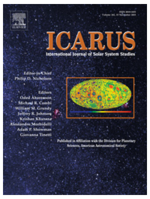
Icarus 288 (2017) 53–68

Contents lists available at ScienceDirect

Icarus

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



Thrust fault modeling and Late-Noachian lithospheric structure of the circum-Hellas region, Mars

Isabel Egea-Gonzalez[a,b,*], Alberto Jiménez-Díaz[c], Laura M. Parro[c], Valle López[d], Jean-Pierre Williams[e], Javier Ruiz[c]

[a] *Departamento de Física Aplicada, Universidad Politécnica de Cartagena, C/ Dr. Fleming s/n, Cartagena 30202, Spain*
[b] *Departamento de Física Aplicada. Escuela Politécnica Superior de Algeciras, Universidad de Cádiz, Algeciras, Cádiz 11202, Spain*
[c] *Departamento de Geodinámica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid, Madrid 28040, Spain*
[d] *Instituto de Geociencias, IGEO (CSIC, UCM), Madrid 28040, Spain*
[e] *Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095, USA*

ARTICLE INFO

Article history:
Received 22 July 2016
Revised 13 January 2017
Accepted 26 January 2017
Available online 29 January 2017

Keywords:
Mars
Mars, Interior
Tectonics
Thermal histories

ABSTRACT

The circum-Hellas area of Mars borders Hellas Planitia, a giant impact ~4.0–4.2 Ga old making the deepest and broadest depression on Mars, and is characterized by a complex pattern of fracture sets, lobate scarps, grabens, and volcanic plains. The numerous lobate scarps in the circum-Hellas region mainly formed in the Late Noachian and, except Amenthes Rupes, have been scarcely studied. In this work, we study the mechanical behavior and thermal structure of the crust in the circum-Hellas region at the time of lobate scarp formation, through the modeling of the depth of faulting beneath several prominent lobate scarps. We obtain faulting depths between ~13 and 38 km, depending on the lobate scarp and accounting for uncertainty. These results indicate low surface and mantle heat flows in Noachian to Early Hesperian times, in agreement with heat flow estimates derived from lithospheric strength for several regions of similar age on Mars. Also, faulting depth and associate heat flows are not dependent of the local crustal thickness, which supports a stratified crust in the circum-Hellas region, with heat-producing elements concentrated in an upper layer that is thinner than the whole crust.

1. Introduction

Lobate scarps are relatively common tectonic structures on the surface of the Moon, Mars and Mercury. These structures are linear or arcuate features that have asymmetric cross-sectional profiles, with a very steep scarp face and a more moderately sloped back scarp, and can exceed 1 km in elevation and several hundred kilometers in length (e.g., Watters and Robinson, 1999; Watters and Schultz, 2010). Lobate scarps offset the walls and floors of cross-cut craters suggesting they are expression of thrust faults which likely deform the crust down to the brittle-ductile transition depth (e.g., Schultz and Watters, 2001; Watters et al., 2002; Watters and Schultz, 2010). The brittle-ductile transition relates the mechanical structure of the lithosphere to the thermal structure. Therefore knowledge of the depth reached by a lobate scarp-related fault provides a means of estimating surface heat flows and subsurface temperatures at the time of faulting (e.g., Grott et al., 2007; Ruiz et al., 2008, 2009; Mueller et al., 2014).

In this work we focus on lobate scarp features in the circum-Hellas area of Mars. Hellas Planitia is a giant impact basin formed during the Early Noachian (Leonard and Tanaka, 2001), around 4.0–4.2 Ga (Frey, 2006; Fasset and Head, 2011), which forms the deepest and broadest depression on Mars, 9 km relief and 2000 km across (Smith et al., 1999). A complex region of fracture sets, lobate scarps, channels, grabens, and volcanic plains with a basin-controlled origin is established around Hellas. Some of these structures may be the surface expression of internal events triggered by the basin-forming impact (e.g., Bratt et al., 1985; Chicarro et al., 1985; Freed et al., 2001; Öhman et al., 2005).

