

EARTH'S GRAVITATIONAL FIELD: SEISMIC TOMOGRAPHY
RESOLVES THE ENIGMA OF THE LAURENTIAN ANOMALY

W.R. Peltier, A.M. Forte, J.X. Mitrovica, A.M. Dziewonski

Reprinted from

**Geophysical
Research
Letters**

Volume 19, Number 15, August 3, 1992

EARTH'S GRAVITATIONAL FIELD: SEISMIC TOMOGRAPHY
RESOLVES THE ENIGMA OF THE LAURENTIAN ANOMALYW.R. Peltier¹, A.M. Forte², J.X. Mitrovica³, A.M. Dziewonski²

Abstract. We demonstrate that the negative free air gravity anomaly over Hudson Bay is not due to glacial isostatic disequilibrium but rather to the influence of large scale mantle convection.

Introduction

In Figure 1 we show the "free-air" gravity anomaly on the Earth's surface according to both surface pendulum observations (plate a) and the recently published (Marsh et al., 1990) GEMT2 satellite solution (plate b). In order to make this comparison direct we have based each of these independent measures of the anomalous field on spherical harmonic expansions truncated at degree and order 32. For the GEMT2 solution this has meant omitting a rather small number of higher degree and order coefficients. For the surface data, on the other hand, this has involved expanding the roughly 600,000 land and marine observations (Goodacre et al. 1987) that are available over Canada on a 5 km x 5 km grid, in spherical harmonics, and then sharply truncating the expansion. Inspection of plates a and b of Figure 1 demonstrates that these two representations of the field agree on both the form and the amplitude of the anomalous signal in this geographical region. It will be observed that the maximum surface pendulum derived anomaly is very slightly less negative than the satellite anomaly (-42 mgal compared to -47 mgal) and that the surface anomaly agrees with the satellite anomaly only over land, a consequence of the fact that no data from offshore Canada or from the United States were employed in our construction of the surface field.

The reason why the large negative free air gravity anomaly over Hudson Bay has usually been interpreted as due to the existing imbalance associated with the glacial isostatic adjustment process should be clear on the basis of Figure 2 (apex). This shows the thickness of ice in the Northern Hemisphere that existed approximately 20,000 years ago at the time of the last glacial maximum of the present ice age, based upon the recently presented ICE-3G model (Tushingham and Peltier 1991). Comparison of Figure 2 with Figure 1 demonstrates that the correlation between the negative free air anomaly and ice sheet topography is reasonably good, suggesting that the former might be entirely explicable as a measure of the degree of glacial isostatic disequilibrium in this region (Walcott 1970).

Glacial isostatic adjustment and the enigma of the
Laurentian anomaly

Analyses of this anomaly published over the past several years have lead to an increasing realization that a problem exists with this interpretation though these were all performed with insufficiently accurate disk load models of the deglaciation history (Wu and Peltier 1983, Mitrovica and Peltier 1989, 1991) and tended to suggest that the Laurentian anomaly was explicable as a response to this forcing. The newly available ICE-3G deglaciation model is of sufficient accuracy that we are now in a position to provide a rather definitive demonstration of the extent to which the deglaciation hypothesis is viable and this we shall do below.

Using the ICE-3G deglaciation model as input to fix the deglaciation history, visco-elastic field theory (Peltier 1989; Mitrovica and Peltier 1989, 1991) has been employed to compute a new sequence of relative sea level (rsl) histories at sites that were covered by Laurentide ice and for different assumed values for the upper mantle - lower mantle viscosity

