Satellite gravity drilling the Earth

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Abstract

Analysis of satellite-measured gravity and topography can provide crust-to-core mass variation models for new insight on the geologic evolution of the Earth. The internal structure of the Earth is mostly constrained by seismic observations and geochemical considerations. We suggest that these constraints may be augmented by gravity drilling that interprets satellite altitude free-air gravity observations for boundary undulations of the internal density layers related to mass flow. The approach involves separating the free-air anomalies into terrain-correlated and –decorrelated components based on the correlation spectrum between the anomalies and the gravity effects of the terrain. The terrain-decorrelated gravity anomalies are largely devoid of the long wavelength interfering effects of the terrain gravity and thus provide enhanced constraints for modeling mass variations of the mantle and core. For the Earth, subcrustal interpretations of the terrain-decorrelated anomalies are constrained by radially stratified densities inferred from seismic observations. These anomalies, with frequencies that clearly decrease as the density contrasts deepen, facilitate mapping mass flow patterns related to the thermodynamic state and evolution of the Earth's interior

1 Introduction

The internal structures of terrestrial planets are commonly constrained by seismic data and geochemical considerations. We suggest that these constraints may be augmented by gravity drilling that focuses on interpreting satellite altitude free-air gravity observations for boundary undulations of the internal density layers related to mass flow. This approach involves separating the free-air gravity anomalies into terrain-correlated and -decorrelated components based on the correlation spectrum between the anomalies and the gravity effects of the terrain (Potts & von Frese, 2003). The terrain-decorrelated gravity anomalies are largely devoid of the long wavelength interfering effects of the terrain gravity and hence provide enhanced constraints for modeling mass variations of the mantle and core. For the Earth, subcrustal interpretations of the terrain-decorrelated anomalies are constrained by radially stratified densities inferred from seismic observations (e.g., Potts et al., 2003; Bott, 1982). For other mass differentiated bodies like the Moon, Mars and Venus, seismic soundings are largely lacking. Here, geochemical and moment-of-inertia considerations must be invoked to constrain the radial density structures in interpreting the terrain-decorrelated free-air anomalies. These anomalies, with frequencies that clearly decrease as the density contrasts deepen, facilitate mapping mass flow patterns related to the thermodynamic state and evolution of the planetary interiors.

2 Methodology

Gravity drilling was first implemented for mapping lunar intracrustal and subcrustal mass variations using the correlation spectrum between the Lunar Prospector satellite free-air gravity estimates and the terrain-decorrelated anomaly components at 100-km altitude (Potts & von Frese, 2003). Folloiwng this approach, we interpreted the EGM96 terrain-decorrelated free-air anomaly components for the Earth at 100-km latitude as shown in **Figure 1**. The related correlation spectrum in **Figure 1B** reveals several branches for separating the terrain-decorrelated anomalies into core, mantle and crustal components. The steepest branch marked by the red shaded triangle, for example, identifies the terrain-decorrelated components that are positively correlated with the free-air anomalies up through spherical harmonic degree 10 that may be interpreted for possible undulations of the Earth's core-mantle boundary. Similarly, the two middle branches of the correlation spectrum for the anomaly components from degrees 11 through 14 (orange shaded triangle) and degrees 15 through 25 (green shaded triangle) can be related to density undulations of the middle, and upper mantle, respectively. Furthermore, the relatively flat branch for the anomaly components at degree 26 and higher (grey shaded trapezoid) can reflect the effects of uncompensated crustal density contrasts. These interpretations of the terrain-decorrelated anomalies can be readily tested against standard geological models of the Earth's interior by inversions of the extracted crustal and subcrustal components. Similar modeling of terrain-decorrelated anomalies using inferred radial density profiles of the Moon, Mars, and Venus may estimate the related core-mantle boundaries and undulations of stratified mantle components that reflect mass flow patterns to help explain the development of surface tectonic features.

3 Discussion

Figure 2 illustrates the potential for extracting subcrustal information from satellite-observed free-air anomalies. In this Antarctic example, the terrain-decorrelated anomalies from (von Frese et al., 1999) that are positively correlated with EGM96 free-air anomalies up to degree 4 at satellite altitude were modeled for the relief of the core-mantle boundary (CMB). The CMB was estimated by least squares inversion using Gauss-Lengendre quadrature integration with a 4-gm/cm^3 contrast in density of the core relative to the mantle across the seismically determined mean core radius of 2,900 km. To first order, these CMB estimates may reflect strongly subducting lithospheric flow in the Pacific (Romanowicz & Gung, 2002). However, the estimates also can constrain core flow, topographic core-mantle coupling, core-mantle thermal coupling and torques that may lengthen the day, and the non-dipolar properties of the core field (e.g., Voorhies, 1995).

