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The tectosphere and postglacial rebound

Michael Manga

Department of Geology and Geophysics, University of California, Berkeley

Richard J. O'Connell

Department of Earth and Planetary Sciences, Harvard University

Abstract. Large lateral variations in the thickness of the lithosphere and viscosity of the mantle may be associated with continental roots. The effects of continental roots, or the tectosphere, on postglacial rebound are calculated using an axisymmetric flow model in which both the mantle and lithosphere are described as Newtonian fluids. Continental roots are shown to have a measurable effect on postglacial rebound, in particular, on the evolution of the peripheral bulge. Effects of continental roots are concentrated near the edge of the tectosphere, and thus often near ocean-continent boundaries where many relative sea-level histories are measured. The pattern and distribution of tectonic and seismic activity associated with deglaciation are affected by a tectosphere.

Introduction

Large lateral rheological variations are expected near the Earth's surface owing to temperature variations associated with convective motions in the mantle and possibly compositional variations associated with continental roots. *Richards & Hager* [1989] and *Forte & Peltier* [1994] found that long wavelength viscosity variations in the mantle have little effect on the dynamic topography, surface stresses and geoid caused by steady loading (e.g. convection). By contrast, Sabadini and coworkers found that viscosity variations near the Earth's surface may have an appreciable effect on dynamic topography and the rate of surface deformation due to transient (e.g. glacial) loading. In a series of papers, Sabadini and coworkers have investigated some of the consequences of lateral viscosity variations on surface observables: lateral viscosity variations are treated numerically as lateral variations of the thickness of the lithosphere, and the surface expressions of relative motion between drifting plates and the lower mantle [*Sabadini et al.,* 1992] and postglacial rebound [*Gasperini et al.* 1990; *Gasperini & Sabadini* 1989] are calculated. Here we consider the effect of lateral variations of the thickness of the lithosphere, associated with the seismically fast regions observed under continents [e.g. *Su et al.,* 1994], on the strain pattern associated with postglacial rebound. In the appendix we argue that continental roots, called the tectosphere by *Jordan* [1975], must be much more viscous than the surrounding mantle if they are to persist for billions of years.

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Model

The effects of lateral thickness variations of the lithosphere are calculated using an axisymmetric Newtonian viscous flow model: the lithosphere has a viscosity of 10^{23} Pas and the mantle is an infinite half space with viscosity 10^{21} Pas. Hereafter, the word lithosphere refers to the very viscous surface layer. The initial surface depression is assumed to be a gaussian curve, $z = z_o e^{-(r/R)^2}$ with $z_o = -1$ km and $R = 1000$ km. The evolution of the surface topography is calculated numerically using a boundary integral method [*Manga et al.,* 1993].

A number of approximations are made which limit quantitative applications of the model, but do allow us to study some of the features related to the presence of a tectosphere. First, we neglect elastic effects and more detailed Earth structure and geometry. Since the Maxwell time for the mantle is $O(100)$ years, the evolution of long wavelength features will be dominated by viscous flow in the mantle. Plate flexure will affect short wavelength features. A more extensive study

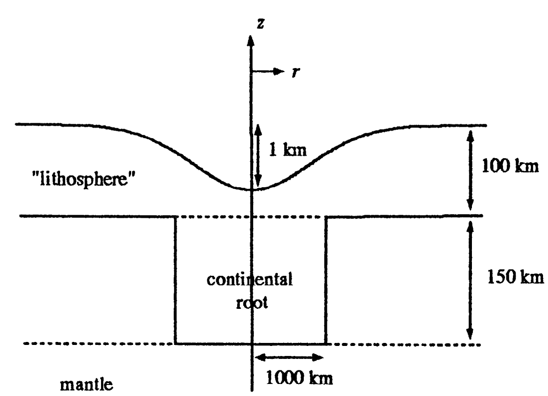

Figure 1. Geometry of the axisymmetric model problem. The lithosphere and mantle are assumed to be Newtonian fluids. The initial surface depression is described by a gaussian curve with an axial depth of 1 km. Calculations are presented for three different lithosphere structures: constant thickness of 100 km, constant thickness of 250 km, and variable thickness (shown with the solid curve).

of the effects of heterogeneities in mantle viscosity on postglacial rebound for a viscoelastic Earth is presented by *Gasperini & Sabadini* [1989]. Second, we also neglect the history of loading and unloading which, combined with neglecting elastic effects, prevents quantitative comparison with observations. Finally, we assume a shape for the lithosphere (figure 1) which is unlikely to characterize any actual continental root, but does capture the particular feature we are trying to study, namely, the change of lithosphere thickness.