Lobate scarps are numerous in the vicinity of Hellas (e.g., Wichman and Schultz, 1989). They mainly formed in the Late Noachian (see Tanaka et al., 2014), probably related to the crustal thickening and lateral pressure variations following the formation of the basin. These circum-Hellas lobate scarps include Amenthes Rupes, the largest lobate scarp on Mars, which is located between the Isidis and Hellas regions and is the more prominent member of a local thrust fault population (Watters and Robinson, 1999).

---

[*] Corresponding author:.
E-mail address: isabel.egea@uca.es (I. Egea-Gonzalez).

http://dx.doi.org/10.1016/j.icarus.2017.01.028
0019-1035/

Apart from several works focused on Amenthes Rupes, lobate scarps around Hellas have been scarcely studied. Schultz and Watters (2001) calculated the depth of the fault beneath Amenthes Rupes by modeling the topography across the lobate scarp through the elastic dislocation program Coulomb (Toda et al., 2005; Lin and Stein, 2004); those authors obtained best-fitting topography models from depths of faulting of 25–30 km. Grott et al. (2007) also followed a dislocation method for Amenthes Rupes, obtaining a depth of faulting of 32–40 km. Ruiz et al. (2008) analyzed the depth of the fault associated with Amenthes Rupes by using elastic modeling of a topographic profile perpendicular to the lobate scarp trace; they concluded that models that best match the topography above Amenthes Rupes were provided by a rectangular fault geometry with a depth of faulting that ranges between 27 and 35 km. Recently, Mueller et al. (2014) applied the fault-related fold theory to study the geometry of the fault associated with Amenthes Rupes, suggesting the presence of a listric fault that reaches a depth of 33–48 km. Finally, Grott et al. (2007) also studied the geometry of the thrust faults associated with two lobate scarps located in the Thaumasia highlands, obtaining faulting depths of 27–35 and 21–28 km, values similar to those found for Amenthes Rupes through dislocation methods for different authors.

Because thrust faults associated with the lobate scarps are considered to penetrate down to the brittle-ductile transition (BDT), which is temperature-controlled for a given composition, the above summarized faulting depth results can be used to model the thermal structure of the lithosphere, and hence used to derive the surface heat flow at the time of faulting. Thus, Ruiz et al. (2008, 2011) obtained a surface heat flow between 18 and 37 mW m^{-2} when Amenthes Rupes was formed. Similarly, Mueller et al. (2014) obtained a range of 24–33 mW m^{-2} for this lobate scarp based on their somewhat deeper BDT depth.

The effective elastic thickness of the lithosphere (T_e) is another way to characterize lithospheric mechanical behavior, used in other works analyzing the circum-Hellas region (e.g., McGovern et al., 2004). T_e is related to the total strength of the lithosphere including contributions from brittle and ductile layers and from elastic cores of the lithosphere (for a review see Watts, 2001). As mantle rock strength depends on temperature, the effective elastic thickness is greatly affected by the thermal state of the lithosphere.

Several effective elastic thickness estimates for Late Noachian and Early Hesperian times are available for the circum-Hellas area. Effective elastic thicknesses for Hellas South rim and Hellas West rim were calculated using gravity/topography admittance spectra in McGovern et al. (2004); these authors obtained T_e values of 20–120 km for Hellas south rim and an upper limit of 20 km for Hellas west rim. Ruiz et al. (2008) calculated a range for T_e of 19–35 km in the Amenthes region by means of a coherence analysis of topography and gravity spectra. T_e values for Hellas west rim and Amenthes region are similar to those found for other martian regions of similar age (for a review see Ruiz, 2014), but the upper part of the range for Hellas south rim may be considered high for Late Noachian/Early Hesperian times.

