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The evolution of the martian elastic lithosphere and implications for crustal and mantle rheology

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Abstract

Estimates of the martian elastic lithosphere thickness T_e imply that T_e increased from around 20 km in the Noachian to about 70 km in the Amazonian period. A phase of rapid lithospheric growth is observed during the Hesperian and we propose that this elastic thickness history is a consequence of the martian crustal rheology and its thermal evolution. A wet crustal rheology is found to generate a mechanically incompetent layer in the lower crust during the early evolution and the rapid growth of T_e during the Hesperian results from the disappearance of this layer due to planetary cooling. The incompetent layer and the related rapid lithospheric growth are absent for a dry basaltic crustal rheology, which is therefore incompatible with the observations. Furthermore, we find that the observed elastic thickness evolution is best compatible with a wet mantle rheology, although a dry mantle cannot be ruled out. It therefore seems likely that rheologically significant amounts of water were retained in the Martian crust and mantle after planetary accretion.

Keywords: Mars; Mars, interior; Thermal histories; Geophysics

1. Introduction

Planetary lithospheres exhibit nonzero mechanical strength over geological timescales and their flexural rigidity is generally expressed in terms of the elastic lithosphere thickness T_e. On the Earth, the continental and oceanic lithosphere have had distinct physical and chemical evolutions and their respective effective elastic thickness is controlled by different processes. The oceanic lithosphere is relatively young, has a single-layer rheology and T_e largely depends on the local thermal age (Watts, 1978). It roughly follows the depth to the 450–600 °C isotherm, reflecting the growth of mechanical strength as the lithosphere cools (Watts, 1978; Watts et al., 1980; Caldwell and Turcotte, 1979; McNutt and Menard, 1982).

In contrast, this simple dependence of T_e on temperature is not applicable to the continents. Although there is a relation between lithospheric strength and thermal state (Karner et al., 1983; Sahagian and Holland, 1993), T_e in the continents cannot be described by a relationship with only one parameter (Cochran, 1980; McNutt et al., 1988; McNutt, 1990; Watts, 1992; Kruse and Royden, 1994; Watts and Burov, 2003). In addition to the geotherm, T_e depends on the state of the crust–mantle interface (mechanical coupling or decoupling of crust and mantle), the thicknesses and proportions of the mechanically competent layers and intraplate stresses (Burov and Diament, 1995).

As a consequence, T_e estimates on the continents vary over a wide range although they are not randomly distributed. Rather, a bimodal distribution with a primary peak at 10–30 km and a secondary peak around 70–90 km is observed (Watts, 1992). This bimodal structure is the consequence of a change of the mechanical state of the crust–mantle interface, with low T_e corresponding to mechanical decoupling and high T_e corresponding to mechanical coupling of crust and mantle. Decoupling in the young and warm lithosphere is caused by the presence of an incompetent layer in the lower crust which later disappears due to lithospheric cooling. This bimodal distribution of elastic thickness values is not observed for the oceans and is a direct consequence of the multilayer rheology of the continental lithosphere (Burov and Diament, 1995).

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Estimates of the martian elastic lithosphere thickness imply that T_e evolved from values around 20 km in the Noachian (McGovern et al., 2004; Grott et al., 2005, 2007; Kronberg et al., 2007) to around 70 km in the Amazonian period (McGovern et al., 2004; Belleguic et al., 2005) and this general trend is well understood in terms of planetary cooling as predicted by thermal evolution models (Hauck and Phillips, 2002; Schumacher and Breuer, 2006). However, the data also implies that the lithospheric thickness rapidly increased during the Hesperian period (McGovern et al., 2004), which may not be explained by the depth evolution of a single isotherm and is reminiscent of the bimodal T_e distribution on Earth's continents.

Therefore, Schumacher and Breuer (2006) have studied the depth evolution of the isotherms corresponding to the onset of plasticity in diabase rock and olivine, i.e., the temperatures above which mechanical strength is lost in the crust and mantle, respectively. They argue that during the early evolution lithospheric strength is carried by the crust alone and that only after the upper mantle has sufficiently cooled T_e is controlled by the brittle–ductile transition in olivine.

In this paper we compile T_e estimates to reconstruct the martian elastic thickness history. This data is compared to models of the elastic thickness evolution, which we construct using thermal evolution models. The elastic thicknesses are calculated using the strength envelope formalism and the mechanical state of the crust–mantle interface is taken into account (Burov and Diament, 1995). Furthermore, the influence of crustal and mantle rheology on the evolution of the martian elastic lithosphere thickness will be investigated.

