On the relative importance of thermal and chemical buoyancy in impact-induced melting on Mars

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Model setup

The early history of the terrestrial planets was strongly shaped by several large impacts. A large impact causes not only severe effects on geologically short timescales, but may also disturb the thermochemical structure of a planet's interior for millions of years (e.g., Roberts and Arkani-Hamed, 2012).

Two-dimensional numerical mantle convection models that include a detailed description of mantle mineralogy and chemistry are coupled with a simple model of core energetics (e.g., Ruedas *et al.*, 2013). These models are combined with a detailed parameterization of the effects of an impact built on the approach of Watters *et al.* (2009) in order to improve existing models in terms of applicability to the real planet Mars. We attempt an assessment of the relative contributions of the thermal and compositional anomalies generated by regular melting and especially by impacts of different sizes.

We consider four pairs of models, three of them with either an Utopia-, Isidis- or Huygens-sized event occurring at 4 Ga. In one model of each pair, the effects of melting on major-element composition and mineralogy, in particular on the density of the residue, are suppressed, so that the buoyant response is entirely due to the thermal effect; trace components are treated regularly in all models, i.e., melting dehydration and radionuclide partitioning are not suppressed in the purely "thermal" models.

Model properties

The present models are not designed to be approximations of the real planet Mars, but they do use the characteristics of three major martian impacts (Utopia, Isidis, Huygens) on a somewhat Mars-like body.

All models: Initial potential temperature: 1700 K; initial T step across CMB: 150 K; 15fold viscosity increase between upper and lower half of mantle; radionuclide concentrations from Wänke and Dreibus (1994), Mg#=0.75, 36 wppm water; melting included, threshold for melt extraction: 0.7%; large ($R_c = 1730$ km) liquid iron–sulfur (16 wt.% S) alloy core, no basal bridgmanite+ferropericlase layer in the mantle; duration: 4.4 Gy

Impacts: S-type asteroid impactor, 2700 kg/m^3, 9.6 km/s, striking at 4 Ga at an angle of 45°; Utopia-sized (final crater diameter: 3380 km, impactor diameter: 699 km), Isidis-sized (final crater diameter: 1352 km, impactor diameter: 244 km), or Huygens-sized (final crater diameter: 467.25,km, impactor diameter: 71 km)

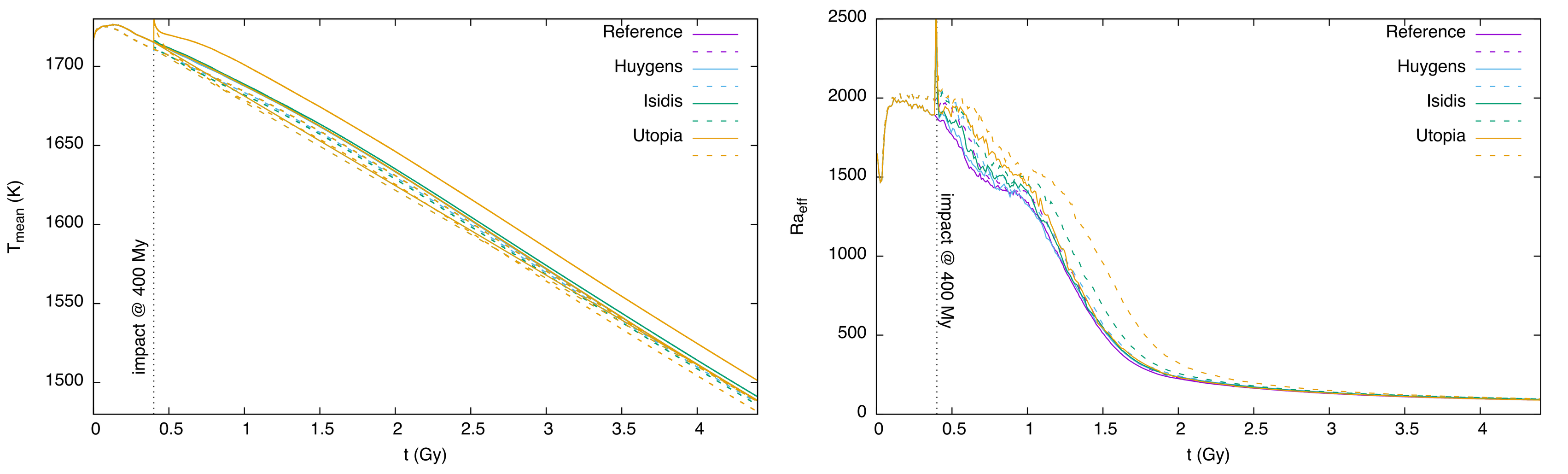

Fig. 1: Temporal evolution of mean mantle temperature (left) and effective Rayleigh number (right); Ra_{eff} is smoothed by averaging over 10 Myr-intervals. Solid lines: thermal+compositional; dashed lines: thermal only.