As T_e is also influenced by temperature, variations of this parameter may reflect differences in the local lithospheric thermal regime, and thus, T_e values can be used to estimate the surface heat flow. As effective elastic thickness values for Late Noachian and Early Hesperian times are available in the circum-Hellas region (McGovern et al., 2004; Ruiz et al., 2008), heat flows in the period of lobate scarps formation can also be analyzed by applying this method. Following this procedure McGovern et al. (2004) obtained heat flows of 20–40 and > 30 mW m^{-2}, respectively, for the Hellas south and west rims. More refined calculations by Ruiz et al. (2011) for the same regions and T_e values yielded values of 12–40 mW m^{-2} and > 21 mW m^{-2}, respectively, for the Hellas south and west rims. Similarly, for the Amenthes Rupes region Ruiz et al. (2008) calculated a heat flow of 31–49 mW m^{-2} from their range of T_e. These results overlap with those obtained by Ruiz et al. (2008, 2011) and (in a narrow range) by Mueller et al. (2014) from the BDT depth below Amenthes Rupes. Moreover, the heat flows deduced in the circum-Hellas regions are similar to those for other regions of similar age on Mars (Ruiz et al., 2011; Ruiz, 2014).

In this work, we study the mechanical and thermal structure of the lithosphere in the circum-Hellas region of Mars through the modeling of the depth of faulting beneath several prominent lobate scarps distributed throughout this region and bordering the Hellas basin (see Fig. 1). Then, we convert the obtained faulting depths, assumed as representative of the BDT, to heat flows. Next, with the help of a crustal thickness model for this region, we estimated crustal (radioactively generated) and subcrustal (mantle) heat flow components. Finally, we analyze and discuss the implications of our results for the structure of the crust in the circum-Hellas region and for the thermal state and evolution of Mars in Noachian to Early Hesperian times.

2. Selected lobate scarps

We have analyzed eight lobate scarps distributed around Hellas (Fig. 1; Table 1). Four of these structures are previously recognized and named lobate scarps: Pityusa Rupes, Chalcoporos Rupes, Thyles Rupes and Amenthes Rupes, which were classified as compressional structures by Tanaka et al. (2014). The rest of lobate scarps have been selected according to their geological and cross-cutting relationships that indicate they are contractional structures. Most of the selected lobate scarps are located on the ejecta blanket of Hellas, concentric to Hellas basin, constituting a “ring” between 2500 and 5000 km from the center of the basin. Lobate Scarp 7, which is closest (1200 km) to the basin center is the exception, with a distinct radial orientation. Scarcity of lobate scarps in the regions northeast and southwest of Hellas basin is probably related to the emplacement of volcanic materials in Malea Planum and Hesperia Planum, which are, respectively, of Noachian and Hesperian age (Tanaka et al., 2014). Fig. 2 shows the studied lobate scarps together with the locations of the topographic profiles that have been used in the modeling process.

Pityusa Rupes (numbered as 1 in Fig. 1 and Table 1) is a SE-NW-trending structure (Fig. 2a), about 150 km long and 600 m high, with a SW vergence within a volcanic region northwest of Pityusa Patera. Topographic profiles across the structure indicate that the northern part is higher and narrower in cross section than the southern part. Because the depth of faulting is deeper when the distance between the leading and the trailing syncline is longer (Grott et al., 2007), we have chosen a topographic profile in the southern edge of the structure in order to model the depth of faulting and obtain information about the BDT depth. There is an elongated depression just at the base of the scarp front (see Figs. 2 and 3); this depression is bounded by the own Pityusa Rupes front and by a lower scarp to the SW, which could be structurally controlled since it relatively linear. This depression would not modify the topography above Pityusa Rupes, but it is so close to the lobate scarp that the floor and the wall of the basin could be confused with the wall and the foot of the lobate scarp, and therefore we have included the basin in the profile in order to avoid this mistake.

Chalcoporos Rupes (numbered as 2 in Fig. 1 and Table 1) is located north of Pityusa Rupes. This scarp is about 260 km long, 700 m high and has a SW-NE trend (Fig. 2b). It is difficult to find topographic profiles across Chalcoporos Rupes suitable to use in the modeling process. The northern and the central areas of Chalcoporos Rupes are complex regions affected by impact craters and other structures, which prevent us from obtaining good models to