EGU21-9238
https://doi.org/10.5194/egusphere-egu21-9238
EGU General Assembly 2021

On the competing roles of volatile outgassing and cumulate compaction in the solidification of magma oceans.

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Planetary bodies with a sufficiently energetic origin are likely to begin their evolution in largely liquid state. Cooling and crystallization at the surface of a mostly liquid magma ocean (MO) is expected to produce a sedimented partially crystallized cumulate of melt and denser mineral grains at its base. The rate of crystallization and cumulate sedimentation are controlled by radiation through an atmosphere devolatilized from the vigorously convecting MO. Melt retained in the cumulate is initially isolated from the overlying MO and atmosphere; but through compaction and buoyant migration in permeable cumulates, retained melt may be discharged into the overlying MO and its dissolved volatiles contributed to the growing atmosphere. The rates of cumulate compaction and radiative cooling though the atmosphere may thus play interacting and competing roles governing the time scale of MO evolution.

We explore these effects using a thermal evolution model similar to that described by Elkins-Tanton (2008; doi.org/10.1016/j.epsl.2008.03.062). In the current study, the top of the cumulate layer is defined by a depositional melt fraction (~50%) and temperature at which a liquid of MO composition behaves like a viscous solid. Heat flux from the MO surface is limited by radiation through a gray H_2O-CO_2 rich atmosphere (Abe and Matsui, 1988; doi.org/10.1175/1520-0469(1988)045<3081:EOAIGH>2.0.CO;2). We consider Mars and Earth-like bodies with initial bulk H_2O-CO_2 concentrations 0.5%-0.1% and 0.05%-0.01% and vary the prescribed amount of retained melt in the cumulate from 0% (instantaneous compaction) to 50% (no compaction). For the Mars-sized body increasing retained melt fraction over this range reduces MO freezing time by nearly one order of magnitude (from ~1 Myr to <0.1 Myr) and two orders of magnitude (from ~0.1 Myr to <0.001 Myr) for the larger and smaller volatile concentrations, respectively. The Earth-like body shows similar behavior.

The melt fraction retained in compacting cumulate deposited at constant, prescribed sedimentation rate is determined by the rate of buoyant melt migration (Shirley 1986; doi.org/10.1086/629088). For reasonable values of cumulate grainsize (~1 mm; Solomatov and Stevenson, 1993; doi.org/10.1029/92JE02839) and interstitial melt viscosity (~0.1 Pa-s). Cumulates in a Mars-sized, 1000 km deep MO solidifying in 0.1 Myr (cumulate thickening rate ~ 10^4 km/Myr) should retain melt fractions in the range of 10 to 30%, consistent with values the above thermal model shows are needed to produce this solidification rate. Nearly an order of magnitude reduction in freezing time due to retained melt can be expected.

Ongoing work integrates the thermal evolution and migration of retained melt into a unified self-consistent model in which the variation of cumulate sedimentation rate with time is determined by the heat flux through the evolving atmosphere. Our results thus far indicate that volatiles contained in melt retained within cumulates, rather than being added to a growing atmospheric mass, could significantly reduce the time scale of MO solidification. Exploring this for small planetesimal-sized bodies will be particularly interesting since smaller gravity will reduce the rate of cumulate melt segregation while atmospheric escape may limit the mass of a growing atmosphere.