Results: Model evolution and dynamics

With time the planetary interior cools for all models, and convective vigor as expressed by the effective Rayleigh number Ra/η'_{ave} decreases (Fig. 1). Impacts provide an instantaneous input of energy that temporarily reverses and hence delays these processes, the stronger the larger the impact. The purely thermal models cool slightly faster due to their slightly stronger convection. The reason for this seemingly paradoxical behavior is that compositional buoyancy is not only a driving force but can also inhibit the ascent of a (mostly) thermally driven upwelling if its buoyancy cannot overcome the compositional density contrast of an overlying depleted layer. This is the case with the depleted global sublithospheric melt source region in the models with both thermal and compositional buoyancy.

Impacts produce especially strong thermal and compositional anomalies that can disturb this otherwise stable layering temporarily. In all cases the impact-generated anomalies spread out at the base of the lithosphere, but only the models that include compositional buoyancy stabilize the anomaly and preserve it as a long-term feature of the uppermost mantle (Fig. 2). This effect highlights the importance of accounting for the compositional dynamical effects of melting and may provide a mechanism that produces long-lived chemical heterogeneities in the martian mantle, even without suppressing large-scale mantle convection in the entire martian mantle early in the planet's evolution.

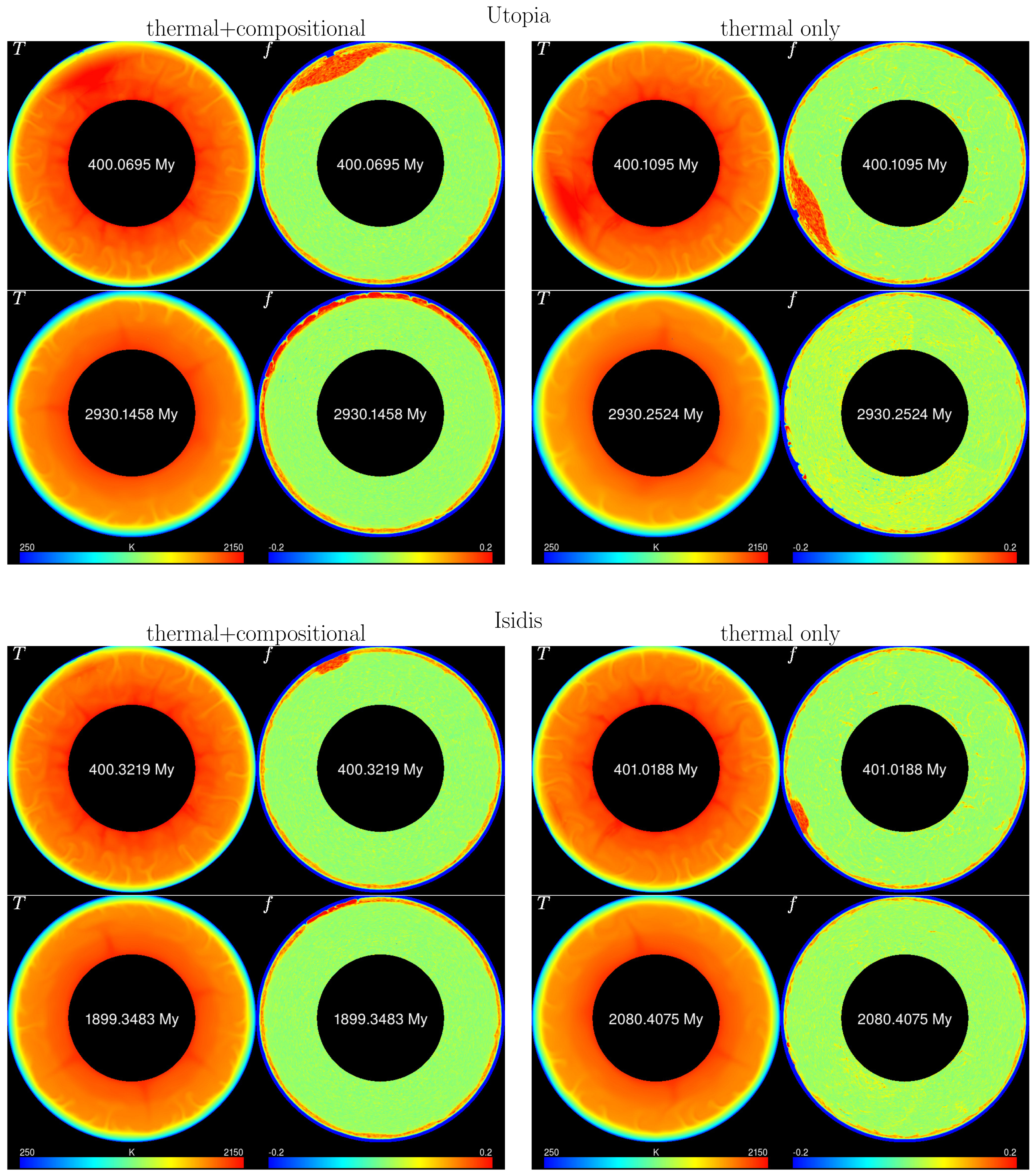

Fig. 2: Temperature (T) and depletion (f) of models with impacts. Each panel shows the state directly after the impact and at a much later time, when the final configuration has already emerged.

