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Plate bending at subduction zones: Consequences for the direction of plate motions

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Abstract

Bending of lithospheric plates at subduction zones is thought to be an important source of dissipation for convection in the Earth's mantle. However, the influence of bending on plate motion is uncertain. Here we use a variational description of mantle convection to show that bending strongly affects the direction of plate motion. Subduction of slabs and subsidence of oceanic lithosphere with age provide the primary driving forces. Dissipation is partitioned between plate bending and various sources of friction at plate boundaries and in the interior of the mantle due to viscous flow. We determine the poles of rotation for the Pacific and Nazca plates by requiring the net work to be stationary with respect to small changes in the direction of motion. The best fit to the observed rotation poles is obtained with an effective lithospheric viscosity of 6×10^{22} Pa s. Bending of the Pacific plate dissipates roughly 40% of the energy released by subduction through the upper mantle.

Keywords: plate motions; mantle convection; rheology of lithosphere

1. Introduction

Cold lithospheric plates impose a kinematic constraint on the motion of the Earth's surface. The plates organize the large-scale flow in the interior [1,2], but it is unclear whether the rheology of the plates affects the dynamics of mantle convection. Recent theoretical [3,4] and experimental [5,6] studies suggest that the work required to bend the lithosphere at subduction zones constitutes a major source of dissipation for convection. Geophysical constraints on plate rheology [7,8] support this contention, but there is little direct evidence for a significant influence of bending on mantle convection.

Present-day plate motions provide a clue to the role of plate bending. Cooling of the lithosphere supplies the primary source of buoyancy for convection in the mantle [9]. However, the cost of bending the lithosphere penalizes subduction of cold, thick plates because bending has a strong dependence on plate thickness. The interplay between subduction and bending influences the direction of motion toward the trench, especially when the downgoing plate has a distribution of ages [10], and hence thicknesses. We search for evidence of the effect of plate bending by examining the direction of motion into subduction zones.

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2. Work done by convection

A global constraint on the motion of the mantle is defined by the net work of forces in the momentum balance. For slow creeping flow (e.g. negligible inertia), the rate of energy supplied by mass anomalies moving through the gravity field is to equal the work done by stresses in deforming the material. We assume that energy is supplied primarily by slabs that sink into the mantle and by subsidence of oceanic lithosphere with age [11]. Both contributions can be expressed in the form

$$\psi = \int_C (U_1 \mathbf{v}_1 + U_2 \mathbf{v}_2) \cdot \hat{\mathbf{n}} \mathrm{d}s, \tag{1}$$

where the integral is taken along the subduction boundaries C, $\hat{n}$ is the unit vector normal to C and the velocities $\mathbf{v}_1$, $\mathbf{v}_2$ define the motion of the plate in two slightly different reference frames; $\mathbf{v}_1$ is the velocity relative to the trench and $\mathbf{v}_2$ is the velocity relative to the ridge. When the size of the plate does not change with time $\mathbf{v}_2 = \mathbf{v}_1$. The contribution to ψ from slabs is given by

$$U_1 = \overline{\Delta\rho} gh(d - h/2), \tag{2}$$

where $\overline{\Delta\rho}$ is the average density anomaly of the slab relative to the mantle, g is the acceleration due to gravity, h is the thickness of the plate at the time of subduction and d is the depth to which slabs sink from an average initial depth of $h/2$. The potential U_2 is defined as the difference in potential energy per unit area [12] between the ridge and the subduction zone,

$$U_2 = \frac{1}{2}\left[\overline{\Delta\rho} g \left(1 + \frac{2w}{h}\right) h^2 - (\rho_\mathrm{m} - \rho_\mathrm{w}) g (w^2 - w_0^2)\right], \tag{3}$$

where w and w_0 are the water depths at the trench and the ridge, ρ_m is the density of ambient mantle and ρ_w is the density of seawater.

