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Detecting volcanic resurfacing of heavily cratered terrain: Flooding simulations on the Moon using Lunar Orbiter Laser Altimeter (LOLA) data

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Early extrusive volcanism from mantle melting marks the transition from primary to secondary crust formation. Detection of secondary crust is often obscured by the high impact flux early in solar system history. To recognize the relationship between heavily cratered terrain and volcanic resurfacing, this study documents how volcanic resurfacing alters the impact cratering record and models the thickness, area, and volume of volcanic flood deposits. Lunar Orbiter Laser Altimeter (LOLA) data are used to analyze three different regions of the lunar highlands: the Hertzsprung basin; a farside heavily cratered region; and the central highlands. Lunar mare emplacement style is assumed to be similar to that of terrestrial flood basalts, involving large volumes of material extruded from dike-fed fissures over relatively short periods of time. Thus, each region was flooded at 0.5 km elevation intervals to simulate such volcanic flooding and to assess areal patterns, thickness, volumes, and emplacement history. These simulations show three primary stages of volcanic flooding: (1) Initial flooding is largely confined to individual craters and deposits are thick and localized; (2) basalt flows breach crater rim crests and are emplaced laterally between larger craters as thin widespread deposits; and (3) lateral spreading decreases in response to regional topographic variations and the deposits thicken and bury intermediate-sized and larger craters. Application of these techniques to the South Pole-Aitken basin shows that emplacement of ~1–2 km of cryptomaria can potentially explain the paucity of craters 20–64 km in diameter on the floor of the basin relative to the distribution in the surrounding highlands.

1. Introduction and background

All of the terrestrial planets have experienced large-scale volcanic resurfacing at some time during their long histories (Head and Coffin, 1997). Mercury is extensively covered with smooth plains thought to be of volcanic origin (Strom et al., 1975), including those found within and around the Caloris basin (e.g., Kiefer and Murray, 1987; Murchie et al., 2008) and in the north polar region (Head et al., 2011). Almost the entire surface of Venus is thought to have been volcanically resurfaced within the last ~300–500 million years (e.g., Phillips et al., 1992; Strom et al., 1994; Ivanov and Head, 2011), and the Earth abounds with examples of large-scale volcanic eruptions, including Large Igneous Provinces (LIPs) like the Deccan traps and continental flood basalts like the Columbia River Basalts (e.g., Coffin and Eldholm, 1994). Examples of large-scale volcanic activity on the Moon and Mars include the mare deposits in lunar basins (e.g., DeHon, 1979; Yingst and Head, 1997; Whitten et al., 2011) and the Hesperian ridged plains on Mars (e.g., Scott and Tanaka, 1986; Watters, 1993; Head et al., 2006).

As indicated by layering in the Deccan traps, these flood basalt deposits are the result of prolonged volcanic eruptions that can take place over millions of years and include multiple eruptions (e.g., Mahoney, 1988; Tolan et al., 1989). Lengthy eruption time scales allow flood basalt deposits to attain total volumes on the order of 10^6 km^3, based on lunar and terrestrial estimates (Coffin and Eldholm, 1994; Head and Coffin, 1997). Individual flow lengths for deposits associated with flood basalts can exceed 600 km (Schaber, 1973; Coffin and Eldholm, 1994; Zimbelman, 1998). On Earth flood basalt deposits are thought to result from fissure eruptions fed by large convecting mantle plumes in the Earth's interior (e.g., Wilson, 1963; Morgan, 1971, 1981). The specific mechanism controlling the eruption of flood basalts on the other terrestrial planetary bodies, such as the Moon, is still a highly debated topic (e.g., Solomon and Head, 1980; Hess and Parmentier, 1995; Wieczorek and Phillips, 2000; Elkins-Tanton et al., 2004; Ghods and Arkani-Hamed, 2007; Whitten et al., 2011).

Taylor (1989) classified planetary crustal formation processes into three types: (1) primary crust in which the early crust is formed from

