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Interior structure of the Moon: Constraints from seismic tomography, gravity and topography

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ABSTRACT

Seismic tomography can be combined with constraints from geoid, topography and other surface observations to gain information about mantle structure and dynamics. This approach has been taken with much success for the Earth mantle, and here it is, for the first time, applied to the Moon. Lunar tomography has much lower resolution as for the Earth and is mostly restricted to the near side, nevertheless we can assess under what assumptions the fit between predicted geoid (based on a tomography model) and observed geoid is best. Among the models tested, we find the most similar pattern (correlation about 0.5) if we only consider tomography below 225 km depth, if density anomalies cause little or no dynamic topography and if we compare to the geoid with the flattening ($l = 2, m = 0$) term removed. This could mean that (a) like for the Earth, seismic anomalies shallower than 225 km are caused by a combination of thermal and compositional effects and therefore cannot be simply converted to density anomalies; (b) the lithosphere is sufficiently thick to prevent dynamic topography more than a small fraction of total topography; and (c) flattening is a "fossil" bulge unrelated to present-day mantle anomalies. However, we have to be cautious with interpreting our results, because for models with a comparatively higher correlation and a conversion from seismic velocity to density anomalies similar to the Earth's upper mantle, the amplitude of the predicted geoid is much lower than observed. This could either mean that the tomography model is strongly damped, or that the geoid is mostly due to shallow causes such as crustal thickness variations, with only a small part coming from the deeper mantle.

1. Introduction

Seismic tomography provides a powerful tool to gain information about the interior of the Earth, in particular if it is interpreted jointly with gravity and topography. This was first attempted in the 1970s (Dziewonski et al., 1977), and by now, tomography of the Earth's mantle has proliferated and led to countless publications. Also in the 1970s, seismometers installed during four of the Apollo missions (Fig. 1) recorded seismograms. Yet only recently this seismic information has been utilized to construct a lunar tomography model (Zhao et al., 2008; Zhao et al., 2012). Even the existence of a lunar core has only recently been proven (Weber et al., 2011). We have thus reached a stage in learning about the lunar interior comparable to where we were regarding the Earth interior in the 1970s. Whereas for all other planets we still have at most gravity and topography information, the Moon now is the only other planetary body besides Earth, where we can jointly utilize information from seismic tomography, gravity and topography. This paper represents the first attempt to do so.

Also recently, improved models of lunar gravity (Araki et al., 2009; Konopliv et al., 2013) and topography (Namiki et al., 2009) have been released. Topography and gravity equipotential surface are shown in Fig. 1A and B. Although the term "geoid" etymologically refers to the Earth, we will use it here also for the gravity equipotential surface of the Moon to follow common practice, although, in analogy "selenoid" would be more appropriate.

A feature that has been noted early on and that is clearly evident in Fig. 1 (B) are geoid highs associated with five nearside ringed maria (Imbrium, Serenitatis, Crisium, Nectaris, and Humorum). These have been attributed to mass concentrations or "mascons" (Muller and Sjogren, 1968) that exist beneath the centre of all of them. Here we would like to investigate possible sources of gravity anomalies in the deep interior of the Moon, and therefore attempt to remove the effect of mascons. This is done in Fig. 1 C and D where we have interpolated geoid and topography inside the mascons from surrounding values.

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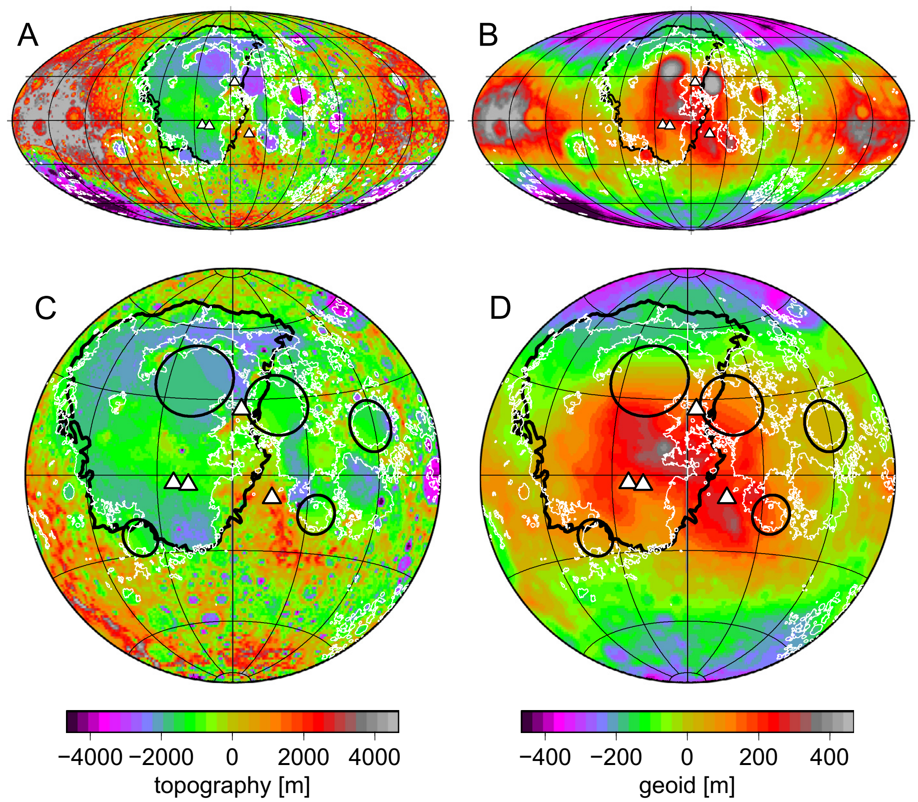