Deformation of the mantle dissipates energy in several ways. Possible mechanisms include viscous deformation of the interior, plastic and brittle failure of the plate during bending, and friction at plate boundaries. We lump the work done by boundary friction and interior deformation into a single term Φ_0, and evaluate the dissipation due to bending using an effective viscosity η_l. The dissipation caused by bending and unbending a viscous plate is given by [4]

$$\Phi_\mathrm{b} = \int_C \frac{2}{3} \left(\frac{h}{R}\right)^3 \eta_l (\mathbf{v}_1 \cdot \hat{\mathbf{n}})^2 \mathrm{d}s \tag{4}$$

where R is the radius of curvature of the plate at the subduction zone. Conrad and Hager [4] argue for a constant R of about 200 km on the basis of earthquake locations in the Benioff zone [13]. On the other hand, analog experiments [6] suggest that the radius of curvature increases linearly with the thickness of the plate (nominally $R \approx 4h$). We consider both possibilities in the discussion below.

The thickness of the oceanic lithosphere is calculated as a function of age using the depth of the ocean and the assumption of isostasy [14]. The ocean depth is fit to a half-space cooling model [15] for ages less than 81 Ma and to a simple parametric function for ages greater than 81 Ma [14], although the results are not changed substantially if we adopt a half-space cooling model for all ages. The age of the plate is inferred from magnetic anomalies on the seafloor [16]. In locations where the age of the downgoing plate is not known, we extrapolate from the nearest isochron in the direction of motion.

Fig. 1 shows the work done by subduction and lithospheric subsidence (e.g. $U_1 + U_2$) for a nominal plate velocity of 0.1 m yr^{-1}. In these calculations we assume that the slab sinks to the base of the upper mantle (e.g. $d = 670$ km). While it is likely that slabs penetrate into the lower mantle [17], the motion of deep slabs is not well constrained by the motion of the surface. Tensile stresses in the shallow part of the slab [18] suggest that the downward motion of the slab is directly transmitted to the surface plates by stresses within the plate itself. A transition to compressive stresses in the slab near the base of the upper mantle implies a different type of coupling to the surface. It is likely that slabs in the lower mantle affect the surface through stresses associated with the large-scale flow. Such broadly distributed stresses cannot account for the distinct velocities of plates with and without subducting slabs [19]. Indeed, viscous flow calculations [20,21] show that mass anomalies in the lower mantle have only a small influence on the direction of subducting plates. Predictions for the motion of the Pacific and Nazca plates indicate that the position of the Euler poles shift by only 1 ° in latitude and longitude when the slabs in the lower mantle are excluded from the calculations [20]. Consequently, we confine our attention to plates that subduct, and adopt the simplifying assumption that deep slabs do not influence the direction of plate motion.

Two examples of bending dissipation are shown in Fig. 1 for $R = 200$ km and $R = 4h$, assuming an effective viscosity of 6×10^{22} Pa s. The choice of R has important consequences for the influence of bending on plate motions. When R is constant the bending dissipation has a strong dependence on h. Cold, thick plates dissipate a large fraction of the work done by subduction, whereas thin plates are less affected by bending. The opposite

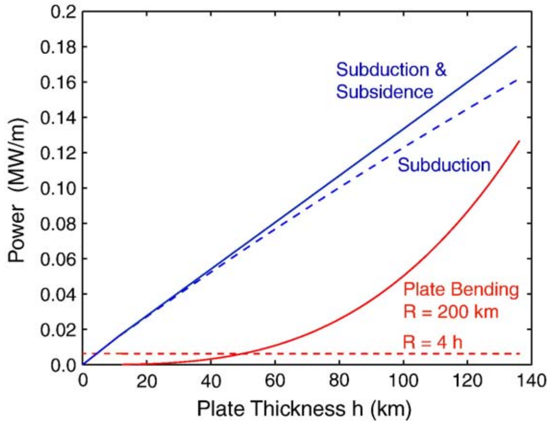

Fig. 1. The work done by subduction, lithospheric subsidence and plate bending as a function of plate thickness for a nominal subduction velocity of 0.1 m yr^{-1}. The thickness of the plate is calculated as a function of age using the assumption of isostasy and a half-space cooling model [15,16]. The average density excess of the slab is $\overline{\Delta\rho} = 65$ kg m^{-3} and the ambient density of the mantle is $\rho_m = 3350$ kg m^{-3}. The work due to plate bending is calculated using a constant effective viscosity $\eta_l = 6 \times 10^{22}$ Pa s and a radius of curvature of either $R = 200$ km (solid) or $R = 4h$ (dashed).

