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Effects of magmatic styles on the thermal evolution of planetary interiors

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It is broadly known that magmatic processes play a key role in cooling planetary interiors. While most studies have analyzed the influence of extrusive magmatism (e.g. Armann and Tackley, 2012, Moore and Webb, 2013), recent investigations have shown that intrusive magmatism could also be very efficient for cooling Earth-like planets (e.g. Rozel et al., 2017, Lourenço et al., 2020). Nevertheless, a systematic investigation of the role that the magmatic styles play in the evolution of different terrestrial planets has never been done. We study the effect of the magmatic style on the thermal evolution of Mercury-, Venus-, Mars-, and Moon-like planets, focusing on the magmatism endmembers i.e. 'fully extrusive' (Io-like heat pipe model, Moore and Webb, 2013) and the 'fully intrusive' (plutonic-squishy lid model, Lourenço et al., 2020).

We use the geodynamical code GAIA in a 2D spherical annulus geometry (Hüttig et al., 2013, Fleury et al., 2024). Our models assume a homogeneous distribution of the heat sources, a depth- and temperature-dependent viscosity (Karato et al., 1986) that follows an Arrhenius law for dry diffusion creep (Karato & Wu, 1993), pressure- and temperature-dependent thermal conductivity and expansivity (Tosi et al., 2013), a time-dependent core cooling (Steinbach & Yuen, 1994), and a melting curve parametrization derived for the Earth's interior (Stixrude et al., 2009). Apart from surface and core temperature, mantle and core density, planet, and core radius, and initial concentration of radioactive elements, we keep the model parameters similar for all bodies. This choice was made to minimize the differences between models due to the particular conditions of each planet, allowing us to focus our analysis on the influence of intrusive vs. extrusive magmatism rather than each planet's evolution.

Melting occurs when the mantle temperature exceeds the solidus. For all bodies, we compute partial melting considering latent heat consumption. We extract the melt either to the intrusive melt depth of 50 km for the fully intrusive cases or to the surface for the fully extrusive cases. We delimit the area of buoyant melt from which melts can be extracted by the lithosphere thickness (to avoid re-melting the hot intrusions) and the density crossover at 11 GPa (Ohtani et al., 1995).

For all studied bodies, the convection pattern is characterized by stronger mantle plumes and more vigorous mantle flow for the fully intrusive cases than for the fully extrusive cases. Throughout the evolution of all planet-like models, cases with intrusions present thinner and warmer lithospheres, cooler mantle and CMB temperatures, higher melt production, shallower melting depths with cooler melt temperatures, and higher surface and CMB heat fluxes. Limiting the melt production in the interior by the density crossover greatly impacts the planetary cooling of bodies with high mantle pressures such as Venus, for which an intrusive magmatism style allows for more efficient cooling of the interior while having a warm and thin lithosphere.

Our study provides the first detailed investigation of the effects of intrusive vs. extrusive magmatism on the global evolution of rocky planets, in a comparative planetology sense.