Exploration of lunar dynamic evolution using samples returned from the lunar South Pole

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Human exploration of the lunar South Pole will enable unprecedented investigation of the Moon's dynamic history using returned samples. In the context of models for lunar evolution, excavated mantle and lower crustal lithologies can be used to "ground truth" first-order predictions for lunar evolution:

1. Cumulate mantle overturn as an important event in lunar differentiation, and a mechanism for reconciling the lunar hemispheric dichotomy

Volcanism, crustal thickness, the distribution of heat producing elements, and other physical properties exhibit hemispheric variations in the lunar surface and subsurface. Hemispheric cumulate mantle overturn has been proposed to explain these properties (e.g., Parmentier et al., 2000), and is supported by recent experimental results (Dygert et al., 2016; Li et al., 2019). Hemispheric overturn models posit that dense late cumulates of the lunar magma ocean flowed into the lunar interior as viscous solids in a giant downwelling "drip", or Rayeligh-Taylor instability. Other models predict downwelling of shorter wavelength instabilities that may not explain the hemispheric dichotomy, but nonetheless would have played a major role in redistributing materials among reservoirs in the lunar interior. Overturn models provide a testable set of observations that can be used to evaluate their validity, namely: (1) rock fabrics produced by viscous flow of the mantle during overturn, (2) mineralogies reflecting dynamical mixing of late and early magma ocean cumulates, partial melting, and melt-rock interactions, and (3) trace element and isotopic variations reflecting the same. Cumulate overturn models can be explored using measurements of the major and trace element chemistry and crystallographic preferred orientations (CPOs) of mantle lithologies. The lunar South Pole represents an important locality for evaluating overturn because it is distant from the lunar nearside where most presently available samples were collected. If overturn was hemispheric, the dynamic evolution of the interior beneath the South Pole and nearside must be consistent.

2. Serial Magmatism as a process that resurfaced the Moon

The lunar crust is thought to have formed from flotation of low-density plagioclase on the lunar magma ocean, but its high purity (e.g., Ohtake et al., 2009; Donaldson-Hannah et al., 2014) may be inconsistent with this origin. Models of crustal evolution suggest that the oldest lunar crust (nearest the present-day surface in a flotation scenario) should have the highest abundance of mafic minerals, which crystallized from melts trapped in the flotation crust, and that deeper units in the crust may be more pure owing to efficient compaction or "squeezing" of trapped melt out of the lower crust as it formed (Piskorz and Stevenson, 2014; Dygert et al., 2017a). The Serial Magmatism model posits that the lunar crust evolved in a global, secondary resurfacing event (e.g., Longhi, 2003), where upwelling diapirs of more pure lower crust flowed from near the crust-mantle boundary to the surface. Similar models are invoked to explain the emplacement of anorthosites on Earth. The validity of the Serial Magmatism model can be tested by characterizing grain sizes and CPOs of crustal rocks that would record a two-stage deformation history: (a) shape-preferred orientations after flotation on the lunar magma ocean, and (b) deformation microstructures originating from viscous flow in crustal diapirs. It can also be explored using trace element characteristics and thermal histories of crustal rocks, which may record thermochemical signatures associated with overturn events thought to drive serial magmatism.

3. Phase assemblages and cumulate stratigraphies associated with specific lunar bulk compositions

Recent experimental work provides constraints on mineralogies and thicknesses of lithological units after crystallization lunar magma oceans with specific bulk compositions (e.g., Lin et al., 2017; Rapp and Draper, 2018; Charlier et al., 2018). Study of returned lower crustal and mantle lithologies in the context of the experimental work may provide constraints on the Moon's bulk composition by direct comparison. Collection of a distribution of phase assemblages would provide even more useful for comparison with the experiments. In the event the returned samples are inconsistent with anticipated lithologies, as suggested by remote sensing (e.g., Melosh et al., 2017), secondary processing mechanisms (e.g., melt rock reaction events) should be explored.

4. Thermal histories in overturn and non-overturn scenarios

Thermal histories associated with secular cooling of a quiescent Moon are straightforward (e.g., Zhang et al., 2013). The Moon radiated heat into space through the thermal boundary layer of the crust, thickening the lunar lithosphere through time. In contrast, thermal evolution after cumulate overturn may have produced an inverted thermal structure, bringing high temperature materials to the crust-mantle boundary (e.g., Elkins-Tanton et al., 2011), after which they would have cooled quickly by heat conduction into the adjacent crust. These expectations are complicated by the potential contribution of heat producing elements beneath the crust in the KREEP layer. Scenarios for thermal evolution can be investigated by applying a battery of geothermometers to lower crustal and mantle samples. These techniques have a well-established history of elucidating geologic mechanisms in astromaterials and terrestrial samples (e.g., Dygert et al., 2017b; Lucas et al., 2020).

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