DID THE ORIENTALE IMPACT MELT SHEET UNDERGO LARGE-SCALE IGNEOUS DIFFERENTIATION BY CRYSTAL SETTLING?

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Introduction: The formation of the Moon's primary crust has been followed by over 4 Gyr of surface modification processes, predominantly in the form of impacts [1,2]. Impacts are a powerful erosive agent [3], modifying the primary crust through fracturing, brecciation, physical mixing, and through shock-induced melting. The shock-induced melting caused by large impact events (*e.g.* those producing a crater ~300 km in dimater or greater; [4]) is predicted to generate significant volumes of melt [5,6]. Given the concentration of large impacts distributed across the surface of the Moon, up to ~5% of the Moon's crust [7] may now be comprised of impact melt products. Despite the potentially significant contribution of impact melt to the compositional variability of the lunar crust, the processes involved in impact melt sheet cooling and crystallization are not well understood.

Following an impact event, impact melt is collected in the excavated crater [5] and begins cooling and solidification. Crystallization of the impact melt may then proceed by one of two end-member scenarios: (1) The melt may undergo igenous differentiation during solidification [7] resulting in a newly developed crustal stratigraphy, or (2) The melt may undergo homogeneous solidification and crystallize in equilibrium [7], thus homogenizing the crustal stratigraphy. A critical requirement for igneous differentiation is the ability of nucelated crystals to separate from the impact melt by sinking or flotation driven by density differences.

Here, we perform a case study on the lunar Orientale basin to explore the possibility for igneous differentiation of the Orientale impact melt sheet by assessing the thermal and physical processes driving cooling and crystallization, focusing on crystal settling.

Cooling and Solidification: Following the impact event, melt created through shock heating collects in the excavated crater [5]. Morphologic measurements of the Orientale impact structure suggest the thickness of the initial molten impact melt sheet, z, was ~15 km [7] (Fig. 1). Given the observed radius of the melt sheet, this yields an initial melt volume of ~$1.5\text{x}10^6$ km^3 [7], in agreement with scaling law predictions [5,6].

The melt sheet is predicted to initially exist in a completely molten state [3] at a temperature, T_i, with heat radiating away from the upper surface of the impact melt sheet. Radiative top-down cooling leads to the formation of an unstable upper thermal boundary layer (Fig. 1) [8] resulting in a large temperature gradient across the melt sheet, with a configuration characterized by very high Rayleigh numbers (~10^{19}). Under these conditions vigorous convection would take place in the impact melt sheet interior [8] with down-going plumes of cool dense material formed at the base of the upper thermal boundary layer (Fig. 1).

The convective cooling of the Orientale impact melt sheet can be estimated with empirically derived relationships which describe the thermal convection processes of terrestrial lava lakes [8] due to the generally analgous geometry and thermal processes, and because a flotation crust is not predicted to form (none of the crystallizing products are buoyant in melt of the upper crust; [7]). Cooling of the impact melt sheet is governed by the amount of heat that can be transported through the upper thermal boundary layer (F) and radiated to space (Fig. 1). The heat flux across the upper thermal boundary layer depends critically on the temperature contrast within the mixed interior (ΔT_c) (Fig. 1) which has been shown to be controlled only by the viscosity (μ) contrast across the layer [8]. We model cooling of the Orientale impact melt sheet by estimating total heat loss from the system and by tracking the solid fraction of the melt sheet (Fig. 2a) as well as the evolution of the system viscosity which is dependent upon temperature and suspended crystal content.

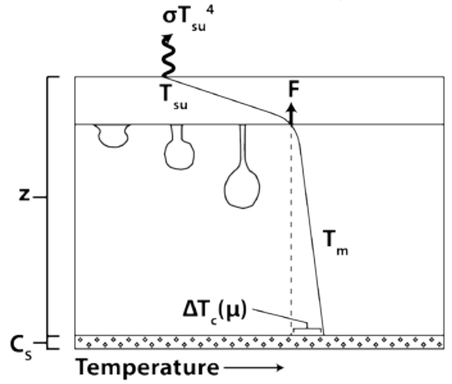

Figure 1. Configuration of the convectively cooling Orientale impact melt sheet showing the upper thermal boundary layer (**d**) and the well-mixed interior (**h**) (where convection maintains a relatively constant interior temperature T_m). The system is divided into the crystal-melt mixture region which contains a fluid phase (**z**), and the accumulating layer of settled crystals (**C$_S$**) which contains no fluid phase.

Crystallization Processes: On the basis of analagous scale and convective vigor, we adopt a crystallization framework developed for vigorously convecting terrestrial magma chambers [9] to assess the crystallization processes involved in impact melt sheet solidification. In this framework [9], vigorous convection within the well-mixed interior of the melt sheet holds crystals in suspension and prevents settling. Instead suspended crystals settle at the boundaries of the system, where convective velocities decay to zero. The crystals in suspension settle out at the boundaries over a characteristic residence time [10] which is dependent on crystal size. Terrestrial and lunar impact melt rocks generally exhibit fine-grained holocrystalline to glassy matrices containing up to ~25% mineral clasts ranging in size from ~0.1-1 mm along with a much smaller volume fraction of lithic fragments up to tens of meters in size [11]. Here we adopt a conservative nominal crystal size of 1 mm and later explore the effects of variable crystal size.

