THE SOURCE OF THE EARTH'S LONG WAVELENGTH GEOID ANOMALIES: IMPLICATIONS FOR MANTLE AND CORE DYNAMICS

Bradford H. Hager and Mark A. Richards
Seismological Laboratory
California Institute of Technology
Pasadena, California 91125

Richard J. O'Connell
Department of Geological Sciences
Harvard University
Cambridge, Massachusetts 02138

The long-wavelength ($\ell \leq 10$) components of the Earth's gravity field result mainly from density contrasts associated with convection in the mantle. However, direct interpretation of the geoid in terms of mantle convection is complicated by the fact that convective flow results in dynamically maintained deformation of the surface of the Earth, the core-mantle boundary (CMB), and any interior chemical boundaries which might exist. (Mid-ocean ridges and deep sea trenches are familiar examples of surface topography resulting from density contrasts of convective origin.) These boundary deformations have effects on the geoid opposite in sign and comparable in magnitude to those of the interior density contrasts driving the flow; thus the total geoid anomaly in a dynamic earth is a small number resulting from the difference of two relatively large quantities.

We have calculated the total geoid response for interior density contrasts as a function of depth and spherical harmonic degree for a series of simple mantle flow models. These models assume a self-gravitating, incompressible fluid with a spherically symmetric, radially layered Newtonian rheology. We consider models both with mantle-wide flow and with chemical stratification between the upper and lower mantle. For a given density contrast, the sign of the total geoid anomaly depends on the variation of viscosity with depth; uniform viscosity, or viscosity decreasing with depth, leads to negative total geoid anomalies for positive density contrasts due to the overwhelming effect of deformation of the upper boundary, while a sufficiently large increase in viscosity with depth results in a total positive anomaly. The amplitudes of the net geoid anomalies get smaller the closer the driving density contrasts get to a boundary. Density contrasts at compositional boundaries are identically compensated and lead to zero net geoid anomalies. For a given density contrast, geoid anomalies are generally much smaller for a chemically stratified mantle than for one of uniform composition. Density contrasts of different wavelengths sample the mantle in different ways, allowing resolution of variations of mantle viscosity with depth if the driving density contrasts can be determined by some other method.

Recent advances in seismic tomography have resulted in images of long-wavelength lateral heterogeneity in seismic velocity. These velocity variations presumably are proportional to density variations, both resulting from temperature differences associated with mantle convection. Using the results from seismic tomography, a geophysical model of subducting slabs, and the effects of Pliestocene deglaciation, in conjunction with the dynamic geoid response for flow models allows us to account for 90% of the variance in the observed long-wavelength (ℓ = 2-9) nonhydrostatic geoid.

This successful explanation of most of the long-wavelength geoid using seismically imaged density contrasts and dynamic flow models has implications for a wide range of problems in mantle and core dynamics:

- Flow models that successfully predict the geoid have several kilometers of dynamically maintained relief at the CMB. This topography, which correlates well with the geoid, may have an important effect on core dynamics and on core-mantle coupling.

- There is substantial agreement between the thermal structures of the upper and lower mantle. Surface hotspots lie above hot regions of the lower mantle and cold lower mantle is associated with subduction in the upper mantle. Either convection is mantle-wide or thermally coupled.

- For mantle-wide flow, about a kilometer of dynamically maintained surface topography is predicted. The pattern and amplitude approximately match observed oceanic depth anomalies and continental hypsographic anomalies. Changes in positions of continents and ocean basins relative to the mantle convection pattern would result in substantial epeirogenic motions and changes in eustatic sea level.

- By interpreting the seismically imaged density anomalies in terms of temperature contrasts, we can use the flow models to calculate the advected heat flux through the lower mantle. By comparing this to the observed global heat flux we conclude that the viscosity of the lower mantle exceeds 10^{23}p.

- Our preferred viscosity model has a 10^{21} p asthenosphere, with viscosity increasing to 3×10^{23} p in the lower mantle. In addition to explaining the geoid, such a model satisfies the relaxation spectra for Fennoscandia, the geoid anomaly over Hudson Bay and the long relaxation time for $\dot{J}_2$. Observations of the rates of change of other long wavelength components of the Earth's gravity field would provide powerful tests of this model.

At present we can explain 90% of the variance in the geoid at long wavelengths. Expected improvement in seismological techniques and computation of the geoid response for more realistic rheologies should allow further improvement. Accurate determination of long-wavelength geoid anomalies in conjunction with these developments should greatly advance our knowledge and understanding of mantle convection and the driving mechanism for plate motions.