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On the structure of the lithosphere of Mars: New insights from crustal composition and rheology of the upper mantle

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Abstract

We conduct an in-depth study of the thermal structure and rheology of the lithosphere of Mars, focusing on the effects of crust composition, creep behaviour of olivine (the main mineral in the lithosphere mantle), and the abundance of iron and water in the mantle.

1. Introduction

An adequate knowledge of the thermal and rheological properties of crust and mantle is fundamental for deciphering and understanding the thermal state and interior evolution of a planetary body. Previously, indirect methods have been used to calculate heat flows for Mars. A commonly used indirect method is based on the relation between the thermal state of lithospheric rocks and their mechanical strength, usually related through the effective elastic thickness of the lithosphere or from the depth to the brittle–ductile transition beneath large thrust faults. The so-obtained heat flows are valid for the time when the lithosphere was loaded or faulted, and therefore when deduced from regions deformed in different ages provides information on the thermal evolution of Mars [1, 2]. Thus, heat flow estimates based on lithosphere strength indicators are strongly dependent on the assumed compositions, the choice of predominant deformation mechanisms, and other thermal and mechanical parameters.

2. The role of the crust

As mentioned previously, Ruiz et al. [1] and Ruiz [2] calculated in a consistent manner upper and lower limits for the surface heat flows derived from the effective elastic thickness of the lithosphere or from faulting depth beneath large thrust faults. In these works the crustal density was assumed to be 2900 kg m^{-3}, which is suitable for a basaltic crust (see below), the thermal conductivity of the crust was assumed to be 2 W m^{-1} K^{-1}, a value appropriate for basalts (see e.g., [3]), and for creep parameters of the Martian crust, it had taken into account the constants for the flow law of diabase [4]. The use of a wet diabase law is appropriate for a basaltic Martian crust and is consistent with extensive evidence for water-related geological activity in early Mars (e.g., [5, 6]).

A crustal density of 2900 kg m^{-3} can be consistent with a basaltic crust somewhat fractured, or consistent with a basaltic crust including a felsic component. Indeed, some recent works suggest that the Martian crust could contain a substantial amount of felsic rocks [7-10], although other works consider as non-solids the orbital-based evidences for a felsic component (see [11]). Moreover, Baratoux et al. [9] proposed a high density (>3200 kg m^{-3}) for the Martian basalts, although a crust so dense is incompatible with geophysical studies [9], maybe favouring the presence of a felsic component.

3. The role of the lithospheric mantle

On the other hand, in these works [1, 2] the ductile strength of the lithospheric mantle was calculated for dry olivine dislocation creep rheology (a flow law obtained for artificially dried dunites; [12]), which gives a generous upper limit to the surface heat flow obtained from lithospheric strength [1, 2]. For wet olivine, the flow law of the Anita Bay dunite [12] was commonly used. This flow law places a lower limit on the strength of wet olivine due to its relative weakness (compared with other wet dunites, such as Aheim dunite), which gives a lower limit to the surface heat flow.

However, Zhao et al. [13] have reported that anhydrous olivine is considerably weaker when it is proportionally iron-rich, as expected for the Martian mantle (for a review see [14]), which would reduce mantle strength and hence the obtained heat flows. Likewise, recent careful examinations of the creep behaviour of olivine under hydrous conditions as a function of iron content suggest that the viscosity of the Martian mantle will be a factor of ~20 lower than the viscosity of Earth's mantle [15]. Also, the behaviour of the upper lithospheric mantle is in turn largely controlled by low-temperature plasticity of olivine-rich rocks, resulting in a rheology significantly weaker than that usually used for the upper mantle (see e.g., [16] for discussion under anhydrous conditions).

4. First steps & Future work

All of these issues motivate us to explore to what extent the composition of the crust or the creep behaviour of olivine could affect the thermal and mechanical structure of the lithosphere of Mars, and hence on the heat flow estimates based on lithosphere strength indicators.

In a first step, we carefully and systematically explore the effects of composition of the crust on the thermal and mechanical structure of the Martian lithosphere (see [17]). To make this, we use suitable parameters (appropriated for, respectively, mafic and felsic materials), in order to evaluate the case of an end-member felsic crust, and its influence on the thermal and mechanical properties of the crust and lithosphere. Also, we identify the parameters that have a major impact on the thermal state and mechanical behaviour of the lithosphere. Finally, we extend our analysis to specific case scenarios and discuss the implications of our results for the thermal state, structure and evolution of Mars (see e.g., [18, 19]).

In a subsequent step, we intend to analyse in detail the influence of the creep behaviour of olivine and the effects of the abundance of iron and water in the mantle on the mechanical behaviour of the lithosphere.

Taken together, these two main lines will provide an integrated overview of the role of the crust and lithospheric mantle within the framework of the thermal and mechanical structure of the lithosphere of Mars. Our first results will be presented in the European Planetary Science Congress 2017.

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