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Short Communication

Impact melt differentiation in the South Pole-Aitken basin: Some observations and speculations

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ABSTRACT

The stratigraphy of the South-Pole Aitken basin (SPA) interior is consistent with that of a massive impact melt sheet that differentiated to form cumulates. Spectroscopic and geophysical constraints on the stratigraphy of SPA suggest a ~12.5 km thick layer of norite above ultramafic pyroxenite and dunite layers. A similar stratigraphy is produced from differentiation by crystal settling of a ~50 km thick impact melt sheet (lunar impact melt sheets >10 km thick likely undergo differentiation by crystal settling) formed by an oblique impact (and thus containing ~20 vol. % crustal material). We propose that impact melt differentiation can account for geophysical (nonzero crustal thickness) and geochemical (~2 ppm Th) anomalies in SPA.

1. Introduction

The interior of the lunar South Pole-Aitken basin (SPA) is more mafic than typical lunar highlands crust (e.g., Metzger et al., 1974; Head et al., 1993; Pieters et al., 2001): nonmare basin floor materials are generally noritic (Pieters et al., 2001; Uemoto et al., 2011) and contain an average of 10 wt. % FeO (Jolliff et al., 2000). Although the SPA interior is a mafic anomaly, it is not anomalously mafic. After all, SPA is the largest (undisputed) lunar impact basin (Wilhelms, 1987). The extent of SPA-associated gravity anomalies indicates that the SPA transient cavity measured >800 km in diameter (Wieczorek and Phillips, 1999; Potter et al., 2012). The depth of crater excavation is about 1/10th the diameter of the crater transient cavity for complex craters and small basins (Croft, 1985); extrapolation of this crater scaling relationship (which seems to apply to basins <1000 km in diameter (Wieczorek and Phillips, 1999)) indicates that the SPA-forming impact ought to have excavated ~100 km into the Moon, through the <50 km thick plagioclase-rich crust (Wieczorek et al., 2013) into the plagioclase-poor, olivine- and pyroxene-rich (Khan et al., 2007) upper mantle. Yet the floor of SPA is (lower crustal?) norite rather than (mantle) olivine pyroxenite, and this norite is evidently not just a superficial veneer—the magnitude of gravity anomalies in the SPA interior suggests a ~12.5 km thick layer of norite (Wieczorek et al., 2013). The SPA interior is anomalously *feldspathic.*

Why is the SPA interior so feldspathic? Perhaps this is the result of post-SPA modification. SPA seems to be the oldest (recognizable) lunar impact basin (Wilhelms, 1987); perhaps crust-derived ejecta from later lunar basins buried (and diluted) mafic materials in the SPA interior. The ejecta thickness and mixing calculations of Petro and Pieters (2004) indicate that probably <1 km (and certainly <1.5 km) of basin ejecta has been emplaced on SPA; the mixing fraction of this foreign material with primary floor material could approach ~50% in SPA interior deposits. Although mixing of plagioclase-rich ejecta with mantle pyroxenite accounts for the noritic composition of the SPA interior, it does not account for its crustal thickness: the 1 km of plagioclase-rich material emplaced by post-SPA impacts is an order of magnitude less than the inferred norite layer thickness of ~12.5 km (Wieczorek et al., 2013). It also seems unlikely that the noritic floor of SPA formed from post-SPA mare (or cryptomare) infill—noritic floor materials (Pieters et al., 2001) display hummocky, non-volcanic morphology; clinopyroxene-poor norite is an unlikely melt composition; and accumulated lava flow thicknesses in other lunar basins are generally <1.5 km (DeHon and Waskom, 1976), again an order of magnitude less than the inferred norite layer thickness of ~12.5 km.

