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The revised tectonic history of Tharsis

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ABSTRACT

Constraining the timing of the emplacement of the volcano-tectonic province of Tharsis is critical to understanding the evolution of mantle, surface environment and climate of Mars. The growth of Tharsis had exerted stresses on the lithosphere, which were responsible for tectonic deformation, previously mapped as radial or concentric faults. Insights into the emplacement history of Tharsis may be gained from an analysis of the characteristics and ages of these tectonic features. The number, total length, linear density of extensional or compressional faults in the Tharsis region and deformation rates are reported for each of the following 6 stages: Early and Middle Noachian (stage 1); Late Noachian (stage 2); Early Hesperian (stage 3); Late Hesperian (stage 4), Early Amazonian (stage 5) and Middle Amazonian to Late Amazonian (stage 6). 8571 Tharsis-related tectonic features (radial or concentric to the center of Tharsis) were assigned to one of these periods of time based on their relationship with stratigraphic units defined in the most recent geological map. Intense faulting at Tempe Terra, Claritas and Coracis Fossae and Thaumasia Planum confirms that tectonic deformation started during the Noachian. However, we report a peak in both compressive and extensive rates of deformation during the Early Hesperian whereas the quantitative indicators for compressional and extensional tectonics vary within less than one order of magnitude from the Late Noachian to the Late Hesperian. These observations indicate a protracted growth of Tharsis during the first quarter of Mars evolution and declining from 3 Gyrs ago.

1. Introduction

The Tharsis dome is the largest volcano-tectonic center on Mars and in the solar system. It is one of the most impressive crustal expressions of the internal dynamics of Mars. Its growth was likely associated with the release of large volumes of volcanic gases having dramatic consequences on climatic evolution and surface environment during a period of time when Mars was habitable (Ehlmann et al., 2016). The growth of Tharsis and the inferred mantle plume exerted stresses on the martian lithosphere. Crustal stresses have resulted in the formation of tectonic features, mapped as compressional or extensional faults, radial or concentric to the center of the dome. The chronology of crustal deformation was elaborated from stratigraphic and cross-cutting relationships and from the number of tectonic features affecting the geological units of various ages in the Tharsis region (e.g., Scott and Tanaka, 1986; Anderson et al., 2001; Dohm et al., 2001; Carr and Head, 2010). From these observations, the major growth episodes of Tharsis are considered to take place during the Middle and Late Noachian Epochs (Phillips et al. 2001; Anderson et al., 2001; Viviano-Beck et al., 2017). The conclusion that Tharsis was largely in place at the end of the Noachian is supported by the high number of tectonic features identified in Noachian terrains in the western equatorial region (Scott and Tanaka, 1986), Alba Patera (Tanaka, 1990), Olympus Mons (Morris and Tanaka, 1994), Valles Marineris (Witbeck et al., 1991), the Syria Planum (Tanaka and Davis, 1988), Tempe Terra and Ulysses Patera (Scott and Dohm, 1990), Alba Patera (Tanaka, 1990) and Thaumasia regions (Dohm and Tanaka, 1999) of Mars.

However, the ages of these different units have been recently revised from more recent and high-resolution imagery (Tanaka et al., 2014). For instance, Ceraunius Fossae, Tempe Terra or Syria Planum, initially assigned to the Noachian era, are now mapped as Early and Late Hesperian units (Tanaka et al., 2014). Moreover, the number of faults may be a meaningless proxy for deformation rates, since it treats a 1 km long fault as being equal to a 1000 km long fault (both of which exist on the surface of Mars in abundance). The number of faults is also sensitive to the resolution of