behaviour is expected if R varies with the plate thickness. In this case the effect of bending is large relative to the work done by subduction when the plate is thin. In the result shown below, we find that the motion of the Nazca plate (with intermediate thickness) is better explained with a constant R. The predictions for the Pacific plate are even better than those for the Nazca plate when R is constant, suggesting that the influence of bending increases for thick plates.

3. Variational description of mantle flow

We estimate the motion of the Pacific and Nazca plates using a variational description of slow viscous flow. Changes in the work done by gravity ψ and in the bending dissipation Φ_b accompany changes in the direction of plate motion. We use δ to denote the change (or variation) in the work terms for a small change in the location of Euler poles. The momentum balance in the mantle requires the variations to obey

$$\delta(\psi - \phi_b - \phi_0) = 0 \tag{5}$$

where the dissipation functions for bending, ϕ_b, and friction in the upper mantle, ϕ_0, are defined by $\phi_b = \Phi_b/2$ and $\phi_0 = \Phi_0/2$ when the relationship between strain-rate and stress is linear. (The factor of 1/2 arises because the dissipation is quadratic in the velocity; modifications for nonlinear rheologies are straightforward in principle.) We assume that the dissipation due to friction depends on the rate of plate motion but not on the direction (e.g. $\delta\phi_0 = 0$). This assumption is not strictly correct, but it is a reasonable approximation given the magnitude of change in the other terms. Consequently, we determine the plate motion by requiring $\psi - \phi_b$ to be stationary with respect to changes in the direction of plate motion. This implies that the direction of plate motion maximizes the work done by gravity, subject to the penalty of bending the plate.

We initially evaluate the integrals for ψ and ϕ_b using the Euler poles and rotations rates from the plate motion model NUVEL-1A in the no-net-rotation frame [22]. The position of the Euler pole for a single plate is iteratively adjusted using a simplex method [23] to search for a maximum in $\psi - \phi_b$. (The integrals for ψ and ϕ_b are evaluated along the current location of all subduction boundaries. While subduction boundaries may shift with changes in the Euler pole, we expect these shifts to become small when the predicted pole approaches the observed position.) A change in the Euler pole will also alter rate of plate motion, so we make small adjustments to the rotation rate to ensure that the total rate of plate destruction, as measured by the integral of $\mathbf{v}_1 \cdot \hat{n}$ over C, is fixed at the NUVEL-1A value. The constrained optimization of $\psi - \phi_b$ is applied to all subducting plates, although we focus attention on the Pacific and Nazca plates because these plates provide the simplest and clearest evidence for plate bending. The Australian plate also has a large bending dissipation by virtue of the old lithosphere subducted at the Java trench. However, the complexity of the northern and western boundary with the Pacific and a series of small (micro) plates makes predictions for the Australian plate motion less reliable. We use the motion of the Pacific and Nazca plates to infer a plate viscosity, and merely estimate the magnitude of the bending dissipation for the Australian plate using the present-day plate motion.