We conclude that the feldspathic SPA interior is primary, a direct outcome of the SPA-forming impact. What impact processes might result in an anomalously feldspathic basin interior? Perhaps SPA did not excavate as deeply as proportional scaling models predict (Wieczorek and Phillips, 1999); perhaps the SPA-forming impact was very oblique, as suggested by the elliptical outer rim structure (Garrick-Bethell and Zuber, 2009), thus excavating only shallowly into the lunar crust (Schultz, 1997). Shallow excavation is also favored by feldspathic SPA ejecta (Wieczorek and Phillips, 1999), although Yamamoto et al. (2012) have found (mantle-derived?) olivine in craters superposing the margins of SPA. Although it is certainly possible that the feldspathic SPA interior is the result of shallow excavation, we do not consider this explanation further. Instead, we

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investigate whether the relatively feldspathic interior of SPA can be attributed to impact melting, a shock process as volumetrically important as excavation in large basins (Cintala and Grieve, 1998).

Impact melting alone is not an explanation for the relatively feldspathic interior of SPA: the depth of melting considerably exceeds the depth of excavation for SPA-scale impacts (Cintala and Grieve, 1998), so the bulk composition of SPA impact melt is more mafic than the bulk composition of SPA ejecta. But impact melt can undergo igneous differentiation (Grieve et al., 1991), concentrating feldspathic components: Morrison (1998) hypothesized that the SPA impact melt sheet had differentiated by crystal settling to form ultramafic cumulates overlaid by a plagioclase-enriched residuum. According to this interpretation, the noritic interior of SPA is a (late-stage) impact melt differentiate, *not* the lower crust (although most of its component alumina is crustal in origin). The idea of Morrison (1998) (that the SPA interior contains a massive impact melt sheet which has undergone igneous differentiation) has enjoyed a recent resurgence, having been used (e.g.) to qualitatively interpret the distribution of ultramafic materials exposed in the central peaks of craters superposing the SPA interior (Nakamura et al., 2009; Yamamoto et al., 2012). For detailed spectroscopic and geophysical purposes, the predictions of the impact melt differentiation hypothesis need to be made more definite, addressing questions such as: Where is the SPA melt sheet? How thick is it? What are the compositions of cumulate layers in the SPA melt sheet? How thick are these layers?

In this paper, we investigate impact melt differentiation in the South Pole-Aitken basin. We begin by marshaling spectroscopic and geophysical constraints on the SPA subsurface. We then consider in turn: (1) the bulk composition and thickness of the SPA impact melt sheet; (2) the critical thickness above which lunar impact melt sheets undergo differentiation by crystal settling and whether the SPA melt sheet differentiated; and (3) the crystallization sequence and cumulate stratigraphy of the differentiated SPA melt sheet, which closely matches our previously established constraints on the SPA subsurface. Finally, we discuss the implications for the geophysics and geochemistry of the SPA interior as well as SPA sample return missions.

2. Spectroscopic and geophysical constraints on the SPA subsurface

Surface nonmare lithologies in the SPA interior are generally noritic (Pieters et al., 2001; Uemoto et al., 2011). What lithologies exist at depth in the SPA subsurface?

2.1. Constraints from central peak mineralogy

The central peaks of complex craters superposing the SPA interior exhume material from tens of kilometers deep in the SPA subsurface. Many authors (e.g., Tompkins and Pieters (1999), Nakamura et al. (2009), Yamamoto et al. (2012)) have characterized the mineralogy of such central peaks. In order to profile the mineralogy of the SPA subsurface, we select twelve complex craters (Fig. 1a) with previously characterized central peaks according to several criteria: selected complex craters (1) should superpose the SPA interior as defined by low topography and high FeO abundance (Garrick-Bethell and Zuber, 2009); (2) should have a well-defined central peak not buried by mare infill (Yingst and Head, 1999); (3) should not display unusual morphology which could confuse determination of central peak sampling depth; (4) should not superpose large basins such as Schrödinger or Apollo which probably confuse the primary stratigraphy of the SPA subsurface. Next, we calculate the sampling depths of these twelve central peaks according to the formula $u = 0.022 D_r^{1.45}$ where u is the stratigraphic uplift of a central peak of a complex crater with (present) rim diameter D_r (Cintala and Grieve, 1998). The stratigraphic uplift is taken to be the sampling depth of the central peak below the unmodified, primary floor of SPA, as the depth of these twelve central peaks below the present floor of SPA is on the same order of magnitude (~1 km) as the amount of foreign material introduced into SPA by large post-SPA basin-forming impacts (Petro and Pieters, 2004). Fig. 1b shows an SPA stratigraphic column color-coded according to central peak mineralogy. Note that we assume radial continuity and symmetry in subsurface strata (i.e., stratigraphic horizons run parallel to the present SPA surface), likely the case for lithologies derived from a melt sheet (or a magma ocean) that underwent differentiation by crystal settling.