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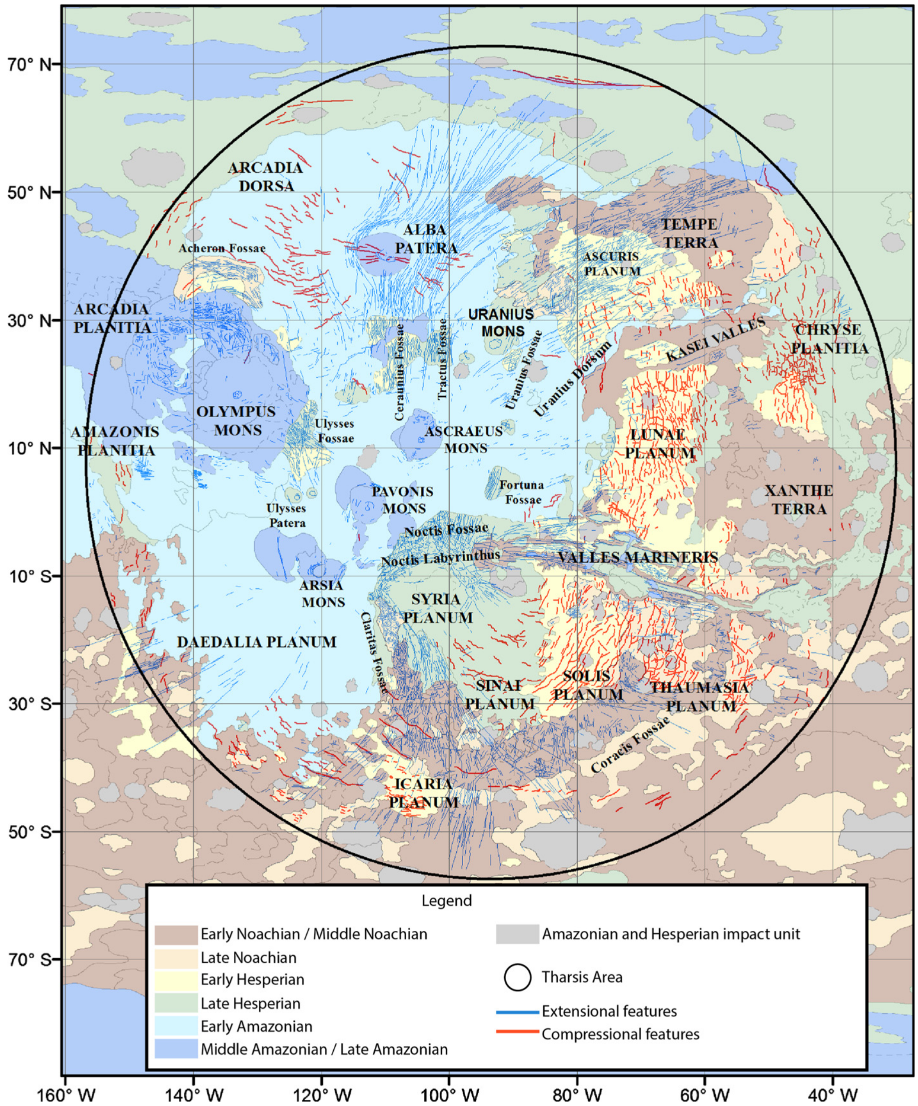

Fig. 1. Simplified geologic map from Tanaka et al. (2014). The different units are grouped into five stages: stage 1, Early and Middle Noachian; stage 2, Late Noachian; stage 3, Early Hesperian; stage 4, Late Hesperian; stage 5, Early Amazonian and stage 6, Middle Amazonian to Late Amazonian. The black ellipse shows the studied Tharsis area. Red lines (compressional) and blue lines (extensional) represent tectonic features from Knapmeyer et al. (2008). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

the data, since many faults are segmented into numerous distinct but closely approaching segments that are likely interconnected in the subsurface.

The purpose of this paper is therefore to revisit the tectonic evolution of Tharsis using quantitative indicators, including fault length and density, that can be related more directly to the deformation rate as a function of time, which is itself related to changes in load intensity. These quantitative indicators are also estimated from the new geological map of this region (Tanaka et al., 2014), which differs significantly from the map used in earlier estimations.

Methodology and data sets

Many authors (Wise et al., 1979; Banerdt et al., 1982; Anderson et al., 2001) provide evidence of the radial nature of the stress field in the volcano-tectonic province of Tharsis. Anderson et al. (2001) suggested that the number of faults groups into 5 different stages was indicative of the intensity of volcano-tectonic activity and its evolution with time. Here we build on this approach and suggest that the growth of Tharsis may be deciphered from the characteristics and ages of tectonic features.

Tectonic features were previously mapped by Anderson et al. (2001) from Viking images, which are heterogeneous in terms of resolution and conditions of illuminations. For this study, we use a global inventory of Mars surface faults based on shaded relief maps from MOLA data (Knapmeyer et al., 2008). This catalog contains a total numbers of 14 835 faults, with 5146 thrust and 9689 normal faults, with a cumulative length of about 941 000 km. The Tharsis region is defined by an ellipse centered at 9°30′29″N and 98°15′26″W and encompasses 8571 tectonic elements of the catalog, including 1376 thrust faults and 7195 normal faults (Fig. 1). Grabens and rifts are bounded by normal faults that result from extensional stresses, and wrinkle ridges are formed by thrust faults that result from compressional stresses (Banerdt et al., 1992; Anderson et al., 2001). The fault catalog is a georeferenced layer loaded in the ArcGIS software.

The age of each fault is determined from stratigraphic and crosscutting relationships among the different geological units mapped by Tanaka et al. (2014) (Fig. 1). A fault appearing in several units of different ages is assigned to the age of the youngest unit affected by the fault. A fault affecting a single unit but having a similar orientation and morphology to faults occurring both