In order to illustrate the effects of continental roots, we present three calculations. The calculation for a variable thickness lithosphere, referred to hereafter as the "variable" model, has a continental root 250 km thick which decreases to 100 km beyond a radius of 1000 km. Results are compared with calculations assuming either a 250 km or 100 km constant thickness lithosphere.

Results

Figure 2 shows the relaxation of the depression at radial positions of 0, 500, 900, 1100, 1500 and 2000 km. The edge of the tectosphere is at 1000 km. Near the center of the thickened lithosphere (for the variable case) the relaxation rate is nearly the same as that for a uniformly thick lithosphere of 250 km. Similarly, far outside the edge of the tectosphere the relaxation rate is similar to that for a 100 km thick lithosphere. Near the edge of the tectosphere, however, the relaxation rate is noticeably different, and not intermediate to the two uniform models; instead it is greater than either.

The surface strain rates for two of the models (250 km constant thickness and variable thickness lithospheres) are shown in figure 3 (strain rates for both constant thickness lithosphere models are qualitatively similar).

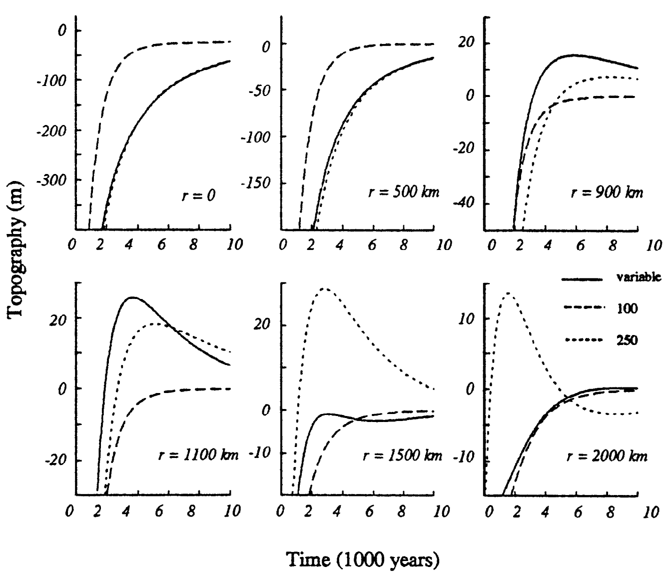

Figure 2. The relaxation of the depression at radial positions of 0, 500, 900, 1100, 1500 and 2000 km. The three sets of curves correspond to the three models illustrated in figure 1. The edge of the tectosphere is at a radial position of 1000 km.

The relative magnitudes of the deviatoric stresses indicates the type of fault motion that is favoured, assuming fault orientation is related to the viscous stresses by Anderson's theory of faulting. In figure 3 the background strain rate is assumed to be zero. We show the three principal components of the rate-of-strain tensor for the thick and variable models based on the initial conditions (i.e. 10 kyr ago, immediately following unloading) and at the present time. Following unloading, radial extension occurs above the formerly glaciated region in both models. For the constant thickness model, the region of extension is surrounded by a band of strike-slip deformation and concentric compression in the far-field (figure 3a), whereas near the edge of the tectosphere a narrow band of concentric extension develops (figure 3c). As the depression relaxes, the magnitude of the viscous stresses decreases and the pattern changes: radial extension still occurs above the middle of the depression, however, a large region of concentric compression develops surrounding the depression (figure 3b). For the calculation with a variable thickness lithosphere, a region of concentric extension also develops just beyond the edge of the continental root (figure 3d). We also note that, near the edge of the thickened lithosphere, strain rates for the variable thickness model are about twice as large as strain rates for the constant thickness model.