What can we infer about the subsurface stratigraphy of SPA from Fig. 1b (bearing in mind the caveat that spectral data incompletely constrain rock type)? (1) Olivine-bearing lithologies (probably olivine-rich lithologies (Yamamoto et al., 2012)) are present only at depth in the SPA subsurface, as evidenced by the central peak of the 184 km diameter Zeeman crater and the olivine-bearing peak rings of the Schrödinger basin (Yamamoto et al., 2012). (2) Orthopyroxene-bearing lithologies overlie olivine-bearing lithologies, and the proportion of orthopyroxene decreases with decreasing depth. However, exceptions to this trend exist

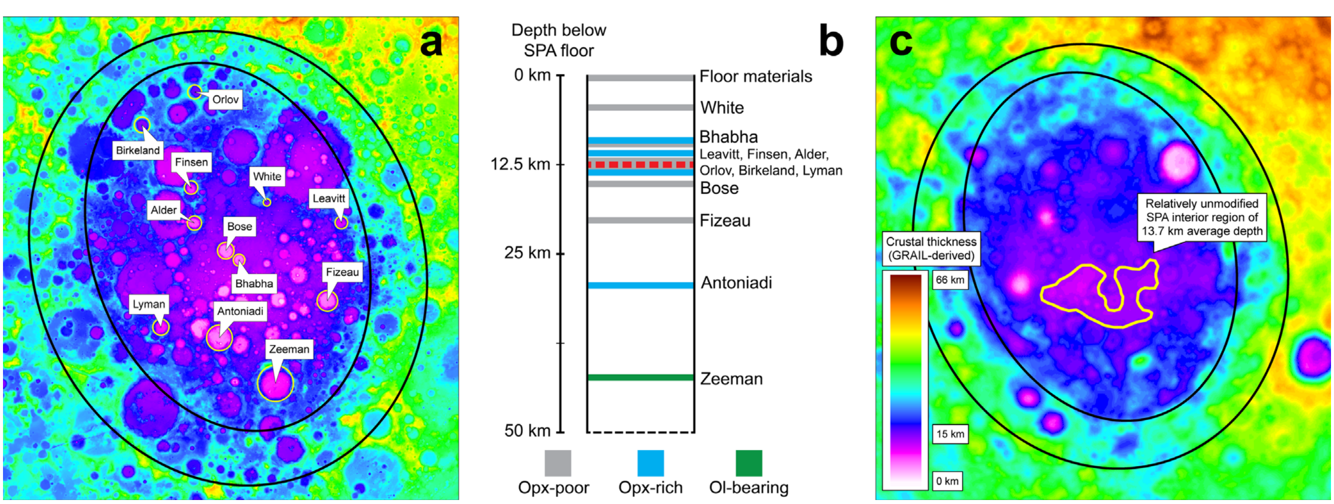

Fig. 1. Spectroscopic and geophysical constraints on SPA subsurface stratigraphy: (a) twelve complex craters with previously characterized central peaks (Tompkins and Pieters, 1999; Nakamura et al., 2009; Moriarty et al., 2011; Yamamoto et al., 2012) mapped on LOLA-derived topography; (b) constraints on subsurface stratigraphy from central peak mineralogy; the dashed red line at 12.5 km depth corresponds to the crust-mantle boundary inferred from (c) the average (GRAIL-derived) crustal thickness (Wieczorek et al., 2013) in a relatively unmodified region of the SPA interior. SPA rim outlines in (a) and (c) are from Garrick-Bethell and Zuber (2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)