Icarus 211 (2011) 389–400

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Magnitude of global contraction on Mars from analysis of surface faults: Implications for martian thermal history

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ARTICLE INFO

Article history:
Received 27 March 2010
Revised 1 November 2010
Accepted 2 November 2010
Available online 11 November 2010

Keywords:
Tectonics
Thermal histories
Mars, Surface

ABSTRACT

Faults provide a record of a planet's crustal stress state and interior dynamics, including volumetric changes related to long-term cooling. Previous work has suggested that Mars experienced a pulse of large-scale global contraction during Hesperian time. Here we evaluate the evidence for martian global contraction using a recent compilation of thrust faults. Fault-related strains were calculated for wrinkle ridges and lobate scarps to provide lower and upper bounds, respectively, on the magnitude of global contraction from contractional structures observed on the surface of Mars. During the hypothesized pulse of global contraction, contractional strain of −0.007% to −0.13% is indicated by the structures, corresponding to decreases in planetary radius of 112 m to 2.24 km, respectively. By contrast, consideration of all recognized thrust faults regardless of age produces a globally averaged contractional strain of −0.011% to −0.22%, corresponding to a radius decrease of 188 m to 3.77 km since the Early Noachian. The amount of global contraction predicted by thermal models is larger than what is recorded by the faults at the surface, paralleling similar studies for Mercury and the Moon, which suggests that observations of fault populations at the surface may provide tighter bounds on planetary thermal evolution than models alone.

1. Introduction

The surface record of tectonic deformation provides a record of a planet's thermal and tectonic evolution (Solomon and Chaiken, 1976; Banerdt et al., 1992; Schubert et al., 1992; Watters, 1993; Andrews-Hanna et al., 2008; Zuber et al., 2010). This relationship has been used on Mercury, the Moon, Mars, and icy outer planet satellites in an attempt to understand and bound the thermal evolution of these bodies. Cooling of a planet's interior would create a net global contraction, which would induce global compressional horizontal stress and contractional strain near the surface (Solomon and Chaiken, 1976; Turcotte, 1983; Solomon, 1986; Banerdt et al., 1992; Schubert et al., 1992; Hauck et al., 2004), potentially resulting in the formation of contractional structures at the surface, such as thrust faults (expressed as either wrinkle ridges or lobate scarps). Wrinkle ridges consist of narrow, asymmetric ridges superimposed on broad arches (Plescia and Golombek, 1986; Banerdt et al., 1992; Watters, 1993) and are interpreted to be anticlines above blind thrust faults (Schultz, 2000; Okubo and Schultz, 2004; Tanaka et al., 2010). They are observed on all terrestrial bodies, including Mercury, Venus, the Moon, and Mars (e.g., Watters 1988). On Mars, wrinkle ridges are distributed globally and occur primarily in Hesperian ridged plains (Hr) (Tanaka et al., 1991; Banerdt et al., 1992; Watters, 1993; Mangold et al., 2000; Head et al., 2002). Lobate scarps are interpreted to be the result of surface-breaking thrust faults (Howard and Muehlberger, 1973; Strom et al., 1975; Lucchitta, 1976; Cordell and Strom, 1977; Binder, 1982; Binder and Gunga, 1985; Watters, 1993; Schultz, 2000; Hauck et al., 2004) and are found on Mercury, Mars, and the Moon. On Mars, the majority of lobate scarps occurs in older geologic terranes (in units Npl_1, Npl_2, Npl_d) and they appear to be primarily Noachian in age (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka et al., 1991; Watters, 1993; Mangold et al., 2000).

Theoretical considerations from thermal evolution models and observations, such as the abundance of lobate scarps on the surface, suggest that Mercury has undergone global contraction (e.g., Strom et al., 1975; Watters et al., 1998; Watters and Nimmo, 2010), with a minimum estimate of planetary radius decrease of 0.8 km (Watters et al., 2009) and a maximum estimate of 17 km, resulting from the complete solidification of an initially molten core (Solomon 1976). Similarly, models for the thermal evolution of the Moon have been evaluated by using tectonic structures on the surface (Golombek and McGill, 1983; Turcotte, 1983; Solomon,

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0019-1035/$ - see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2010.11.003

1986). These studies conclude that there has been little or no decrease in lunar radius (<1 km) since the end of the heavy bombardment and emplacement of the maria 3.8 byr ago (Solomon and Chaiken, 1976; Cordell and Strom, 1977; Solomon, 1986; Solomon and Head, 1979, 1980; Golombek and McGill, 1983; Watters and Johnson, 2010). Recent work (Watters et al., 2010) has identified a number of apparently young (<1 Ga) lobate scarps in the lunar highlands. They suggest that the small-scale lobate scarps accommodate late-stage global contraction corresponding to a planetary radius decrease of $\sim$100 m. The identification of these and potentially other lobate scarps in the newly acquired imagery may place additional constraints on thermal evolution models of the Moon.

Net global expansion is an important process for the outer planet satellites. On icy satellites, ice phase transitions in the interior may lead to satellite expansion. The phase change from liquid water to ice I produces large tensile surface stresses (Cassen et al., 1979; Squyres and Croft, 1986; Nimmo, 2004; Collins et al., 2010) and extensional structures at the surface. The transition from ice V to ice II may lead to an increase in surface area of 1% (Squyres and Croft, 1986). Expansion as a result of this process may lead to surface area increases of up to several percent given complete freezing of small satellites (Squyres and Croft, 1986). Satellite differentiation by movement of silicate material to the core and less dense ice to the surface leads to a decrease in mean satellite density, requiring an increase in volume (Squyres and Croft, 1986). On Ganymede and Callisto, the total increase in surface area could be as much as 6% (Squyres, 1980; Squyres and Croft, 1986), and radius increases have been inferred (Squyres, 1980; Mueller and McKinnon, 1988; Collins et al., 2010) to have occurred as a result.

