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Towards self-consistent modelling of the Martian dichotomy: The influence of one-ridge convection on crustal thickness distribution

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In order to find a possible explanation for the origin of the Martian crustal dichotomy, a number of recent papers have examined the effect of layered viscosity on the evolution of a degree-1 mantle convection, e.g. [1] and [2]. It was found that a mid-mantle viscosity jump in the Martian mantle, combined with highly temperature- and depth-dependent viscosity, are effective in developing a degree-1 convection within 200-300 Million years of core formation. Such a layered viscosity profile could be justified by Martian mineralogy, where both olivine to spinel and garnet/pyroxene to majorite transitions occur below a mantle depth of 1000 km. All of these high-pressure mineral phases show higher strength than their corresponding upper mantle phases and thus a higher viscosity might be expected.
However, the actual effect of a degree-1 convective planform on the crustal thickness distribution has not yet been demonstrated. Also, the general shape of the dichotomy, which is not symmetrically hemispherical, has not yet been fully investigated. In this study we therefore discuss, how the evolution of low-degree mantle convection inside the planet Mars is reflected on its surface in terms of crustal thickness distribution. This will allow us to draw some conclusions towards a possible theory of how the dichotomy was formed in early Martian history.

This study involves full planet-scale modelling of the crustal patterns produced by 3D-spherical models of Martian mantle convection. All results are computed using the finite-volume multigrid code StagYY [3]. By using tracer particles to track composition, a self-consistent treatment modelling melting and chemical differentiation has been added to models of thermal convection. This allows us to obtain model maps of the crustal thickness distribution as it evolves with time on the whole planetary surface due to underlying convection patterns. To obtain rapid reduction of convective degree, a strongly depth- and temperature-dependent rheology has been applied with additional viscosity jumps at each mineralogical phase transition.

The most striking feature of the results is the fact that the obtained convective planform does not satisfy the expectation of a spherically symmetrical one-plume convection (l=1). It is rather like what we would call ‘one-ridge convection’ where the upwelling is a ridge-shaped feature covering a variable angle around the CMB. A closer look at this feature reveals that it consist of two plumes at each end, interlinked by a sheet-like upwelling region of lower intensity. From this point of view, it represents a stable transition state between l=1 and l=2 convection.
Most melt in our model runs is generated above the major ridge-shaped upwelling region and thus crustal thickness distribution to a first order reflects the large-scale upwelling pattern in the mantle. Additional melting occurs where small-scale convection is active underneath the rigid lid. Due to this effect, the hemisphere of downwelling is covered by crust, too, but it is remarkably thinner than above major upwellings.
Although mean crustal thickness is slightly overestimated in all of our models, the relative distribution of crustal thickness seems to be quite Mars-like. We find that, although absolute values of crustal thickness are above values inverted for Mars, the relative crust distribution of our best-fit model shows intriguing similarity to that obtained from a MOLA crustal thickness model [4].

Although many questions still remain, the obtained results demonstrate that it is indeed possible to form a crustal dichotomy as a consequence of very low degree (l=1 to l=2) mantle convection very early in the planet’s history and, furthermore, that some of the observed patterns show intriguing first order similarities to the general non-spherical shape of the Martian dichotomy.

In all of our models, the region of thick crust came to be located over the region of mantle upwelling, whereas crustal thinning above upwellings seemed to be a rather minor effect. The region of upwelling itself proves not to be strictly hemispherical, but is rather a ridge-like structure spread over more or less one half of the planet's body. We call this type of convective planform one-ridge convection in analogy to the commonly known term one-plume convection.

This one-ridge convection could well turn out to be a successful approach to future, more systematic modelling of the Martian crustal dichotomy. Furthermore, this study demonstrates how important it is to model closely linked processes like thermal convection and melting in an integrative and self-consistent way to gain more insight into terrestrial planetary evolution.

References

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