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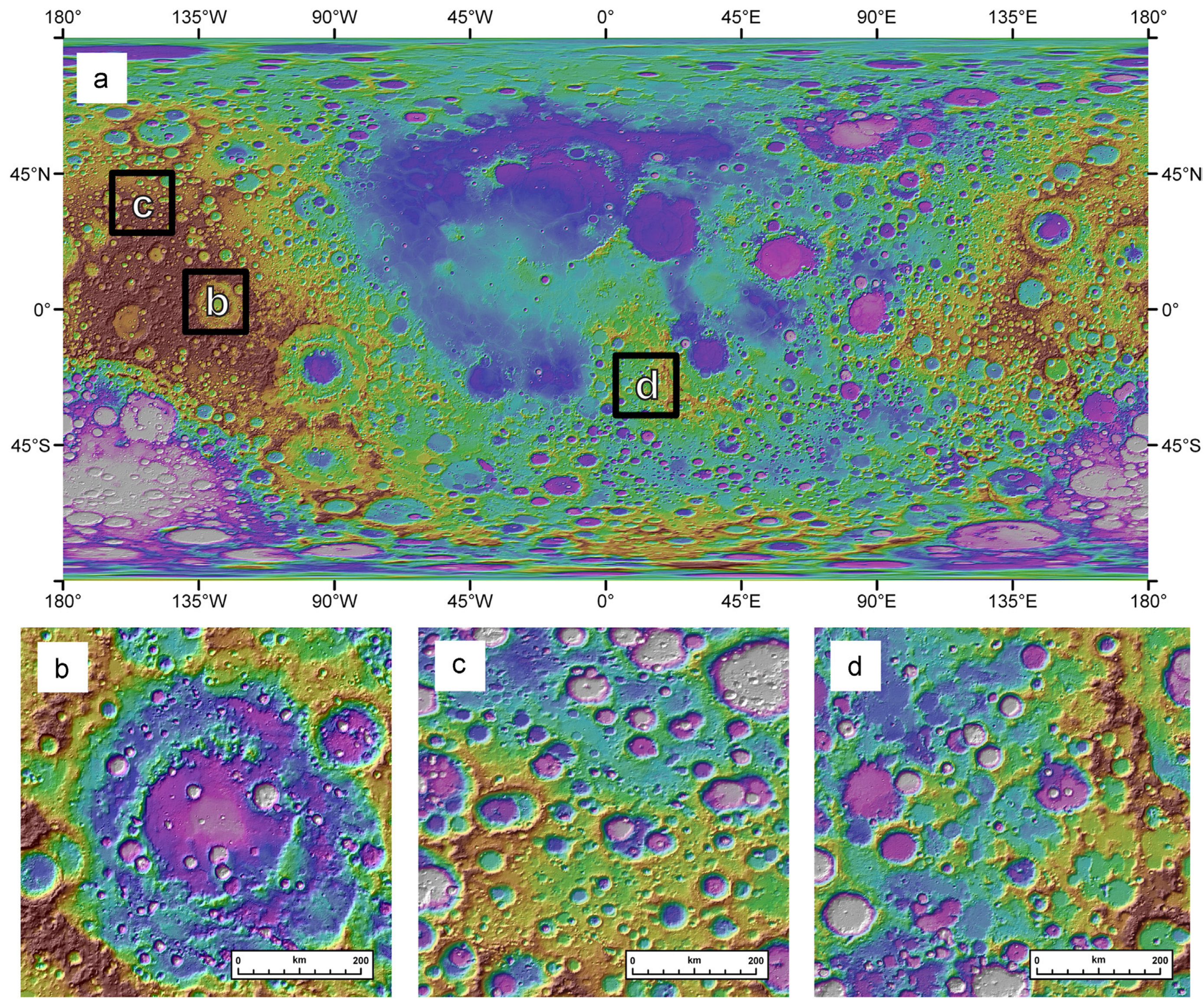

Fig. 1. Location of the three study regions. (a) Global map outlining location of study regions; (b) Hertzsprung basin; (c) farside cratered terrain (Head et al., 2010) and (d) central highlands. LOLA 128 pixel/deg topography data overlaying LOLA hillshade map.

the melting of the outer part of a planet by accretional energy; (2) secondary crust, formed by partial melting of the mantle subsequent to primary crust formation (e.g., the lunar maria, seafloor basalts, and volcanic plains on Mars); and (3) tertiary crust, formed from the reworking of primary and secondary crust (e.g., continental crust on Earth, impact melt). Particularly crucial to the understanding of the early thermal evolution of planets is the onset, timing and flux of secondary crustal formation. However, detection of early volcanic deposits that mark the transition from primary to secondary crust is often obscured by the high impact flux early in solar system history. To assist in the recognition and understanding of the relationship between heavily cratered terrain developed on a primary crust and volcanic resurfacing typical of secondary crustal formation, this study documents how volcanic resurfacing alters the impact cratering record and provides guidelines to measure the thickness, area, and volume of volcanic flood deposits.

Data from the Lunar Orbiter Laser Altimeter (LOLA) instrument (Smith et al., 2010; Zuber et al., 2010) aboard the Lunar Reconnaissance Orbiter (LRO) satellite (Vondrak et al., 2010) are used to simulate lava flooding for three different regions of primary crust, including the Hertzsprung basin, a farside heavily cratered region (FHC) and the central highlands (CH; Fig. 1). Artificial flooding experiments have previously been used to investigate volumes and thickness of volcanic deposits (Greeley and Womer, 1981; Head, 1982; Howard, 1999) and have been found to be more accurate at estimating volumes than measurements of buried and partially buried craters (DeHon, 1974, 1979). In this analysis we begin to address planetary thermal evolution by understanding the effect of volcanic flooding on pre-existing terrains, providing insight into the behavior of flood basalts on terrestrial planets. Measurements of lava volumes necessary to cover pre-existing topography and alter crater size-frequency distributions (CSFDs) are recorded to understand how to identify ancient heavily cratered volcanic deposits. In this analysis we investigate whether or not a crater population can aid in identifying ancient volcanic deposits. The techniques and results developed from these simulations are then applied to the identification of early lunar volcanic deposits.

2. Methods

The heavily cratered primary lunar crust is dominated by four major topographic elements: (1) broad regional to hemispherical