Thermal history models for Mars suggest that the planet was initially hot and subsequently cooled over geologic time (Schubert and Spohn, 1990; Schubert et al., 1992). These models predict a long period of global contraction as a result of the cooling of the interior, although the rate of contraction was not necessarily constant; a global array of contractional structures (wrinkle ridges and lobate scarps) is cited as evidence of this global contraction (Schubert and Spohn, 1990; Tanaka et al., 1991; Zimbelman et al., 1991; Schubert et al., 1992; Watters, 1993; Golombek and Phillips, 2010).

The hypothesis that Mars underwent a period, or pulse, of enhanced global contraction during the Late Noachian (LN) through the Early Hesperian (EH) was first made by Schubert et al. (1992) as a likely explanation for the abundance of wrinkle ridges in Hesperian-aged rocks (e.g., Tanaka et al., 1991). The Early Hesperian basaltic plains units correspond to a global-scale volcanic resurfacing event (Tanaka et al., 1988; Greeley and Schneid, 1991; Frey, 1992; Watters, 1993; Head et al., 2002). Since then, many studies (e.g. Watters, 1993; Mangold et al., 2000; Andrews-Hanna et al., 2008; Golombek and Phillips, 2010) have assumed a causal relationship between contractional structures on Mars and global contraction, yet the correspondence between the two has remained only qualitative.

Several previous studies of tectonic and loading models of Tharsis have invoked stresses related to global thermal contraction to fit the location of the suite of wrinkle ridges surrounding Tharsis (Tanaka et al., 1991; Watters, 1993; Dimitrova et al., 2008), the formation of lobate scarps along the eastern dichotomy boundary (Watters, 2003a,b), and concentric thrust faults around Utopia Basin (Searls and Phillips, 2007). Although a few studies have been conducted on the amount of global contractional strain that should be predicted from thermal models (Hauck et al., 2003; Andrews-Hanna et al., 2008), to date the amount of global contractional strain accommodated at the surface of Mars by thrust faults has not been quantified, hindering a quantitative test of global contraction predictions.

The global contraction of Mars is hypothesized to have peaked during the Late Noachian to Early Hesperian (3.8–3.6 Ga; Hartmann and Neukum, 2001) based on the abundance of wrinkle ridges found in rocks of this age (e.g., Tanaka et al., 1991; Watters, 1993). However, thermal evolution models (Schubert and Spohn, 1990; Schubert et al., 1992; Andrews-Hanna et al., 2008) imply that secular cooling of Mars' interior began in the Early Noachian and continued through the present, predicting an increasing accumulation of compressional stress and contractional strain at the surface. These models also imply that if the compression was global in extent as has been hypothesized, all units older than Early Hesperian should contain contractional structures such as wrinkle ridges.

The hypothesis that the wrinkle ridges and lobate scarps were formed in association with global contraction on Mars is tested here by calculating the horizontal crustal strain accommodated by the contractional structures for two time periods. First, we test the hypothesis of a pulse of global contraction during the Late Noachian through the Early Hesperian. Then we test the cumulative magnitude of global contraction from the Early Noachian through the Late Amazonian. Strain for both scenarios is converted into planetary radius change, permitting a quantitative comparison between fault-related strain and strain predicted by models of the thermal evolution of Mars. We then discuss the implications of our findings for the magnitudes of global contraction predicted for Mars and for Mercury.

2. The global contraction hypothesis

Following the Mariner 9 mission in 1971, the view of Mars was that its surface was dominated by extensional structures, such as normal faults and graben (Schubert et al., 1992). Thermal history models based on these early observations involved net global warming and required planetary expansion over much of Mars' history (Solomon and Chaiken, 1976; Schubert et al., 1992), consistent with the extensive graben systems in Tharsis (Hartmann, 1973; Carr, 1974; Solomon and Chaiken, 1976; Schubert et al., 1992) and elsewhere.

Following the imaging of numerous contractional structures by Viking Orbiter, the view of martian geologic and thermal histories changed significantly. The abundance of globally distributed contractional structures has been cited as evidence for planetary contraction associated with net cooling of the martian interior (Schubert and Spohn, 1990; Tanaka et al. 1991; Zimbelman et al., 1991; Schubert et al., 1992; Watters, 1993; Golombek and Phillips, 2010). During planetary cooling predicted by the thermal models (Schubert and Spohn, 1990; Schubert et al., 1992), the magnitude of horizontal compressional stress at the surface would initially increase in the Early Noachian, then decrease to a minimum at the present time. This appears to be in qualitative agreement with the temporal distribution of contractional structures, with a large number inferred to have been formed in the Late Noachian to Early Hesperian (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka et al., 1991; Watters, 1993). Thermal history models additionally predict monotonically declining volcanism (Schubert and Spohn, 1990; Schubert et al., 1992), in contrast with an apparent pulse in the total area and average rate of volcanism in the Early Hesperian (Zimbelman et al., 1991; Frey, 1992; Watters, 1993).

Hauck et al. (2003) calculated the surface horizontal contractional strain for several scenarios. For global thermal contraction due to planetary heat loss and core growth, they calculate strain rates on the order of $10^{-20}\,s^{-1}$ in the Hesperian, corresponding to an average value of $\sim$0.003% contractional strain (Hauck et al., 2003). For contraction due to extensive Hesperian volcanism (Tanaka et al., 1988; Greeley and Schneid, 1991; Frey, 1992; Watters, 1993; Head et al., 2002), they calculate $\sim$0.0005% surface contractional strain (Hauck et al., 2003). More recently, Andrews-Hanna et al. (2008) used the thermal evolution model