Discussion

The results presented in figure 2 indicate that a comparison of relaxation rates with depth-dependent models should provide local estimates of lithosphere thickness to within a few hundred km of the edge of the tectosphere. For example, the relative sea-level (RSL) histories from Hudson Bay studied by *Mitrovica & Peltier* [1993] should be insensitive to variations associated with continental roots since the locations are far from ocean-continent boundaries. However, near the edge of the thickened lithosphere, the variable thickness calculation produces very different relaxation curves. *Tushingham & Peltier* [1992] have identified a set of anomalous RSL observations which typically show much faster RSL rises than predicted by their ICE-3G model: examples include sites along the coast in Greenland and Norway. Although the change in thickness of the lithosphere does result in more rapid relaxation, the detailed shapes of the observed RSL curves do not resemble those shown in figure 2.

Owing to the neglect of background stresses and the history of loading and unloading, in addition to the simplified geometry and rheology, it is not surprising that neither model in figure 3 is consistent with the detailed distribution and orientation of seismically inferred faults in Baffin Bay and the Labrador Sea [*Stein et al.,* 1979]. In addition, the present day stresses in North America are thought to be dominated by contemporary tectonic stresses at plate boundaries [*Zoback* 1992], so that postglacial rebound probably does not play an important role in present day seis-

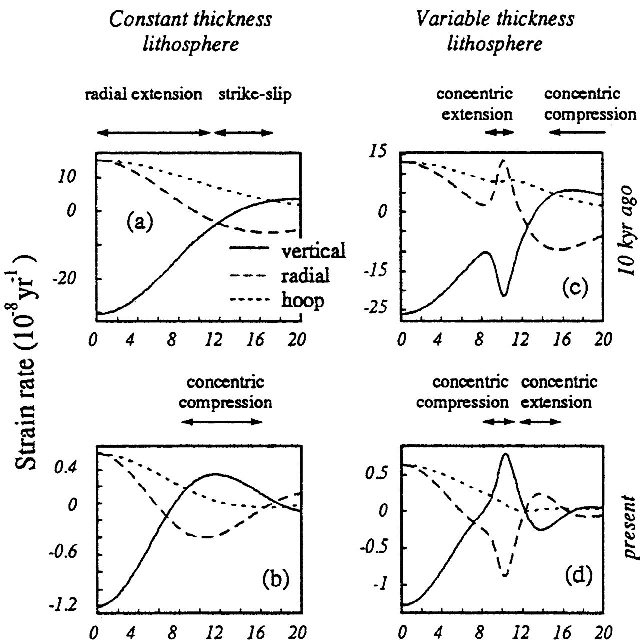

Figure 3. Surface strain rates for a constant thickness lithosphere (left) and variable thickness lithosphere (right), based on the initial unloaded conditions (top) and at the present time (bottom). The corresponding pattern of surface deformation (i.e. the pattern of faulting promoted by rebound induced strains) is labeled on the figures. In each graph the three curves correspond to the vertical strain rate (solid curve), radial strain rate (dashed curved), and hoop or tangential strain rate (dotted curve). Background strain rate is assumed to be zero.

micity and faulting, except perhaps in the St-Lawrence valley [*James & Bent* 1994]. However, during the early stages of postglacial rebound when stresses were up to two orders of magnitude greater (the viscous deviatoric stresses in figure 3ac are $\approx 50-100$ MPa), stresses associated with rebound may have dominated tectonic and seismic activity. *Spada et al.* [1991] have shown that if viscosity increases by a factor of 10 or more in the lower mantle, sufficiently large stresses may still remain from deglaciation to affect seismicity. Here we have shown that the presence of a tectosphere is an additional factor which will influence the pattern and evolution of surface deformation, and the resulting tectonics and seismicity, and that the effects of the tectosphere will be concentrated near the edge of the tectosphere.

The results presented in figure 3cd indicate that, in addition to increased viscous stresses near the edge of the tectosphere, regions of both concentric compression and extension (i.e. faults striking parallel to the margin) may have formed at passive margins off North America and Europe. It has been suggested that the initiation of subduction may arise from extensional deformation of the lithosphere [e.g. *Kemp* 1994]. The large extensional (and compressional) stresses produced at passive margins due to glacial unloading may play some role in the initiation of subduction, in addition to sediment loading, external plate tectonic forces and thermal effects, and thus there exists the possibility that climate variations (which cause glaciation and deglaciation) can influence mantle dynamics.

