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Melting and core formation during accretion of the Earth

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The most significant differentiation event in the history of the Earth resulted in the formation of the Earth's iron-rich core and silicate mantle. Core formation involved the segregation of metal from silicate for which high temperatures were required. At least the metal, and probably also the silicate, had to be in a molten state for segregation to occur efficiently. Although the decay of short-lived isotopes provided sufficient heat for the core-mantle differentiation of early-formed planetary bodies, this heat source was only effective during the initial 2-3 My of Solar System history. The heat required for core-mantle differentiation of the Earth was derived primarily from high-energy collisions with other planetary bodies that culminated in the Moon-forming giant impact.

In order to study the compositional evolution of the growing planets, we have combined N-body accretion simulations with a model of multistage core formation (Rubie et al., 2015, Icarus 248, 89-108). Impacts of embryos and planetesimals with growing proto-planets are considered to result in large-scale melting, magma ocean formation and an episode of core formation. Metal-silicate equilibration at high pressure and temperature results in equilibrated metal and silicate compositions that are determined by mass balance combined with element partitioning data. The evolving compositions of the mantles and cores of the terrestrial planets can thus be modelled simultaneously. Model parameters are constrained by fitting the final composition of the mantles of Earth-like planets to the composition of the Earth's primitive mantle. However, current results are based on the simplifying assumption that metal-silicate equilibration pressures are always a constant fraction (typically around 0.7) of the proto-planet's core-mantle boundary pressure.

In order to further develop the model of Rubie et al. (2015), we are now calculating the depth of melting for each impact in the N-body simulations, which enables the P-T conditions of metal-silicate equilibration to be specified. Full three-dimensional models of planetary collisions are computationally too time-consuming for the large number (hundreds to thousands) of impacts in the N-body accretion simulations. Two-dimensional models cannot be used for non-vertical impacts due to their assumed symmetry in the third dimension. Therefore, a parameterised model is used which describes the amount and depth of melting based on the energy needed to melt a dunite mantle together with the energy provided by the impact. The available energy depends on the impact angle and velocity as well as on the impactor mass and the material properties of the impactor and the target.

A deep melt pool, formed by a collision between bodies of similar size, will spread over the planet's surface to form a global magma ocean as the result of isostatic readjustment. Subsequent planetesimal impacts may occur while this magma ocean is still present, in which case metal-silicate equilibration will take place near its base. With a simple cooling model, an estimate can be made of the depth of the magma ocean as a function of time. Using this method, equilibration temperatures and pressures are calculated for each impact. This approach is being used to constrain the accretion history and the presence or absence of a dense insulating atmosphere during the early history of the Earth.

Keywords: magma oceans, giant impacts, differentiation, high pressure