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Excavation of the lunar mantle by basin-forming impact events on the Moon

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ABSTRACT

Global maps of crustal thickness on the Moon, derived from gravity measurements obtained by NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission, have shown that the lunar crust is thinner than previously thought. Hyperspectral data obtained by the Kaguya mission have also documented areas rich in olivine that have been interpreted as material excavated from the mantle by some of the largest lunar impact events. Numerical simulations were performed with the iSALE-2D hydrocode to investigate the conditions under which mantle material may have been excavated during large impact events and where such material should be found. The results show that excavation of the mantle could have occurred during formation of the several largest impact basins on the nearside hemisphere as well as the Moscoviense basin on the farside hemisphere. Even though large areas in the central portions of these basins were later covered by mare basaltic lava flows, surficial lunar mantle deposits are predicted in areas external to these maria. Our results support the interpretation that the high olivine abundances detected by the Kaguya spacecraft could indeed be derived from the lunar mantle.

1. Introduction

The Moon is a differentiated body composed of geochemically distinct crust, mantle, and core. Most current theories for lunar formation involve a giant impact into the proto-Earth (Hartmann and Davis, 1975; Benz et al., 1986, 1987, 1989; Canup and Asphaug, 2001; Canup, 2004; Ćuk and Stewart, 2012; Canup, 2012) and rapid accretion of material from a hot circum-terrestrial disk, yielding a Moon with a global magma ocean that subsequently crystallized and differentiated (for a review, see Shearer et al., 2006). Analyses of the mare basalts (e.g., Longhi, 1992) and simulations of lunar magma ocean crystallization (e.g., Elkins-Tanton et al., 2011) indicate that the mantle is composed predominantly of the minerals olivine and pyroxene, in contrast to a crust that consists mostly of anorthite (e.g., Wieczorek et al., 2006). Results of inversions of seismic travel-time data acquired by the Apollo seismic network are also consistent with the view that the lunar mantle is composed primarily of olivine and pyroxene (Khan et al., 2007; Kronrod and Kuskov, 2011), but there is no consensus on which of these two minerals is dominant. That no samples of the lunar mantle have been found to date in the lunar sample collection limits our understanding of the Moon's early differentiation.

Initial analyses of the Apollo seismic data indicated that the crust of the Moon was about 60 km thick on the central nearside, and even thicker on the farside (Toksöz et al., 1974). Given such a thickness, only the largest impact basins would have been capable of excavating through the crust and into the underlying mantle, such as the Imbrium and Serenitatis basins on the nearside (Spudis, 1993). Geochemical analyses of impact melt breccias believed to be derived from the Imbrium impact have been modeled as a mixture of anorthositic crustal materials, KREEP-rich materials, and a highly forsteritic olivine component that may have been derived from the upper mantle (Korotev, 2000).

Crustal thickness models derived from gravity and topography datasets acquired by the Clementine and Lunar Prospector missions resolved regions of extremely thin crust beneath the largest nearside impact basins (Zuber et al., 1994; Neumann et al., 1996). These models demonstrated that the largest basins

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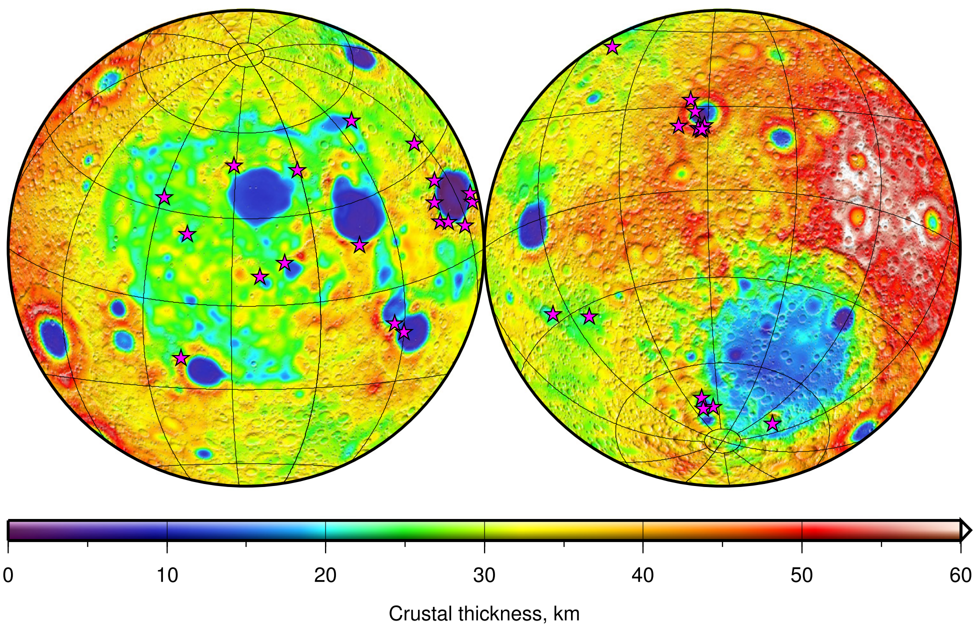