Predictions for the Pacific and Nazca plate motions are shown in Fig. 2. The calculated Euler poles are shown for a constant R and a series of plate viscosities. The pole position labelled by 0 corresponds to a calculation with no bending dissipation. Large deviations from the present-day Euler poles in NUVEL-1A are predicted for both the Nazca and Pacific plates when the bending dissipation is absent. The misfit between the predicted and observed Euler poles improves as the plate viscosity increases from 0×10^{22} Pa s to 6×10^{22} Pa s. For the Pacific plate, the increase in plate viscosity penalizes the subduction of old lithosphere in the western Pacific, shifting the direction of motion toward the northwest. Further increases in the plate viscosity cause the misfit to increase. Our best fit to the observations is obtained with an effective viscosity of roughly 6×10^{22} Pa s and a constant radius of curvature

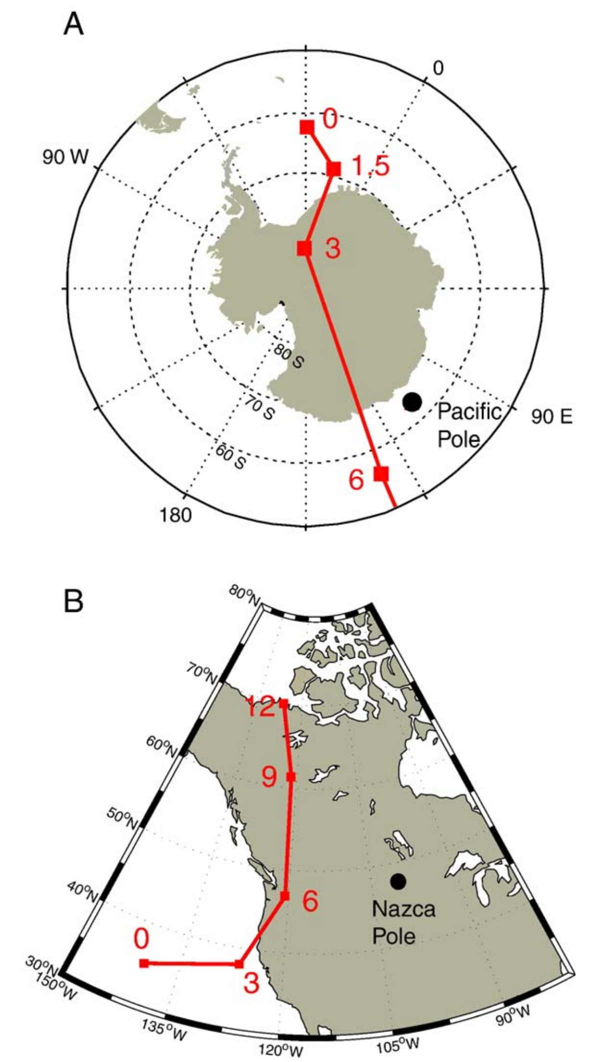

Fig. 2. The observed and predicted locations of the Euler poles for the (A) Pacific and (B) Nazca plates. The predicted positions (red squares) are labelled according the effective plate viscosity used in the calculation (in units of 10^{22} Pa s). The observed Euler poles (black circles) are taken from NUVEL-1A in the no-net-rotation frame [22]. The misfit between the observed and predicted Euler poles is minimum when the effective viscosity is roughly 6×10^{22} Pa s.

$R = 200$ km. This value of viscosity is much lower than laboratory-based estimates at representative temperatures [24], but it is consistent with the previous geophysical bounds [3,5,8]. Calculations with a variable radius of curvature (not shown) increase the misfit to the observed Nazca and Pacific poles for all values of plate viscosity.

Table 1 summarizes the importance of the work terms for several individual plates and for the system as a whole. The energy released by subduction of the Pacific plate accounts for nearly half of the energy released by all subducting plates. Smaller contributions to the energy release arise from thickening and subsidence of the oceanic lithosphere. The bending dissipation is most pronounced for the Pacific plate, where it accounts for 36% of the energy released by subduction. Much smaller effects are predicted for the younger and thinner Nazca and Cocos plates, consistent with expectations from Fig. 1. Even though the effect of bending on the Nazca plate is smaller, it is encouraging to find a best fit with the same viscosity adopted for the Pacific plate. The only adjustable parameter in this study is η_l / R^3. This makes the effective viscosity dependent on the value assumed for R.