2. Data

The elastic thickness of Earth's continents has been estimated in numerous studies and Fig. 1a shows a compilation by Watts (2001) of T_e values as a function of plate age (see his Table 6.2 and references therein). Although the data exhibits a large scatter a clear correlation of T_e with plate age is visible. To demonstrate this, we have calculated average T_e for time-bins of 0–500, 250–750, 500–1000, 750–2000 and 1000–3000 Myr, and the results are indicated by shaded rectangles in Fig. 1a. During the first 1000 Myr, T_e slowly grows from 23 ± 18 to 25 ± 20 and 37 ± 16 km before rapidly increasing to 56 ± 27 and 64 ± 32 km between 750–2000 and 1000–3000 Myr, respectively. Therefore, T_e values exhibit a bimodal distribution with low T_e corresponding to young and high T_e corresponding to old lithospheric plates.

Mostly owing to the limited resolution of the available gravity data, estimates of the elastic lithosphere thickness are much sparser for Mars. Furthermore, the determination of plate and loading ages pose severe problems, and the time of loading can usually only be constrained to within a specific epoch, which might span several gigayears. We have compiled T_e estimates derived from gravity and topography data (McGovern et al., 2004; Belleguic et al., 2005), forward modeling of thrust faults (Schultz and Watters, 2001; Grott et al., 2007) and the analysis of rift flank uplift (Grott et al., 2005; Kronberg et al., 2007) and converted the epoch of the loading event to absolute ages using the cratering chronological model of Hartmann and Neukum (2001). We do not consider estimates for which only lower limits on T_e are available and have substituted 0 km for a lower limit if only upper bounds existed. Also, we have calculated the mean and standard error for each structure where multiple estimates were available.

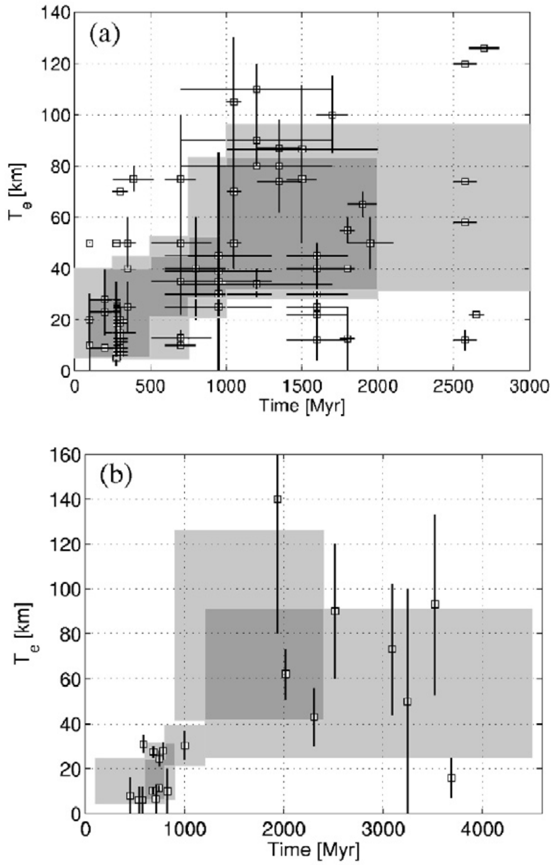

Fig. 1. (a) Elastic thickness estimates for Earth's continents as a function of plate age. [Data adopted from the compilation of Watts (2001), see his Table 6.2 and references therein.] Average elastic thickness values have been computed for the time-bins 0–500, 250–750, 500–1000, 750–2000 and 1000–3000 Myr, yielding average T_e of 23 ± 18, 25 ± 20, 37 ± 16, 56 ± 27 and 64 ± 32 km, respectively. The average elastic thickness values for each time-bin are indicated by shaded rectangles and overlapping bins have stronger shading. (b) Elastic thickness estimates for Mars as a function of time. Average elastic thickness values have been computed for time-bins corresponding to the Noachian (100–800 Myr), Noachian–Hesperian (600–900 Myr), Hesperian (800–1200 Myr), Hesperian–Amazonian (900–2400) and Amazonian (1200–4500 Myr) epochs, yielding average T_e of 15 ± 10, 19 ± 13, 30 ± 7, 84 ± 42 and 58 ± 33 km, respectively. The average elastic thickness for each time-period is indicated by shaded rectangles and overlapping bins have stronger shading.

The resulting elastic thickness estimates comprise 20 datapoints which are shown as a function time in Fig. 1b. Averages of T_e for the martian epochs have been calculated by merging the data into time-bins corresponding to the Noachian (100–800 Myr), Noachian–Hesperian (600–900 Myr), Hesperian (800–1200 Myr), Hesperian–Amazonian (900–2400 Myr) and Amazonian (1200–4500 Myr) periods. The time coordinate of individual data-point has been shifted from the center of the corresponding epochs for better visibility. Mean elastic thicknesses