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

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Abstract

We ran series of 2D numerical mantle convection simulations of the thermochemical evolution of a Mars-like planet. In order to study the importance of compositional buoyancy of melting mantle, the models were set up in pairs of one including all thermal and compositional contributions to buoyancy (TC) and one accounting only for the thermal contributions (T). Single large impacts were introduced as causes of additional strong local anomalies, and their evolution in the framework of the convecting mantle was tracked. They confirm that the additional buoyancy provided by the depletion of melting mantle can establish a global stable stratification of the convecting mantle and throttle crust production. Furthermore, it is essential in the stabilization and preservation of local compositional anomalies directly beneath the lithosphere and offers a possible explanation for the existence of distinct, long-lived reservoirs in the martian mantle. Such anomalies will be detected by gravimetry rather than by seismic or heat flow measurements. The crustal thickness can be locally overestimated by up to 15–22 km if impact-induced density anomalies in the mantle are neglected.

1. Introduction

Convection in planetary mantles is driven by buoyancy that results from density variations, which may have thermal or compositional causes. We study the relative importance of the thermal and compositional contributions to the buoyancy of melt-induced density heterogeneities in Mars by coupling two-dimensional, fully dynamical convection models with a detailed model of the mineralogy and material properties of martian peridotite (e.g., [1, 2]). The main focus lies on the anomalies created by giant impacts, which lead to particularly intense, high-degree melting that may reach deeper than the regular global asthenospheric melting zone. We investigate the differences in the evolutions of models with only thermal and with both thermal and compositional buoyancy for impacts of different sizes; the compositional aspect has been neglected in most previous studies (e.g., [3, 4, 5]).

2. Method

The convection code is a modified version of STAGYY [6] and solves the conservation equations of mass, momentum, and energy in the compressible, anelastic approximation on a two-dimensional spherical annulus grid [7]. Material properties are derived from mineral physics improved and updated after [1]. For the models with purely thermal buoyancy, the compositional contribution was suppressed by forcing the density (and other physical properties) to remain at the value they would have for undepleted mantle, although the melting degree and changes in trace element composition are changed as usual.

The impact itself is represented as an instantaneous thermal anomaly, with shock-heating derived from the peak shock pressure based on the impedance-match model (cf. [4]); the material properties of the target are derived from the convection model, and the pressure decay with distance from the impact center is given by the "inverse-r" parameterization from [8]. As we model the impacts after existing martian craters, we use their observed final diameters D_f as input and deduce impact parameters such as the impactor size from them using empirical scaling laws [9].

3. Model

The general model parameters used in all models are listed in Table 1. Impacts of three different sizes corresponding to the Huygens ($D_\mathrm{f} = 467.25\,\mathrm{km}$), Isidis ($D_\mathrm{f} = 1352\,\mathrm{km}$), and Utopia ($D_\mathrm{f} = 3380\,\mathrm{km}$) impact basins, respectively, are considered. All impacts are assumed to occur at 4 Ga, i.e., 400 My after the model run begins; this choice approximates reasonably well the estimated age of the three craters and ensures that the model has developed a lithosphere of a certain thickness, comparable to that of Mars at that age. Most models assumed a bulk water content of 36 ppm by mass, as proposed by [10], but we also ran some models with the higher initial concentrations; this parameter affects mostly the rheological behavior.

Table 1: Important model parameters

Mantle thickness	1659.5 km
Surface temperature	215 K
Init. potential temperature	1700 K
Init. core superheating	150 K
Simple/complex transition	5.6 km
Bulk silicate Mars Mg#	0.75
Present K, Th, U	305 ppm, 56, 16 ppb
Init. bulk water content	*36*, 144 ppm

4. Results

Figure 1 shows the temperature and melting degree fields for the model pair with an Isidis-sized impact and a planet with an initial bulk water content of 36 ppm. In the model with both thermal and compositional buoyancy (TC), the strongly depleted compositional anomaly from the impact, visible as a dark red patch at 400 My, spreads beneath the lithosphere and remains there as a stable layer, which is progressively incorporated into the growing thermal lithosphere. By contrast, the compositional anomaly in the purely thermal model (T) is mixed back into the mantle and leaves no coherent trace that survives to the present. The thermal anomaly decays by diffusion within a few tens of millions of years in both cases. The additional melt production results in additional crust production at the impact site, but the net effect is not necessarily a thickened crust, because the impact itself also removes a large amount of crustal material, and a part of it is deposited outside the final crater as ejecta. The results further suggest that the crustal thickness can be locally overestimated by up to 15–22 km if impact-induced density anomalies in the mantle are neglected.

The different behavior displayed by the two model variants is due to the additional density deficit caused by compositional changes of the melting rock, especially the loss of iron. The density deficit suggests that the signature of an impact-generated compositional anomaly may be detectable by gravimetric methods, but a detection with seismic means would not be expected with instrumentation whose deployment on Mars can be expected within the next decades.

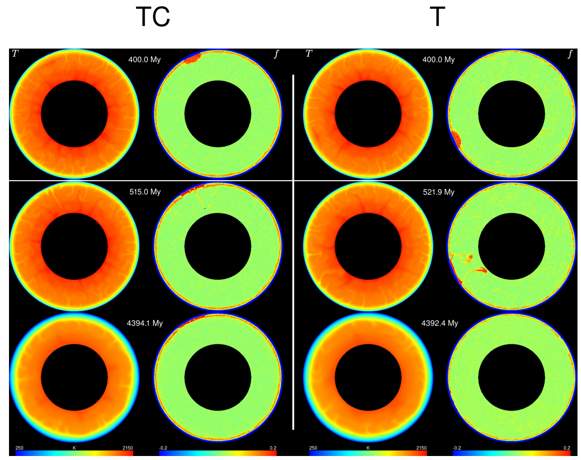

Figure 1: Temperature (T) and composition (f, positive values indicate depletion/melting degree) fields for the models with an Isidis-like impact.

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