismically fastest direction, ψ , appears to be well aligned with the plate motion direction at depths >100 km, consistent with motion of the overlying lithosphere accommodated through viscous flow of peridotite. In shallower portions of the system, ψ is at a high angle to the plate motion direction, suggesting that plate motion direction has changed since it was “frozen in” during thickening of the lithosphere. Importantly, the depth to which ψ is well-aligned with the plate motion direction appears to depend on plate age, roughly in accord with standard thermal models for oceanic upper mantle. Based on these motivating observations, we test the previously suggested hypothesis (13, 15, 17, 18) that the well-aligned region represents a relatively low-viscosity asthenosphere, whose upper boundary is thermally controlled.

Second, recent seismological studies (13, 15) suggest a transition in the magnitude of radial anisotropy (ξ , the ratio between the velocity of horizontally polarized S-waves and vertically polarized S-waves) as a function of depth. Although these surface-wave studies have not included the high-frequency data required to fully resolve anisotropy at the shallowest depths, a transition from low values of ξ at shallow depths to higher values of ξ at greater depths appears to occur near 80

km. The depth of this change in ξ exhibits very little — if any — dependence of depth on plate age and correlates well with estimates for the location of the Gutenberg discontinuity (13). This discontinuity in ξ has been attributed to ubiquitous melt structures in a partially molten asthenosphere (13, 19), but that hypothesis does not explain the presence of strong azimuthal anisotropy described above unless melt-rich layers are significantly inclined from horizontal (5). Alternatively, this discontinuity has been attributed to processes occurring near mid-ocean ridges (13, 20). We support the latter hypothesis by specifically suggesting that this discontinuity results from the crystallographic alignment of olivine grains, which forms in partially molten rocks at shallow depths beneath the ridge axis. This process imparts a seismologically observable weakening in the alignment of the fast axes of olivine, reducing the magnitude of anisotropy, but does not dramatically modify the viscosity structure of the mantle.

To test these hypotheses, we draw on the results from a combination of new (Table S1) and recently published (21, 22) laboratory deformation experiments conducted on (i) nominally melt-free (<1% melt) and (ii) melt-present (>1% melt) olivine aggregates. These torsion experiments, which reached shear strains as high as 18, provide insight into the evolution of olivine textures, likely the primary source of upper-mantle anisotropy (23). This data set is unique in that most previous estimates of the evolution of anisotropy have been based on experiments conducted in transpression (24, 25) rather than simple shear, as achieved here. At high shear strain (>10), all samples exhibit steady-state textures (Figure 1). Nominally melt-free samples have [100] dominantly parallel to the shear direction and [010] dominantly normal to the shear plane, consistent with previous investigations of experimentally (21, 22, 24, 25) and naturally (26, 27) deformed

olivine (Figure 1A). Melt-present samples exhibit weaker textures than nominally melt-free samples, with [100] and [001] distributed in a horizontal girdle, similar to previous experimental results (28, 29) (Figure 1B).

The observed textural evolution in these samples can be used to predict systematic changes in seismic anisotropy as deformation progresses (Figure 2). Nominally melt-free samples (red squares) exhibit a systematic increase in ξ and alignment of ψ with the shear direction with increasing strain, until a steady state is reached at $\xi \approx 1.06$ and $\psi \approx 0^\circ$ (parallel to flow). This value of ξ is close to maximum observed values in the upper mantle, which are on the order of $\xi \approx 1.08$ (13, 15), while $\xi = 1$ indicates isotropy. Melt-present samples (4% melt fraction, blue circles) all exhibit reduced values of ξ ($\xi \approx 1.03$) relative to nominally melt-free samples, since textures developed in this deformation regime are weaker. Thus, even after a melt phase has been extracted or crystallized, textures related to earlier melt-present deformation could explain the relatively low values of ξ observed at shallow depths. A similar reduction in the magnitude of azimuthal anisotropy might be expected, a feature observed in tomographic models (13, 15). In addition, melt-present samples exhibit values of $\psi > 60^\circ$, typically about 90° (normal to flow).

A combination of laboratory observations can explain the seismological observations. In a qualitative sense, high values of ξ observed at depths >80 km in the mantle are consistent with values in nominally *melt-free* samples, and low values of ξ observed at depths <80 km are consistent with values in *melt-present* samples. However, fast shear-wave propagation directions observed in the upper mantle are generally much less than 60° to the absolute plate motion direction (13), a proxy for flow direction, suggesting that values of ψ both above and below 80 km are only consistent with values observed in *melt-free* samples. Thus, at depths <80 km, values of ξ are consistent with

melt-present samples, but values of ψ are consistent with melt-free samples. To resolve this discrepancy, we propose that regions with crystallographic textures similar to those in our melt-present samples are heterogeneously distributed throughout the mantle at depths <80 km. If seismological surveys sample at length scales larger than these heterogeneities, the measured anisotropy would result in reduced values of ξ , but relatively unchanged values of ψ relative to the melt-free case. In support of this proposition, observations of natural samples reveal heterogeneity in the distribution of melt-free and melt-present texture types throughout major portions of the lithosphere on length scales <1 km (30), whereas tomographic models of upper-mantle anisotropy constructed from surface waves tend to have depth resolutions >10 km.

We ran a simple numerical flow model for a viscous fluid deforming in simple shear with a thermal structure determined by half-space cooling to quantitatively predict the seismic anisotropy variation of the oceanic upper mantle (Figure S2). This approach provides a prediction of finite strain as a function of depth and plate age. The laboratory-derived relationships between seismic anisotropy and shear strain (Figure 2) were used to predict the spatial and temporal distribution of anisotropy. We modeled the macroscopic anisotropy resulting from a mixture of the two texture types to predict the effect of a heterogeneous distribution of melt-present textures on seismic anisotropy. Mixtures with 50% to 90% of the volume characterized by the melt-present texture yields an evolution of ξ similar to that observed for melt-present samples and an evolution of ψ similar to that for melt-free samples, consistent with seismological observations at depths <80 km (black triangles in Figure 2 and Figure S1).