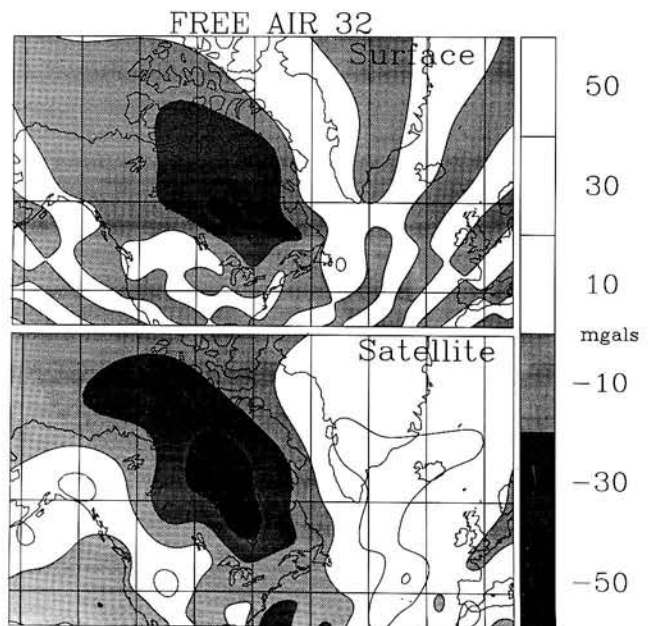


Fig. 1. The free air gravity anomaly over Canada as determined on the basis of surface pendulum observations (plate a) and on the basis of analyses of the orbits of artificial Earth satellites (plate b). Both maps have been constructed on the basis of spherical harmonic expansions of the field truncated at degree and order 32. The Gibbs oscillations evident in the surface field off the east and west coasts of North America are an artifact of the fact that only data from the continental interior were employed to determine the spherical harmonic coefficients.

¹Department of Physics, University of Toronto

²Department of Earth and Planetary Sciences, Harvard

³Harvard Smithsonian Center for Astrophysics

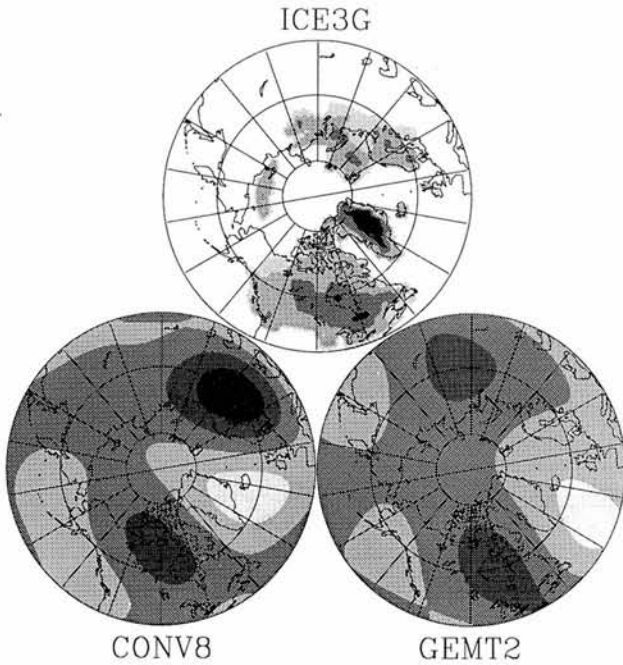


Fig. 2. The thickness of Northern Hemisphere ice at the last glacial maximum (apex) according to the recently presented ICE-3G reconstruction¹³. The colour bar employed to represent the field changes discontinuously at 1 km intervals. The greatest thickness of ice occurs over Hudson Bay where it exceeds 3 km. The lower hemispheres present the satellite observed (GEMT2) and convection predicted (CONV8) free air gravity anomaly fields for the Northern Hemisphere.

contrast. These synthetic sea level histories are presented on Figure 3 for the set of six locations shown on the inset. On the six individual plates of Figure 3 the observed data are denoted by the vertical bars (for the rsl histories, time is in sidereal rather than ¹⁴C years). Theoretical predictions are superimposed for four new models (each of which has an upper mantle viscosity of 10²¹ Pa s down to 670 km depth and an elastic lithosphere of thickness 120 km), having lower mantle viscosities of 1 x 10²¹ Pa s, 2 x 10²¹ Pa s, 4.5 x 10²¹ Pa s, and 10²² Pa s respectively. Inspection of these plates demonstrates that only the first two models are able to provide a satisfactory reconciliation of the data.

Using the same newly constructed ICE-3G deglaciation model, and under the sufficiently accurate assumption that the ocean basins are filled eustatically by the melting ice, we have also computed (Figure 4) the present day free air gravity anomaly expected over the entire surface of the earth for the same sequence of mantle viscosity stratifications (using spherical harmonic expansions truncated at degree and order 64). Inspection of this Figure clearly demonstrates the seriousness of the enigma that we are obliged to face. Only the model with a lower mantle whose viscosity that is ten times higher than the viscosity of the upper mantle comes close to reconciling the observed free air anomaly (the extremum of which is near -47 mgal) and even with this large viscosity contrast the peak magnitude of the theoretical prediction is low by 15 mgals. This conflict, originally reported by us in Peltier et al. (1991) has recently been further noted by James (1992).

