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On the evolving P-T conditions in a magma ocean with implications for terrestrial core formation

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The formation of an iron core in a terrestrial planet occurs during planet accretion and is hence inextricably linked to chemical and dynamical processes operating in a magma ocean. Accretionary impacts provide both material (e.g., Fe, Si) and energy (heat) that drive the growth of the core (and planet), in part by sustaining a magma ocean near the surface. Constraining the conditions in a magma ocean as it cools and crystallises is critical for understanding the bulk and trace element chemistry of Earth's mantle and core, and furthermore provides insights into the evolution of rocky planets at large. This is because in a magma ocean, Fe–Si components partly or fully chemically equilibrate and major and trace elements partition into the core and mantle. Partition coefficients depend on pressure (P), temperature (T), and oxidation state, which evolve according to the conditions in a magma ocean. Furthermore, degassing of a magma ocean produces a primary atmosphere that subsequently controls the cooling rate of the magma ocean, demonstrating a strong coupling between the major layers in a terrestrial planet: the core, mantle, and atmosphere.

We present a thermal evolution model using the SPIDER code (Bower et al., 2018) to determine the $P-T$ conditions in a magma ocean that can be used in geochemical models to determine the partitioning of elements between the mantle and core during accretion. Previous geochemical models typically assume that chemical equilibration between silicate and core material occurs at a single temperature and pressure which is often associated with the middle of a magma ocean of predefined depth. However, the partitioning of moderately siderophile elements is strongly determined by $P-T$ conditions that are known to evolve in time as a magma ocean cools and crystallises. We complement our numerical simulations with an analytical model to describe the advancement of the melt–solid interface (the rheological front) through the silicate mantle as a function of time. The $P-T$ conditions that occur at this interface are a reasonable proxy for the depth of a magma ocean. We investigate the range of $P-T$ paths that are traced by the rheological front for a range of protoplanetary masses and primary atmospheres, presenting models with black body cooling, imposed surface heat fluxes, and self-consistent interior–atmosphere coupling. Ultimately, we provide a straightforward fitting function to enable our results to be used by researchers interested in accretion, geochemical partitioning, or magma ocean processes relevant to Earth or other terrestrial planets in the solar system or extrasolar systems.