Summary

The results presented here and elsewhere [e.g. *Gasperini et al.,* 1990] indicate the potentially large effect of variations in the thickness of the lithosphere on postglacial rebound. Detailed postglacial rebound studies [e.g. *Lambeck* 1993; *Tushingham & Peltier* 1992] have found an excellent agreement between observations and models which assume depth-dependent viscosity structures which suggests that the tectosphere might not exist. However, *Gasperini & Sabadini* [1989] have shown that lateral viscosity variations can be interpreted as radial variations. Future postglacial rebound studies might also consider inverting for the thickness and effective viscosity of continental roots.

In the simple model investigated here, we have not included a more realistic depth-dependent viscosity structure, nor any elastic effects. However, such simplifications should not affect the general conclusion that the continental tectosphere, if it exists, should have a noticeable effect on postglacial rebound, in particular, near the edge of the tectosphere which is often near ocean-continent boundaries (where most tide gauges and observations of relative sea-level are located). Lateral variations of the viscosity and structure of the lithosphere will affect postglacial rebound rates, and thus the inferred sea-level change due to global warming, as well as the distribution of tectonic and seismic activity associated with deglaciation.

Finally we note that the scaling arguments presented in the appendix suggest that the tectosphere must be at least $O(10^2)$ times more viscous that the surrounding mantle in order to persist for more than one billion years. However, numerical calculations by *Gasperini & Sabadini* [1989] indicate that viscosity contrasts of up to only 1-2 orders of magnitude can be consistent with sea-level observations. This discrepancy suggests that current models may be deficient; a possibility is that the effective viscosity of the tectosphere depends on the time-scale (or strain rate) of interest.

Appendix: The tectosphere

Regions of seismically fast mantle beneath continents extending to depths up to 400 km [e.g. *Su et al.,* 1994], have been interpreted as being compositionally distinct mantle which forms stable (i.e. persistent and old) continental roots which translate coherently with moving plates [*Jordan* 1975]. This model involves a "delicately balanced tectosphere" produced by dynamic and magmatic processes associated with the Wilson cycle; specifically, the persistence of the tectosphere beneath Archean cratons for 3 b.y. requires that the tectosphere is chemically buoyant relative to the mantle, possibly as a result of the extraction of basaltic and komatiitic melt leaving behind and iron and calcium depleted residuum [*Jordan* 1978]. This interpretation has received support from a recent inversion of seismic tomography for density variations beneath continents: *Forte et al.* [1995] have found that the seismic velocity variations are consistent with combined thermal and chemical variations beneath continents. Here we present a short scaling argument which suggests that the continental tectosphere must be several orders of magnitude more viscous than typical mantle, and thus large long-wavelength lateral viscosity variations are likely to exist.

Consider a high viscosity continental root with characteristic thickness a, an effective Newtonian viscosity $\lambda\mu$ and density $\rho + \Delta\rho$ in a mantle with viscosity μ and density ρ. If $\lambda \gg 1$ the characteristic strain-rate arising from buoyancy forces is $O(\Delta\rho g a/\lambda\mu)$. Since we expect that the strain over the last 3 b.y. is $< O(1)$, and choosing $a = 300$ km, $\mu = 10^{21}$ Pas, we find $\lambda > O(300\Delta\rho)$ where $\Delta\rho$ is measured in kg/m^3. Assuming a density difference of 0.01 % (a very small density difference) leads to $\lambda > O(100)$. Density heterogeneities inferred from seismology are O(1%) [cf. *Forte et al.* 1995].

Deformation of continental roots may also occur due to viscous stresses exerted by a convecting mantle. The rate of deformation will be approximately $\dot\epsilon/\lambda$, where $\dot\epsilon$ is the mantle strain rate. If we again require that the cumulative strain over some time τ is less than $O(1)$ and that a typical mantle strain rate is 10^{-15} s^{-1}, we require $\lambda > O(10^{-15}\tau)$ where τ is measured in seconds. Assuming the mantle flow is steady over a period of 3 b.y., $\lambda > O(100)$. Although the actual deformation history will be complicated, and will depend on the thermal, chemical and convection history of the whole mantle, these simple scaling arguments suggest that the tectosphere, if it is to exist and persist over long geologic times, must be substantially more viscous than the surrounding mantle.

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M. Manga, Department of Geology and Geophysics, University of California, Berkeley, CA 94720-4767.

R.J. O'Connell, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138.

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