The model illustrates that only a region undergoing sufficiently fast deformation relative to the rate of change in plate motion direction can maintain ψ parallel to the plate motion direction. A region of well-aligned ψ develops over a depth interval of ~ 100 to 200 km, a similar range to that

observed in the Pacific upper mantle (Figure 3A) (15). Additionally, the upper boundary of the well-aligned region exhibits a distinct dependence of depth on plate age, reflecting thermal control on finite strain and hence mineral alignment. The shallow anisotropy structure is primarily established near the ridge axis, where temperatures are above the peridotite solidus (Figure S2) such that texture development is influenced by the presence of melt (Figure 2). Once material is transported out of the melting region and melt is crystallized or extracted, the crystallographic alignment related to melt-present deformation is “frozen in” due to decreasing temperature and strain rate (Figure 3B). At depths $\lesssim 80$ km, a region of relatively low ξ develops due to the presence of melt. At greater depths, ξ predicted from the textural evolution of melt-free samples provides a reasonable match to seismic observations (Extended Data Figure 3). Because we reproduce observations of anisotropy without deformation being focused beneath the discontinuity in ξ (and the associated Gutenberg discontinuity), we conclude that the Gutenberg discontinuity represents a relatively minor change in composition rather than a major rheological boundary.

Our laboratory-based predictions are compared to seismological observations in Figure 4. The predicted depth to the top of the well-aligned region is of similar magnitude and follows a similar timescale of evolution as that observed in the Pacific ocean basin (13, 15) (Figure 4A). The predicted depth to the change in ξ also agrees reasonably well with seismological observations (Figure 4B). Importantly, the model captures the lack of an age dependence in the depth of the change in ξ . Comparison of both vertical changes in anisotropy to the predicted viscosity structure (Figure 4) suggests that the top of the well-aligned region correlates well with steep vertical gradients in viscosity. At depths > 80 km, both the elasticity and viscosity structure is governed by temperature, supporting the classic viewpoint of the lithosphere as a rheological boundary layer that is thermally controlled (31). Small ($< 1\%$) amounts of melt may be present in this region reducing the absolute

seismic velocity (7). However, our experiments suggest that melt fractions <1% do not affect the developed anisotropy. Small concentrations of dissolved water are also possible, but large concentrations might induce a measureable change in the direction of azimuthal anisotropy (23). Thus, melt or water may be associated with both a discontinuity in velocity and a discontinuity in ξ . This suggestion is consistent with the magnitude of the velocity change across the boundary, >5% (4, 6, 10–12), which cannot be accounted for by a change in anisotropy alone (11). However, the amounts of melt or water must be small enough to not substantially modify viscosity, which would alter the strain distribution and therefore the distribution of azimuthal anisotropy. We therefore conclude that the vertical change in ξ cross-cuts the viscosity structure (Figure 4B), while the vertical change in ψ (Fig. 4A) correlates with the base of the high-viscosity lithosphere, corresponding to a rheological definition of the LAB. Thus, our results indicate that the often observed vertical change in ξ and the corresponding Gutenberg discontinuity are intra-lithospheric features rather than the LAB itself, established by melting processes near the ridge.

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Figure legends

Figure 1: Characteristic olivine textures in experimental samples. Olivine textures are presented for (A) nominally melt-free aggregates and (B) aggregates of olivine + 4% basalt. Samples were deformed in torsion to approximately the same shear strain. Each data point corresponds to the orientation of one grain, and each pole figure depicts 1000 individual grain orientations. Data points are colored by the corresponding value of the orientation distribution function. The addition of a basaltic melt weakens the overall texture, leading to decreased magnitudes of seismic anisotropy.

Figure 2: Calculated values of seismic anisotropy as a function of strain. Values are given for (A) the orientation of azimuthal anisotropy (fastest direction in the horizontal plane) relative to the

shear direction and (B) the magnitude of radial anisotropy taking the shear plane to be horizontal.. Vertical lines indicate one standard deviation. Weaker anisotropy in melt-present samples than melt-free samples results in larger error bars. Thin red squares are from *Hansen et al. (22)* and thin blue circles are from *Qi et al. (29)*. All other data are from this study. Fits to data (solid lines) from melt-free aggregates and numerical mixtures are provided with 95% confidence intervals (dashed lines).

Figure 3: Predicted distribution of seismic anisotropy in the Pacific upper mantle, based on evolution of the plate away from a mid-ocean ridge at 0 Myr. (A) Difference between predicted values of ψ and plate motion direction, using relationships illustrated in Figure 2a. The plate motion direction is prescribed to change by $0.3^\circ/\text{Myr}$, and only the most actively deforming regions are able to maintain anisotropy subparallel to the current plate-motion direction. (B) Predicted values of ξ . In the melt-present region, anisotropy was calculated using the evolution illustrated by black triangles in Figure 2. Elsewhere the anisotropy was calculated using the evolution illustrated by red squares in Figure 2.

Figure 4: Depths of discontinuities in anisotropy as a function of plate age and compared to the predicted viscosity structure. (A) Depth to top of the well-aligned region in Figure 3A, compared to seismic observations. Vertical lines indicate one standard deviation about the mean of depths determined at all locations of similar age (13, 15). Both predicted and observed data roughly correlate with the transition between a high-viscosity lithosphere and a low-viscosity asthenosphere. (B) Depth to base of low anisotropy region in Figure 3B. Both predicted and observed data exhibit no age dependence to the discontinuity depth, which cross-cuts the predicted viscosity structure.