Results: Observables

The integration of a mineralogical and geochemical model into convection calculations permits the self-consistent prediction of many geophysical and geochemical observables, and the suppression of the compositional influence in one model of each pair permits the identification of the compositional contribution to an observational anomaly. Fig. 3 shows the elastic lithospheric thickness as an example.

Most of the crust is formed within the first few hundred millions of years, but minor sporadic magmatism at isolated centers related to mantle plumes may occur much later. The omission of the dynamical effect of compositional buoyancy removes the gravitationally stable layering in the melting zone beneath the lithosphere and results in enhanced melt production, which may lead to a thicker crust in the purely thermal models. Individual impacts also enhance crust formation locally (Figs. 2, 4a) and thus increase the global average. However, the excavation of the transient crater and redistribution of crustal material as ejecta offsets the effect of increased melt production.

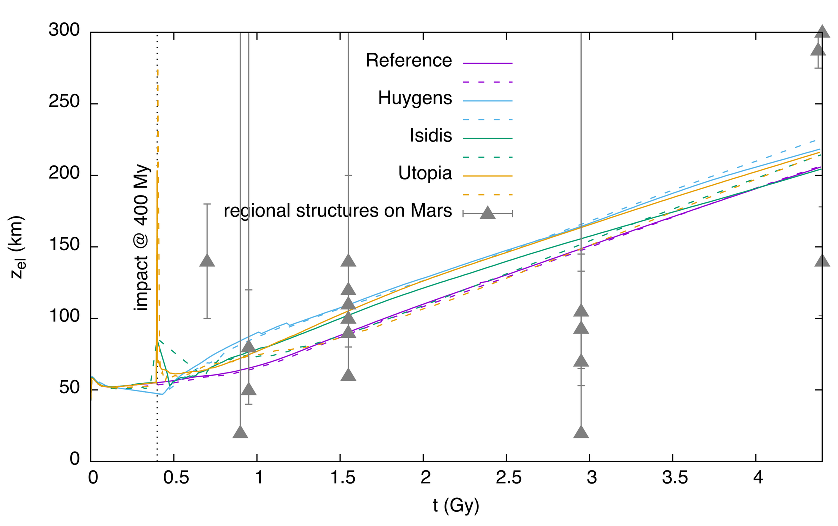

Fig. 3: Estimated elastic thickness of the lithosphere within the basins; the reference curves are the global averages of the impact-free models. The triangles are lithospheric thickness estimates for some regional structures from the literature (e.g., McGovern *et al.*, 2002; Phillips *et al.*, 2008); their ages are mean values based on the geological epoch assigned to them. Solid lines: thermal+compositional; dashed lines: thermal only.