Fig. 1. Crustal thickness of the Moon derived from GRAIL gravity data (Wieczorek et al., 2013), updated with the gravity model of Konopliv et al. (2013), and locations of olivine-rich exposures (stars) as documented by Kaguya (Yamamoto et al., 2010). The largest expanses of olivine are observed around the Crisium and Moscoviense basins, which have crustal thickness values close to zero. The maps are Lambert azimuthal equal-area projections centered over (left) the Procellarum KREEP Terrane (20°N, 335°E) and (right) the opposite hemisphere; grid lines are spaced every 30°.

excavated several tens of kilometers into the crust and that the crust is nearly absent beneath a few impact basins, notably Crisium (Wieczorek and Phillips, 1998, 1999). Updated gravity models from the Kaguya mission of the Japan Aerospace Exploration Agency (JAXA) confirmed these results and further suggested that the crust is also nearly absent beneath the Moscoviense basin on the lunar farside (Ishihara et al., 2009).

Recent global maps of lunar crustal thickness derived from gravity measurements obtained by NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission (Zuber et al., 2013) show that the crust is substantially thinner on average than previously thought and that the average density of the crust has been markedly lowered by impact fracturing (Wieczorek et al., 2013). GRAIL-derived crustal thickness models are the first to satisfy revised interpretations of the Apollo seismic data (Khan and Mosegaard, 2002; Lognonné et al., 2003; Chenet et al., 2006) and imply an average crustal thickness that is somewhere between 34 and 43 km (Wieczorek et al., 2013). With crustal thicknesses that are less than previously thought by as much as a factor of two, the likelihood that the mantle was excavated by large impacts is increased. As with previous models, the GRAIL crustal thickness models predict that the crust is nearly absent beneath both the nearside Crisium and farside Moscoviense basins. Other basins, such as Humboldtianum, Apollo, and Poincaré, also have predicted interior crustal thickness values less than 5 km.

Surface reflectance data collected by the spectral profiler on the Kaguya spacecraft have detected regions on the lunar surface with anomalously high abundances of olivine (Yamamoto et al., 2010, 2012). The spectra of these exposures are consistent with olivine-dominated lithologies (i.e., dunite), though small quantities of admixed plagioclase cannot be excluded (Yamamoto et al., 2010, 2012). These olivine-rich exposures have horizontal extents of several kilometers and are, for the most part, located within relatively narrow regions along the prominent innermost rings of the largest basins. There are no olivine-rich sites observed in the central regions of these basins, though most have been flooded by mare basalts, or exterior to the main topographic rims.

The reports from the Kaguya mission are not the first time that olivine-rich areas were detected on the surface of the Moon, but they do represent the first detections of nearly pure olivine from orbit. Prior to the Kaguya mission, some of the highest abundances of olivine were detected in the central peak of Copernicus (e.g., Pieters and Wilhelms, 1985; Isaacson et al., 2011), with analyses of Clementine spectral reflectance data suggesting a troctolitic composition of about 72% olivine and 22% plagioclase (Cahill et al., 2009). High abundances of olivine (up to nearly 50%) have also been detected in some mare basalts (e.g., Lucey, 2004).

The most prominent olivine-rich areas detected by the Kaguya spacecraft surround the Crisium basin on the nearside and the Moscoviense basin on the farside, with less prominent areas associated with the Imbrium, Serenitatis, Nectaris, Humorum, and Humboldtianum basins on the nearside and Schrödinger on the farside (Fig. 1). Observations by the Moon Mineralogy Mapper (M3) on the Chandrayaan-1 spacecraft have confirmed many instances of olivine-rich areas reported by Yamamoto et al. (2010) and added several additional olivine-rich locations within the Crisium (Powell et al., 2012), Moscoviense (Isaacson et al., 2011), and Nectaris (McGovern et al., 2013) basins. Because olivine may be an important mineral in the upper mantle of the Moon, particularly if the crystallization products of the magma ocean overturned after solidification (Hess and Parmentier, 1995; Elkins-Tanton et al., 2011), the observed olivine-rich deposits may have been brought to the surface during large basin-forming events (Yamamoto et al., 2010, 2012).

Previous hydrocode simulations of the impact basin formation process have predicted that a substantial amount of mantle material was excavated during the largest impact events on the Moon (Ivanov et al., 2010; Potter et al., 2012a, 2012b, 2013). Moreover, Potter et al. (2013) showed that the maximum excavation depth differed by less than 2% for two identical impacts into targets with thermal profiles that differed by ∼500 K at a depth of 100 km. However, whereas the pre-impact temperature-depth profile has little effect on crater excavation, it is an important parameter that governs the final morphology of an impact basin, including the final diameter of the region of crustal thinning (Miljković et al., 2013). In part because of the complex nature of the basin formation process, these previous studies did not investigate the locations where exposed mantle should be found at the surface,