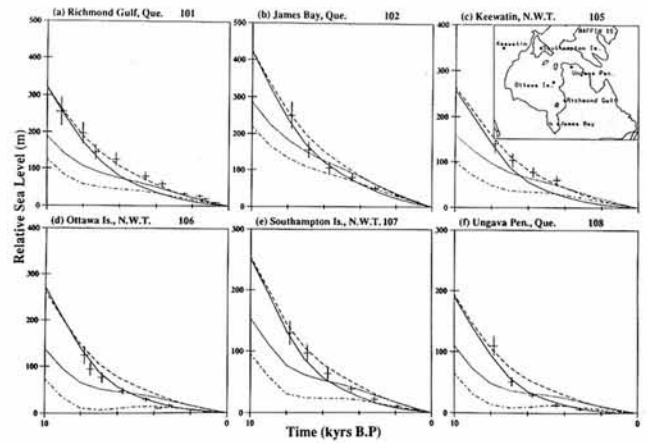


Fig. 3. Observed relative sea level histories for the sites shown on the inset location map are represented by the vertical bars. At each site we show predictions of the relative sea level history for four different viscosity models, each of which has a 120 km thick lithosphere in which the viscosity is assumed infinite and an upper mantle extending to 670 km depth in which the viscosity is assumed to be equal to 10²¹ Pa s. The solid, dashed, dotted, and dash-dotted curves are for models in which the lower mantle viscosity is 10²¹ Pa s, 2 x 10²¹ Pa s, 4.5 x 10²¹ Pa s, and 10²² Pa s respectively.

Mantle convection, seismic tomography, and the gravity field over Laurentia

Over the past decade, major advances have been achieved in understanding the non-hydrostatic structure of the planet's gravitational field. These advances have been the

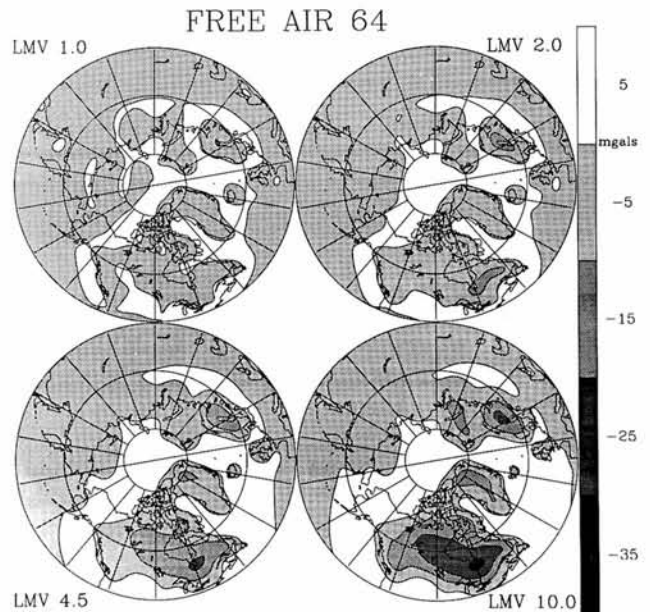


Fig. 4. Present day northern hemisphere free air gravity anomaly maps predicted using the same four mantle viscosity structures as were employed for the relative sea level calculations presented on Figure 5. The models are distinguished on the four plates by the lower mantle viscosity (LMV) values which characterize them. The lower mantle viscosities are indicated in multiples of 10²¹ Pa s.

consequence of developments in seismic body wave and surface wave tomography (e.g. Masters et al. 1982, Dziewonski 1984, Woodhouse and Dziewonski 1984). This methodology delivers models of the three dimensional temperature structure in the interior which may be converted into models of the density field, enabling simple convection models to be integrated to predict a number of different geophysical observables. The earliest analyses of this type focused upon the large scale features in the non-hydrostatic geoid (Hager 1984) and these analyses have demonstrated that much of the long wavelength variance in this field (for $\ell, m \leq 8$) could be thereby explained. More recent analyses (Forte and Peltier 1987, 1991) have established that the poloidal component of the surface plate velocity spectrum can also be understood in this way, as can the seismically observed topography on the core-mantle interface, all in terms of models with radial viscosity contrast that matches that required by the glacial isostatic adjustment data over the range of depths to which these data are sensitive.