The EGM96 free-air gravity estimates over the polar regions are seriously incomplete due to the lack of gravity observations. Hence, we expect to improve significantly the CMB estimates in **Figure 2.A** using the enhanced gravity anomalies mapped by the CHAMP and GRACE missions. These results can offer new insights on the Earth's deep interior to complement more conventional constraints like the seismic CMB estimates shown in **Figures 2.B** and **2.C**. For example, the correlation matrix in **Figure 2.D** reveals that our results favor most strongly the seismic CMB estimates of **Figure 2.B** relative to the CMB estimates in **Figure 2.C.**

4 Conclusions

Gravity drilling of mass differentiated planets such as Earth provides a useful and alternate approach to modeling subcrustal mass variations. Most terrestrial planets, other than the Earth and to a limited extent the Moon, lack seismic data but have global coverage of satellite gravity and topography data. Although lacking seismic data, interior mass differentiation models from joint analysis of gravity and topography data can provide new insights for understanding the evolution of their surface tectonic features. For example, the correlation spectrum for Venus shows no secondary branches for the mantle components compared to Earth suggesting that mass flow in the Venusian mantle is limited compared to vigorous mantle dynamics on Earth (Potts et al., 2003). Also, the utility of this approach can provide further insights on fluctuations in planetary rotation rates over decadal scales due to the topographic couplings between their respective cores and mantles (Hide & Malin, 1970).

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References

Bott, M.: The Interior of the Earth: Its Structure, Constitution, and Evolution. Elsevier, New York, 1982.

Hide, R., and Malin, S.R.C.: Novel correlations between global features of the Earth's gravitational and magnetic fields, Nature, 225, 605-609, 1970.

Ishii, M., and Troon, J.: Even-degree lateral variations in the Earths mantle constrained by free oscillations and the free-air gravity anomaly, Geophys. J. Int., 145, 77-96, 2001.

Potts, L.V., and von Frese, R.R.B.: Comprehensive mass modeling of the Moon from spectrally correlated free-air and terrain gravity data, J. Geophys. Res., 108(E4), 5024, doi:10.1029/2000JE001440, 2003.

Potts, L.V., Leftwich, T.E., Kim, H.R.,, Han, S-C., and von Frese, R.R.B., Gravity drilling of mass differentiated planets. In Lunar Planetary Science XXXIV, Abstract #1934, Lunar Planetary Institute, Houston, (CD-ROM), 2003.

Romanowicz, B., and Gung, Y.: Superplumes from the core-mantle boundary to the lithosphere: Implication for heat flux, Science, 296, 513-516, 2002.

Sze, E.K.M., and van der Hilst, R.D.: Core mantle boundary topography from short period

PcP, PKP, and PKKP data, Phys. Earth Planet. Inter., 135, 27-46, 2003.

von Frese, R.R.B., Tan, L., Kim, J.W., and Bentley, C.R.: Antarctic crustal modeling from the spectral correlation of free-air gravity anomalies with the terrain, J. Geophysical. Res., 104, 25275-25296, 1999.

Voorhies, C.V.: Time-varying fluid flow at the top of Earth's core derived from Definitive Geomagnetic Reference Field models, J. Geophys. Res., 99, 6685-6693, 1995.