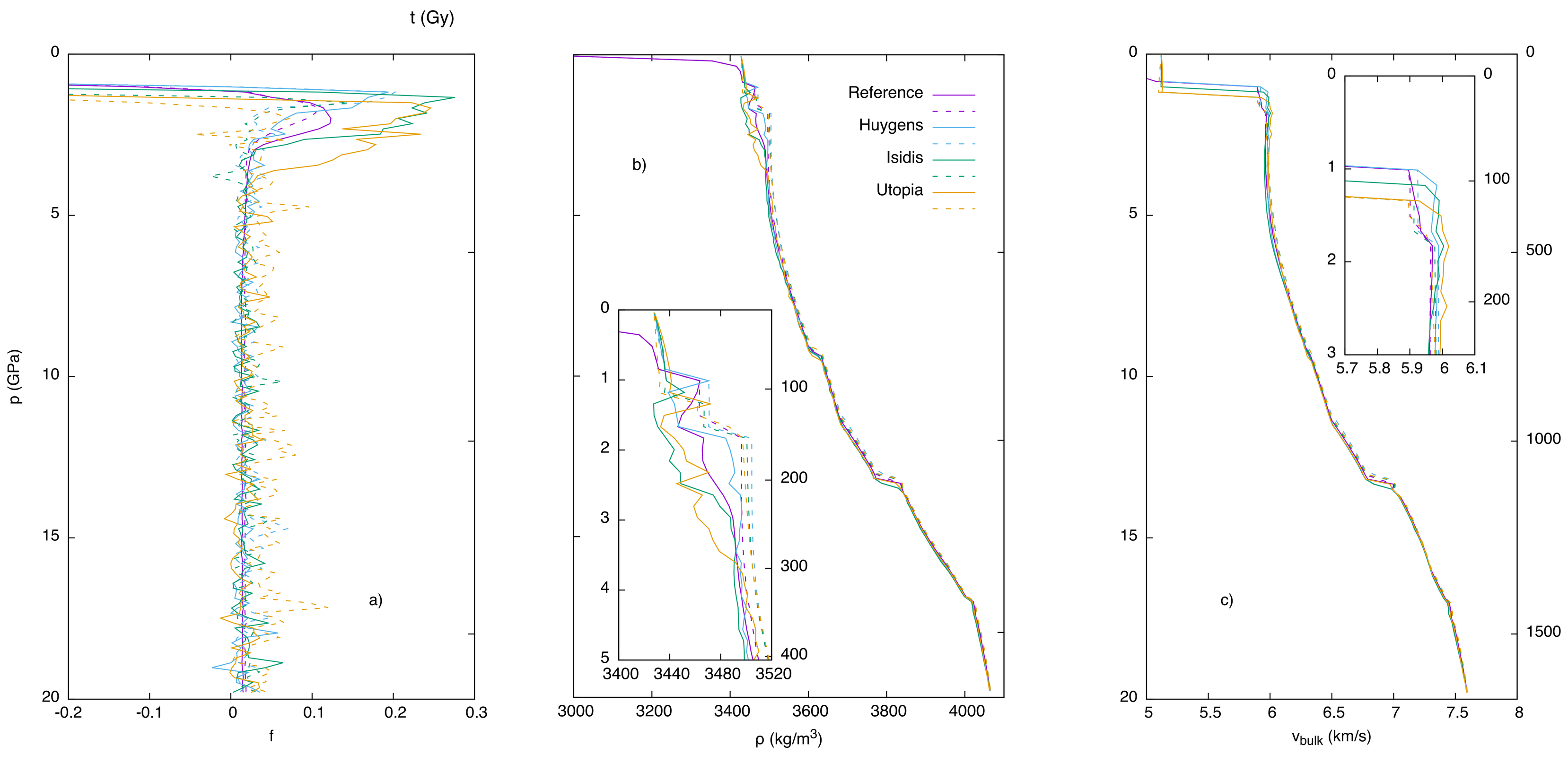

Fig. 4: Depth profiles of composition (a), density (b), and bulk sound velocity (c) at the impact site at present. The reference depth profiles are global averages.

The average thickness of the elastic lithosphere, z_{el}, was estimated following the procedure by Grott and Breuer (2008); it compares reasonably well with some estimates from flexure models from the literature, which are based on regional structures. Impacts cause a transient variation of z_{el}.

By their effect on composition, impacts modify the density of the target and thus leave a low-density anomaly (Fig. 4b) that is expected to be visible in gravity measurements; its detection by seismic means, however, would be possible only under very favorable conditions with a local network (Fig. 4c).

The crustal thickness determined from satellite altimetry can be locally overestimated by several kilometers if impact-induced density anomalies in the mantle are neglected.

Summary

- The compositional buoyancy of depleted mantle obstructs upwelling into the melting zone (cf. Plesa and Breuer, 2014) and counteracts long-lived melting. This process makes extensive crust production up to recent times difficult.
- Impacts may produce long-lived compositional heterogeneities stabilized by their own compositional buoyancy even if convection in the deeper mantle continues to the present.
- The thermal signature of individual ancient anomalies will be obliterated by now, but their compositional signature may have survived, although it may be difficult to detect with geophysical methods.

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