In assessing the extent to which the nonhydrostatic structure of the gravitational field due to flow induced by the three dimensional temperature structure in the mantle may be contributing to the observed free air gravity anomaly over Laurentia, we will make use of the very recently constructed model SH425.2 of the lateral heterogeneity of the SH-wave seismic velocity in the mantle obtained by Su and Dziewonski (1991).

The seismic velocity heterogeneity described by model SH425.2 has been converted to an equivalent model of density heterogeneity, $\delta\rho^{S-D}(r, \theta, \psi)$, by selecting the proportionality factor $\partial\ln\rho/\partial\ln v_s = 0.3$ from the surface to 400 km depth and $\partial\ln\rho/\partial\ln v_s = 0.3$ in the lower mantle also. These values are in good accord with recent high-temperature laboratory studies. In the transition zone (400-670 km depth), we find that optimal fits to the geoid over the entire surface of the earth are obtained by selecting $\partial\ln\rho/\partial\ln v_s$ in the range 0.5 - 1.5, in which the latter value provides the best fit to the global geoid data. The optimal two-layer viscosity profile of the mantle which allows us to achieve this very good fit to the global nonhydrostatic geoid is characterized by a factor of 11 viscosity increase at 1200 km depth below which the postglacial rebound data have little sensitivity. This preference for a modest viscosity jump deep in the lower mantle agrees with our previous analyses (Forte and Peltier 1987, 1991).

The theory of infinite Prandtl number thermal convection in a spherical shell of fluid which is employed to make the nonhydrostatic geoid predictions discussed above delivers a prediction of the spherical harmonic coefficients of the surface free air gravity anomaly in the form:

$$\Delta g_{\ell m} = \int_b^a FA_{\ell}(v, r) \delta\rho_{\ell m}^{S-D}(r) dr \quad (1)$$

in which $FA_{\ell}(v, r)$ is the kernel for the free air gravity anomaly, $v(r)$ is the radial profile of mantle viscosity, and b and a are the radii of the core-mantle boundary and of the earth respectively. The kernel FA_{ℓ} differs from that for geoid height simply by a constant multiplicative factor and an $(\ell-1)$ weighting and therefore also depends solely upon the ratio of upper mantle to lower mantle viscosity rather than upon the absolute magnitude of the viscosity in either layer (Forte and Peltier 1987).

Free air gravity and geoid height maps predicted for the Laurentide platform using the spherical harmonic coefficients to degree and order 8 delivered by model SH425.2, using (1)

and its' equivalent for geoid height, are shown on the first two plates of Figure 5, on the basis of which the reader will immediately note that the convection model predicts a region of negative geoid anomaly over all of North America and a region of negative free air anomaly over Canada. Comparing the free air anomaly predicted by the convection model to the GEMT2 field in the same range of spherical harmonic degree and order (last plate in Figure 5) we notice a striking similarity in both magnitude and form. Across a traverse over Hudson Bay at 60°N latitude the free air anomaly predicted by the tomographic model fits the satellite field extremely well, with the observed anomaly being only about 5 mgal deeper than that predicted by the convection model, a residual that is easily reconciled by the additional anomaly due to incomplete glacial isostatic adjustment (see Figure 4).

In our view this analysis provides an extremely satisfactory resolution of the enigma posed by the magnitude of the long wavelength negative free air gravity anomaly that is centred over the Hudson Bay region of the North American continent.