Fig. 1. (A): Lunar topography (Namiki et al., 2009) relative to the geoid. Triangles indicate Apollo seismometer locations. Procellarum KREEP terrane (Wieczorek and Phillips, 2000) is outlined in black. Following Laneuville et al. (2013), we use the 4 ppm Thorium abundance contour to define the KREEP outline. High-altitude abundances are adopted from Lawrence et al. (2000), on-line at http://www.lunar.lanl.gov/pages/GRSthorium.html. Also shown are the distribution of mare units (white, after Werner and Medvedev, 2010) that fill the large impact basins with basaltic material mostly on the near-side of the Moon. Map projection centred on near side. (B): Lunar geoid (Araki et al., 2009) relative to a sphere. Other features as in (A). (C): Near-side topography with depressions associated with mascons removed. The five mascons considered are shown as circles. At grid points inside circles, topography is initially set to zero, and iteratively replaced by the mean of values at the four neighbouring grid points until, after 1000 iterations, convergence has been approximately achieved. In this way, topography above mascons is interpolated from surrounding values. (D): Near-side geoid after the effect of mascons has been removed in an analogous manner to (C).

Another notable feature is the flattening of the lunar geoid which is, to its largest part, non-equilibrium, as the Moon is now rotating very slowly. It has been suggested to represent a fossil shape frozen into the lithosphere early in its orbital evolution (Jeffreys, 1976; Lambeck and Pullan, 1980). However, it may also be merely a consequence of internal density anomalies, and the fact that any planetary body always orients itself relative to its spin axis such that geoid highs are close to its equator (the minimum energy configuration for a synchronously rotating satellite, e.g. Lambeck, 1988), although these density anomalies and shape may also be a ‘‘fossil'' remains from a previous convection state (Matsuyama, 2012).

Regions of low topography generally coincide with mare units (Fig. 1). The relatively younger mare units in the west (Hiesinger et al., 2011) lie within a region known as Procellarum KREEP terrane (Wieczorek and Phillips, 2000; Grimm, 2013) which has been suggested to be underlain by hotter than average mantle that could also be responsible for the relatively recent volcanism until $\approx$1 Gyr (Hiesinger et al., 2011) or even younger (Braden et al., 2014).

The relation of internal density anomalies and geoid depends on whether the lunar mantle is still convecting, and if so, at what depths. Although the Moon is geologically ‘‘dead'' with its surface preserved for billions of years, therefore presumably has a thick rigid outer shell, it is possible that convection is still ongoing in its deep interior (Turcotte and Oxburgh, 1970; Meissner, 1977; Schubert et al., 1977).

In this paper, we first present spectral characteristics of lunar geoid and topography. In Section 2 we present our analysis, similar to previous work, to show that there are indications for both a deep and a shallow origin of lunar geoid undulations. Hence in this way we motivate and set the stage for the new work combining information from seismic tomography, geoid and topography, previously not applied to the Moon, to learn more about the interior of the Moon. Seismic tomography, the moonquake data it is based on, and possible inferences on the lunar internal density structure are discussed in Section 3, and how such density anomalies relate to geoid and topography in Section 4. Because there are rather large uncertainties in (i) the seismic velocity anomalies, (ii) conversion to density anomalies, and (iii) elastic lithosphere thickness, hence how internal density anomalies relate to topography and geoid, we will make certain approximations which we think are justified based on the low level of accuracy we can expect to achieve. Because many of the uncertainties are also hard to quantify, we will not attempt a formal error analysis. Rather, we will use the approach that – for the same reasons – is common in geodynamic modelling of the Earth mantle: That we vary certain parameters and assumptions within a range that appears reasonable based on what we know, and compare results with observations available. In this way, we expect to find out which parameters and assumptions are most suitable to explain the available data.

2. Lunar geoid and topography: spectral characteristics and correlations

Gravity and topography, as well as density anomalies, can be expressed in terms of spherical harmonic coefficients, e.g., the