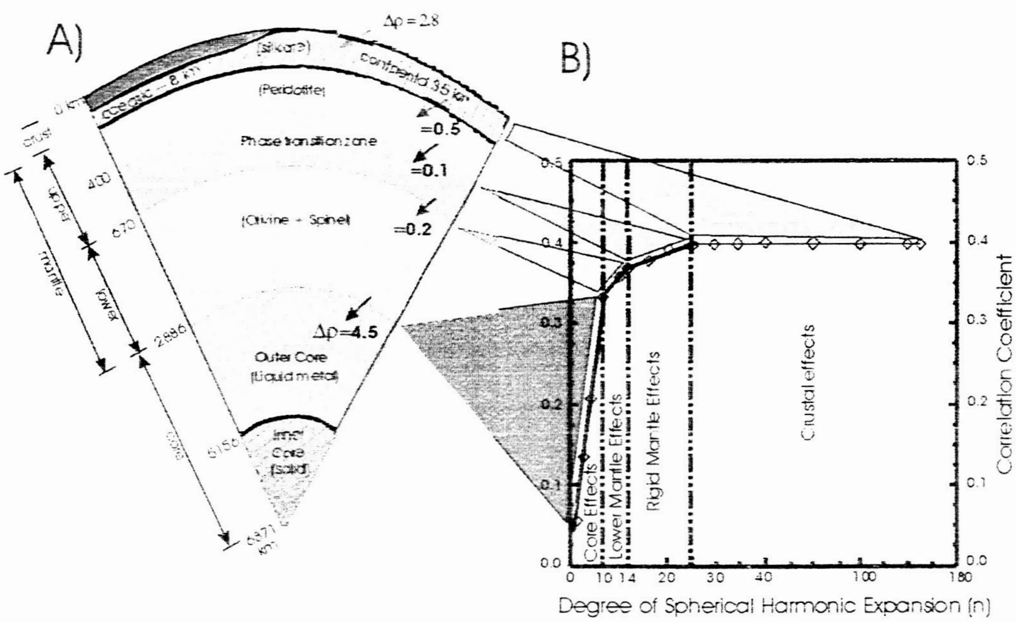
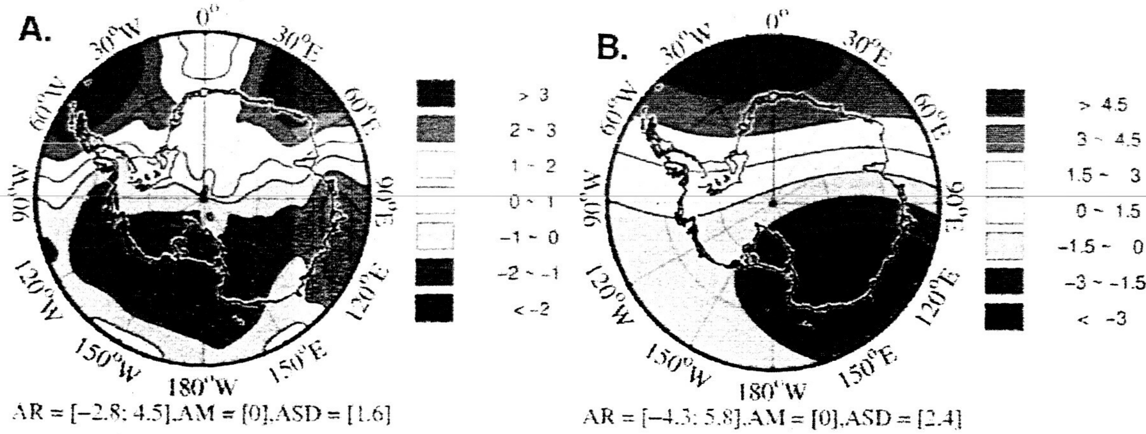
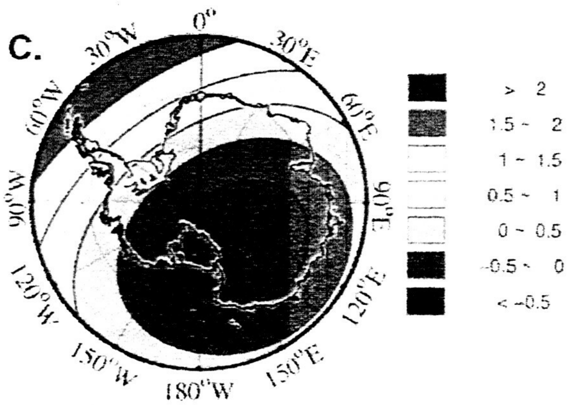


Figure 1. Geologic framework for interpreting terrain-decorrelated free-air gravity anomalies of the Earth. A) radial density contrast ($\Delta\rho$ in gm/cm^3) profile generalized from seismic and geochemical analyses and moment-of-inertia models. B) Correlation spectrum between the terrain-decorrelated and free-air gravity anomalies.





D.

	A	B	C
A	1	0.81	0.62
B		1	0.80
C			1

Figure 2. Comparing A) gravity CMB estimates (km) with seismic CMB estimates from B) Ishii & Troon (2001) and C) Sze & van der Hilst (2003) yields the correlation matrix shown in D).

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The internal structures of terrestrial planets are commonly constrained by seismic data and geochemical considerations. We suggest that these constraints may be augmented by "gravity drilling" that focuses on interpreting satellite altitude gravity observations for variations of the internal density structure. In this method we divide the satellite altitude gravity observations into two groups, those that are related to the Earth's topography and those that are not. Obviously the gravity signals related to the topography are produced by these surface features while those gravity signals that are not related to the topography, or are de-correlated with topography, are produces by deeper sources. In the de-correlated signals the ones with the longer wavelength are interpreted as coming from deeper sources in the Earth. By studying the longest wavelengths we may be able to study the deepest parts of the Earth, even the core-mantle boundary.