Implications of the continental gravity-convection connection

Inspection of Figure 4 demonstrates that although the free air gravity anomaly predicted by the glacial isostatic

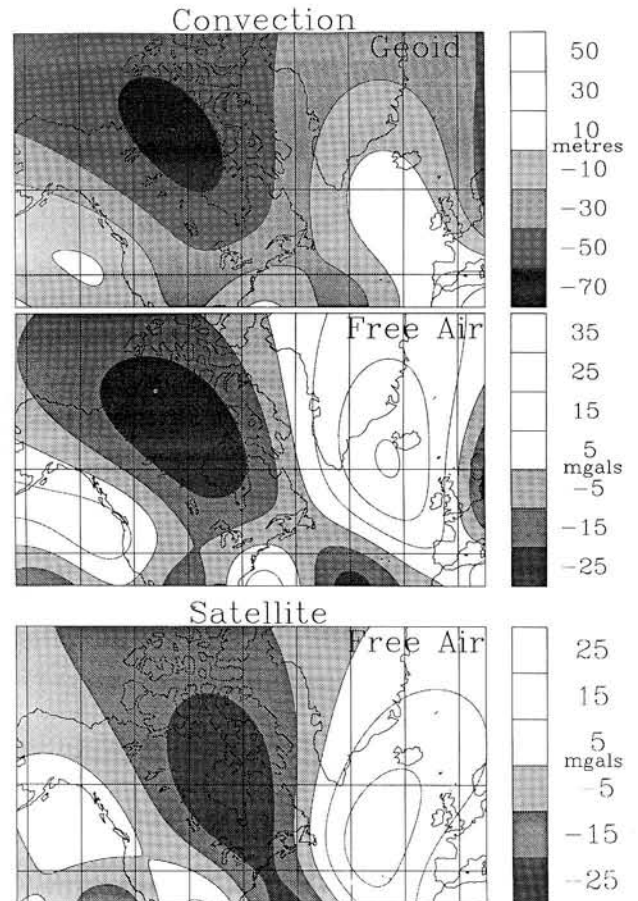


Fig. 5. Geoid (plate a) and free air gravity anomaly maps for the North American continent predicted using the two layer mantle convection model described in the text. Both maps are based upon spherical harmonic expansions truncated at degree and order 8. The model of the internal density heterogeneity employed to make the predictions is model SH425.2 described in Su and Dziewonski³⁸. Plate (c) shows the GEMT2 satellite field over the same geographic region and at the same resolution.

adjustment model for the Hudson Bay region is not adequate to fit the observed anomaly, the same is not true for Fennoscandia. In the latter region the ICE-3G deglaciation model predicts an anomaly of about -12 mgals with an increase in viscosity from the upper to the lower mantle of only a factor of two, which is of course acceptable to the relative sea level data as we have already discussed. Since there is no significant convection component of the signal in this region (Figure 2) the explanation of the free air anomaly must continue to lie in the glacial isostatic adjustment process.

The most significant implication, we believe, of the large negative free air anomaly that the mantle convection process induces over the Precambrian Shield of Canada (and the similar anomalies that it predicts over Eurasia and Antarctica), concerns the dynamic topographic relief that is induced by the flow. The full convection theory that delivers the prediction (1), and on the basis of which our maps of the free air and geoid anomalies were computed, predicts an approximately 3 km negative surface topographic undulation to be associated with the circulation. It is this topographic contribution to the surface gravity field that determines its sign. This large dynamic topographic relief associated with large scale convection is considerably in excess of that associated with small scale convection under the oceanic lithosphere (Colin and Fleitout 1990, Cazanave and Lago 1991). In the most recent tomographic reconstructions of the interior density field (Su and Dziewonski 1991), deep seated regions of anomalously high density extending from the surface well into the lower mantle appear to be characteristic of most shield areas and these all induce downwelling flow. It may be that these downwellings are associated with instability of the cold surface boundary layer. In a companion paper (Forte et al. 1992) we demonstrate that the dynamic topography predicted by our convection models is rather precisely equal to the observed dynamic topography after the actual topography has been "filtered" to remove the component that is isostatically supported by the lateral density heterogeneity associated with oceanic and continental crust. This result has rather clear implications for the understanding of continental tectonics, perhaps especially concerning the origin of intracratonic sedimentary basins such as the Hudson Bay Basin, the Williston Basin, and the Illinois and Michigan Basins of the North American continent. The cold downwelling flow, derivative perhaps of boundary layer instability, could be the agency through which the basin formation process is activated.

