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The early thermal and magnetic state of the cratered highlands of Mars

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Abstract

Surface heat flows are calculated from elastic lithosphere thicknesses for the heavy cratered highlands of Mars, in terms of the fraction of the surface heat flow derived from crustal heat sources. Previous heat flow estimations for Mars used linear thermal gradients, which is equivalent to ignoring the existence of heat sources within the crust. We compute surface heat flows following a methodology that relates effective thickness and curvature of an elastic plate with the strength envelope of the lithosphere, and assuming crustal heat sources homogeneously distributed in a radioactive element-rich layer 20 or 60 km thick. The obtained results show that the surface heat flow increases with the proportion of heat sources within the crust, and with the decrease of both radioactive element-rich layer thickness and surface temperature. Also, the results permit us to calculate representative temperatures for the crust base, rock strength for the upper mantle, and lower and upper limits to the crustal magnetization depth and intensity, respectively. For Terra Cimmeria, an effective elastic thickness of 12 km implies between 30% and 80% of heat sources located within the crust. In this case the uppermost mantle would be weak at the time of loading, and temperatures in the lower crust cold enough to favor unrelaxed crustal thickness variations and to permit deep Curie depths in the highlands, as suggested by the observational evidence.

Keywords: Mars; elastic thickness; heat flow; thermal structure; Curie depth

1. Introduction

The heavily cratered highlands of Mars, mainly located in the southern hemisphere, contain the oldest terrain on the planet (Fig. 1 shows a map with the geographical features discussed in this paper). Martian highlands basement dates from the Early Noachian period (e.g., 1), which ended between 3.8 and 4.1 Gyr ago [2]. The Noachian epoch is the earliest period of the Martian chronology (established by crater counts), ranging from the formation of the planet to between 3.5 and 3.7 Gyr ago (the start of the Hesperian epoch [2,3]). The existence of long-wavelength crustal thickness variations in the highlands has been inferred from inversions of topography and gravity data [4]. Such variations probably have survived throughout Martian history and therefore require ancient lower crust temperatures cold enough to prevent their relaxation until the present day [4–7]. Some regions of the

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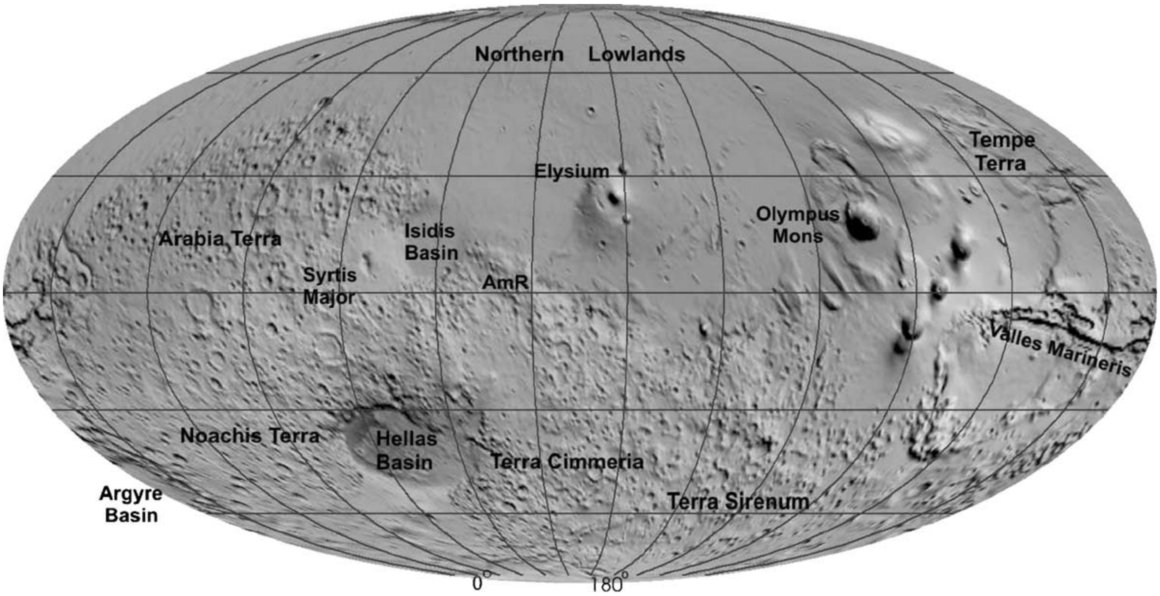

Fig. 1. Map of Mars with the geographical features discussed in this paper and other representative features indicated on MOLA topography [42]. The label AmR indicates the Amenthes Rupes region. The cratered highlands are mainly located in the Southern Hemisphere.

highlands (principally in Terra Cimmeria and Terra Sirenum) display strong (likely remnant) magnetization [8–10]. The thickness of the strongly magnetized material is limited by the depth to the Curie temperature, for the minerals that carry the magnetization, at the time when the magnetization was established. So, the thermal state of the highlands has important implications for the stability of crustal thickness variations against relaxation, and for the thickness of the magnetized crust.

Previous works have estimated surface heat flow for diverse regions of Mars, deduced from the effective elastic thickness of the lithosphere at the time of loading (e.g., [4,11–15]), or from faulting depth [16]. Such heat flow estimates are relevant for the loading and the faulting time, respectively. These studies used linear thermal gradients (equivalent to ignoring the presence of heat sources within the crust), so that the obtained heat flow values are lower limits.

In this paper we take into account the existence of crustal heat sources in the calculation of surface heat flows for Mars. From arguments drawn from Martian surface materials analyzed in Pathfinder soils and rocks, or from orbital observations, it has been proposed that over 50%, or even 75%, of radioactive heat sources in Mars are located in the crust [17]. For comparison, in the Earth, roughly half of the heat flow lost in continental areas originates from crustal heat sources. We used our results to calculate representative temperatures for the base of the crust (of critical importance to considerations of stability against relaxation of the highlands crust thickness variations), to calculate rock strength in the uppermost mantle (in order to analyze the possible bounds on heat sources located in the crust), and to obtain lower and upper limits to the crustal magnetization depth and intensity, respectively.

2. Crustal temperature profiles and estimation of surface heat flows

The temperature-depth profile in a planetary crust is a function of the amount and distribution of crustal heat sources. Apart from general considerations (e.g., [17]), the distribution (and intensity) of heat sources in the Mars' crust is poorly constrained. For this reason, here we assume crustal heat sources homogeneously distributed in a radioactive element-rich layer (not necessarily equivalent to the whole crust) 20 or 60 km thick. The higher value corresponds to a typical value for mean thickness of the highland crust deduced from topography and gravity [18,19]. The lower value is taken to make the lower limit agree with the estimations of 20–30 km for the thickness of an enriched crust deduced from the geochemistry of Martian meteorites [20]. A nearly homogeneous distribution of radioactive heat sources is in accordance with the suggestion that vertical differentiation in the Martian crust is less important than in the terrestrial continental crust [17].

If f is the fraction of the surface heat flow derived from crustal heat sources, the temperature at