We compare the time required to nucleate crystals within the impact melt sheet against the residence time of suspended crystals, to derive the fraction of suspended crystals able to settle throughout the cooling process (Fig. 2b). This fraction is used, in conjunction with the total solid fraction of the melt sheet (Fig. 2a), to estimate the relative fraction of crystals suspended (Fig. 2c) versus settled (Fig 2d) throughout the cooling and solidification process.

Conclusions: Analysis of the cooling and crystallization processes of the Orientale impact melt sheet indicates that crystals typical of impact melts 1 mm in size or smaller are not able to efficiently settle out at the boundaries of the convecting melt system (Fig. 2c & 2d). As a result, crystals nucleated within the melt remain in suspension, causing a near-linear increase in the suspended crystal fraction (Fig. 2c) throughout solidification until a maximum value of 0.6 [12] is reached after ~10 kyr (Fig. 2a). Once the maximum suspended crystal fraction is reached the crystal-melt mixture takes on a solid-like behavior [13], subduing convective and settling motions, and causing any further cooling and crystallization to occur in situ. Therefore, the Orientale impact melt sheet is predicted to solidify by equilibrium crystallization with no large-scale igneous differentiation. Analysis of the effects of variable crystal size indicate that equilibrium crystallization is predicted to occur for a dominant crystal size of 0.1 mm, but fractional crystallization is predicted for a crystal size of 1 cm (Fig. 2c & 2d). Assessment of the crystallization history of the thinner Copernicus crater impact melt deposits (Fig. 2e & 2f) indicates that impact melt sheet thickness does not significantly influence crystallization history. The predictions of this analysis are supported by results from petrologic studies [7] which also predict that the Orientale impact melt sheet underwent equilibrium crystallization. These results suggest that crystallization of lunar basin impact melt deposits may have compositionally homogenized up to ~5% [7] of the upper lunar crust.

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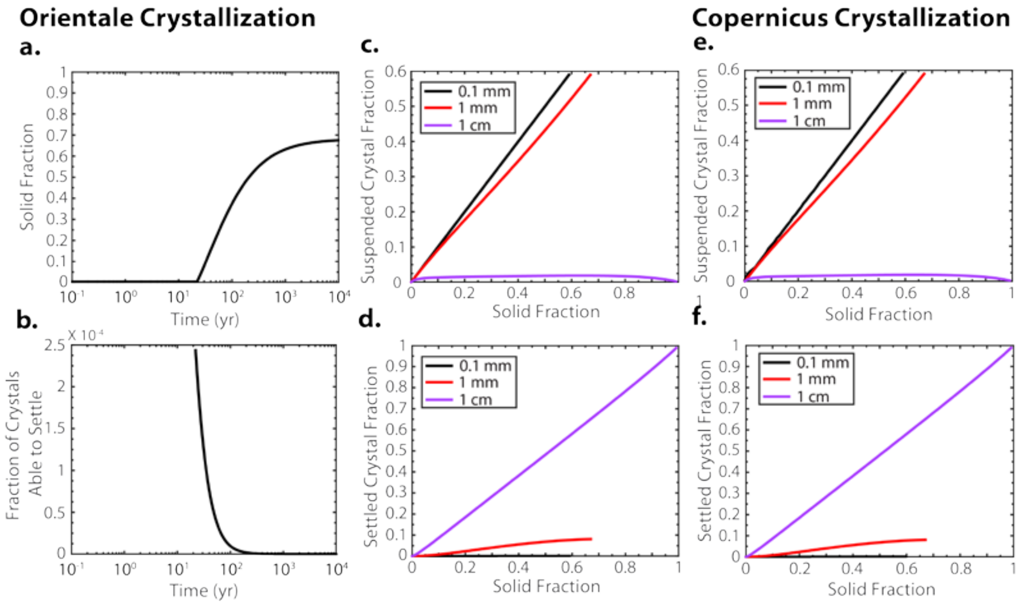

Figure 2. (**a.**) Solid fraction of the Orientale impact melt sheet as a function of time during the cooling and crystallization process following formation with a crystal size of 1 mm. (**b.**) Fraction of 1 mm crystals suspended within the melt which are able to settle throughout cooling and solidification of the impact melt sheet. (**c.**) Fraction of crystals within the Orientale impact melt sheet that remain in suspension throughout the cooling and solidification process for a range of crystal diameters from 0.1 mm to 1 cm. (**d.**) Fraction of crystals that have settled out of suspension throughout the cooling and solidification process for crystal diameters from 0.1 mm to 1 cm. As the crystal size decreases, the fraction of crystals kept in suspension throughout cooling and solidification increases while an increase in crystal size causes an increase in the fraction of crystals settled. (**e.** & **f.**) Same as (**c.**) and (**d.**) for the Copernicus impact melt sheet, showing similar trends in the predicted crystallization history.