References

- Cazanave, A., and B. Lago, Long wavelength topography, seafloor subsidence and flattening, *Geophys. Res. Lett.*, **18**, 1257-1260, 1991.
- Colin, P., and L. Fleitout, Topography of the ocean floor: Thermal evolution of the lithosphere and interaction and interaction of deep mantle heterogeneities with the lithosphere, and interaction of deep mantle heterogeneities with the lithosphere, *Geophys. Res. Lett.*, **17**, 1961-1964, 1990.
- Dziewonski, A.M., Mapping the lower mantle: Determination of lateral heterogeneity in P velocity up to degree and order 6, *J. Geophys. Res.*, **89**, 5929-5952, 1984.
- Forte, A.M. & Peltier, W.R., Plate tectonics and a-spherical earth structure: the importance of poloidal-toroidal coupling, *J. Geophys. Res.*, **92**, 3645-3679, 1987.
- Forte, A.M. & Peltier, W.R., Viscous flow models of global geophysical observables. I. Forward problems, *J. Geophys. Res.*, **96**, 20,131-20,159, 1991.
- Forte, A.M., W.R. Peltier, A.M. Dziewonski, J.R.L. Woodward, Dynamic surface topography: a new interpretation with mantle flow derived from seismic tomography, *Geophys. Res. Lett.*, submitted, 1992.
- Goodacre, A.K., Grieve, R.A.F., & Halpenny, J.F., *Free Air Gravity Map of Canada*, Geol. Survey of Canada, Can. Geophys. Atlas, Map 2, scale 1:10,000,000, 1987.
- Hager, B.H., Subducted slabs and the geoid: constraints on mantle rheology and flow, *J. Geophys. Res.*, **89**, 6003-6015, 1984.
- James, Thomas S., The Hudson Bay gravity anomaly and glacial rebound, *Geophys. Res. Lett.*, **19**, 861-865, 1992.
- Marsh, J.G., Lerch, F.J., Putney, B.H., Felsenberger, T.L., Sanchez, B.V., Klosko, S.M., Patel, G.B., Robbins, J.W., Williamson, R.G., Englis, T.L., Eddy, W.F., Chandler, N.L., Chinn, D.S., Kapoor, S., Rachlin, K.E., Braatz, L.E., & Paulis, E.C., The GEM-T2 gravitational model, *J. Geophys. Res.*, **95**, 22043-22071, 1990.
- Masters, G., Jordan, T.H., Silver, P.G., & Gilbert, F., A-spherical earth structure from fundamental spheroidal mode data, *Nature*, **298**, 609-613, 1982.
- Mitrovica, J.X. & Peltier, W.R., Pleistocene deglaciation and the global gravity field, *J. Geophys. Res.*, **94**, 13651-13671, 1989.
- Mitrovica, J.X. & Peltier, W.R., Free air gravity anomalies associated with glacial isostatic disequilibrium: Load history effects on the inference of deep mantle viscosity, *Geophys. Res. Lett.*, **18**, 235-238, 1991.
- Peltier, W.R., A.M. Forte, J.X. Mitrovica and A.M. Dziewonski, Mantle convection and the free air gravity anomaly over Laurentia, *EOS*, October 29, 507, 1991.
- Su, W.J. & Dziewonski, A.M., The red spectrum of mantle heterogeneities, *Nature*, in press.
- Tushingham, A.M. & Peltier, W.R., ICE-3G: A new global model of late Pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea level change, *J. Geophys. Res.*, **96**, 4497-4523, 1991.
- Walcott, R.I., Isostatic response to the loading of the crust in Canada, *Can. J. Earth Sci.*, **7**, 716-727, 1970.
- Wu, Patrick & Peltier, W.R., Glacial isostatic adjustment and the free air gravity anomaly as a constraint on deep mantle viscosity, *Geophys. J.R. astr. Soc.*, **74**, 377-449, 1983.
- Woodhouse, J.H. & Dziewonski, A.M., Mapping the upper mantle: three dimensional modelling of earth structure by inversion of seismic wave forms, *J. Geophys. Res.*, **89**, 5953-5986, 1984.

W.R. Peltier, Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

A.M. Forte and A.M. Dziewonski, Department of Earth and Planetary Sciences, Hoffman Laboratory, Harvard University, Cambridge, MA 02138 U.S.A.

J.X. Mitrovica, Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138 U.S.A.

(Received June 15, 1992

Accepted June 29, 1992.)