Geophysical Research Abstracts
Vol. 19, EGU2017-4038, 2017
EGU General Assembly 2017

Advancing dynamic and thermodynamic modelling of magma oceans

Dan Bower (1), Aaron Wolf (2), Patrick Sanan (3), and Paul Tackley (1)

(1) ETH Zürich, Institut für Geophysik, D-ERDW, Zürich, Switzerland (dan.bower@erdw.ethz.ch), (2) Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI, USA (aswolf@umich.edu), (3) Institute of Computational Sciences, Università della Svizzera italiana, Lugano, Switzerland (patrick.david.sanan@usi.ch)

The techniques for modelling low melt-fraction dynamics in planetary interiors are well-established by supplementing the Stokes equations with Darcy's Law. But modelling high-melt fraction phenomena, relevant to the earliest phase of magma ocean cooling, necessitates parameterisations to capture the dynamics of turbulent flow that are otherwise unresolvable in numerical models. Furthermore, it requires knowledge about the material properties of both solid and melt mantle phases, the latter of which are poorly described by typical equations of state. To address these challenges, we present (1) a new interior evolution model that, in a single formulation, captures both solid and melt dynamics and hence charts the complete cooling trajectory of a planetary mantle, and (2) a physical and intuitive extension of a "Hard Sphere" liquid equation of state (EOS) to describe silicate melt properties for the pressure-temperature (P-T) range of Earth's mantle. Together, these two advancements provide a comprehensive and versatile modelling framework for probing the far-reaching consequences of magma ocean cooling and crystallisation for Earth and other rocky planets.

The interior evolution model accounts for heat transfer by conduction, convection, latent heat, and gravitational separation. It uses the finite volume method to ensure energy conservation at each time-step and accesses advanced time integration algorithms by interfacing with PETSc. This ensures it accurately and efficiently computes the dynamics throughout the magma ocean, including within the ultra-thin thermal boundary layers ($<$ 2 cm thickness) at the core-mantle boundary and surface. PETSc also enables our code to support a parallel implementation and quad-precision calculations for future modelling capabilities. The thermodynamics of mantle melting are represented using a pseudo-one-component model, which retains the simplicity of a standard one-component model while introducing a finite temperature interval for melting (important for multi-component systems). Our new high P-T liquid EOS accurately captures the energetics and physical properties of the partially molten system whilst retaining the largest number of familiar EOS parameters.

We demonstrate the power of our integrated dynamic and EOS model by exploring two crystallisation scenarios for Earth that are dictated by the coincidence of the liquid adiabat and melting curve. Experiments on melting of primitive chondrite composition predict that crystallisation occurs from the "bottom-up", whereas molecular dynamics simulations of $MgSiO_3$ perovskite suggest crystallisation occurs from the "middle-out". In each case, we evaluate the lifetime of the magma ocean using our model and find that in both scenarios, initial cooling is rapid and the rheological transition (boundary between melt- and solid-like behaviour) is reached within a few kyrs. During this stage efficient mixing prevents the establishment of thermal and chemical heterogeneity, so it may be challenging to locate a signature of the earliest phase of magma ocean evolution. At the rheological transition, cooling is governed by gravitational separation and viscous creep, and even in the absence of iron partitioning our models predict long-lasting ($>$ 500 Myr) melt at the base of the mantle.