4. Discussion

It is reasonable to question whether our interpretation of plate bending is affected by the neglect of deep slabs or buoyant upwelling. We have previously argued on the basis of calculations by Conrad and Lithgow-Bertelloni [20] that deep slabs have only a small influence on the direction of the Pacific and Nazca plates. Calculations by Becker and O'Connell [21] yield similar conclusions for the Pacific and Nazca plates when the seismic model of Masters et al. [25] is used to estimate the density anomalies in the upper and lower mantle. (Compare the direction of torques in Figs. 9 and 10 of [21] for model SB4L18). On the other hand, differences between various models of mantle density are sufficient to cause substantial variations in the direction of the plate torques [21], so it is diffcult to draw definitive conclusions from any individual density model. Still, it does appear that deep slabs in many models of mantle density merely increase the speed of the Pacific and Nazca plates [21,26,27] without substantially altering the directions. In this case the neglect of deep slabs should not alter our interpretation of plate bending. An added advantage of confining our attention to plate direction is that we lessen our sensitivity to uncertainties in mantle viscosity, so long as the condition $\delta\phi_0 = 0$ is reasonably well satisfied.

Table 1
Work terms based on present-day NUVEL-1A plate motions

Plate	Subduction (TW)	Subsidence (TW)	Bending (TW)	Net (TW)
Pacific	1.431	0.144	0.522	1.053
Nazca	0.385	0.022	0.053	0.354
Australia†	0.353	0.034	0.121	0.266
Cocos	0.128	0.005	0.008	0.125
All	2.841	0.234	0.766	2.309

† Includes only the contribution from the Java trench.

Buoyant upwelling may also contribute to the direction of plate motion. To assess this contribution we note that the local rate of work due to gravity (e.g. the buoyancy flux) is proportional to the convective heat flux, assuming the density anomalies are thermal. Consequently, we use estimates of the convective heat flux at the top and bottom of the mantle to determine the relative roles of upwelling and downwelling. Sclater et al. [28] obtained an estimate of 28×10^{12} W for the convective heat flux at the surface due to subduction of oceanic lithosphere. By comparison, the heat flux across the core–mantle boundary is thought to be 5 to 10×10^{12} W [29]. Numerical [30] and laboratory [31] studies suggest that 30% to 50% of the basal heat flow is absorbed by cold material and the rest is carried away in buoyant plumes. The upward heat flux in these plumes could be as large as 7×10^{12} W, given the preceding estimates, or about 25% of the heat flux due to subducting slabs. We conclude that the work done by upwelling could be as much as 25% of the work done by subduction.

This value should be compared with the rate of dissipation due to bending. For example, bending the Pacific plate dissipates about 36% of the work of subduction for our preferred estimate of plate viscosity. Such a large work term is sufficient to account for most of the discrepancy in the position of the Euler pole, although the prediction is not perfect (see Fig. 2). The same effective viscosity for the Nazca plate explains only half of the discrepancy in the position of the Euler pole, although this value still provides the best fit to the observations. Bending the Nazca plate dissipates about 14% of the work due to subduction (see Table 1), so we might expect the influence of bending in this case to be smaller than it was for the Pacific plate. In fact, the residual discrepancy for the Nazca plate implies a missing work term that is comparable in size to the effect of bending (e.g., 14% of the work due to subduction). By attributing all of this missing term to upwelling, we infer a plume heat flux of slightly less than 60% of our upper bound, or about 4×10^{12} W.

5. Conclusions

We have shown that the addition of plate bending yields substantial improvements in the motion of the Pacific and Nazca plates. This agreement is achieved with a single adjustable parameter, which contains the effective viscosity of the plate. Our preferred viscosity estimate, 6×10^{22} Pa s, assumes a radius of curvature of $R=200$ km. Large changes in the plate motion for a plausible range of plate viscosity suggest that plate bending is an important part of mantle convection.

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