

# Mars thermal history based on its tectonic and structural systems

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Received: July 10, 2001; accepted: November 5, 2001.

## RESUMEN

Se sugiere una interpretación de la historia térmica de Marte, basada en las deformaciones corticales que aparecen en los mapas tectónicos. Las deformaciones locales, asociadas a un incremento del gradiente térmico con el tiempo, indican esfuerzos de tensión en centros eruptivos como Alba Patera, Ascraeus, Pavonis, Arsia y Elysium Mons. Las deformaciones regionales, asociadas a la dicotomía cortical y al bulbo Tharsis, sugieren erosión subcortical (dicotomía) y una componente térmica de soporte litosférico (bulbo). Las deformaciones globales, a manera de crestas rugosas, podrían indicar una contracción planetaria en etapas tempranas de la evolución geológica marciana.

**PALABRAS CLAVE:** Marte, dicotomía cortical, crestas rugosas, evolución térmica.

## ABSTRACT

We suggest an interpretation of the thermal history of Mars based on crustal deformations. Local deformations are associated with an increase of the thermal gradient with time and indicate tensional stresses in eruptive centers such as Alba Patera, Ascraeus, Pavonis, Arsia and Elysium Mons. Regional deformations are associated to the crustal dichotomy and to the Tharsis bulge; they suggest subcrustal erosion (dichotomy) and a thermal component of lithospheric support (bulge). Global deformation of wrinkle ridges may be due to a planetary contraction in the early stages of Martian geologic evolution.

**KEY WORDS:** Mars, crustal dichotomy, wrinkle ridges, thermal evolution.

## 1. INTRODUCTION

Geologic and geophysical studies of Mars raise questions such as: how thick is the crust and the lithosphere under the Tharsis uplift? How does it relate to the rest of the planet? The uplift may have resulted from intense volcanic activity, connected with the internal dynamics and with the dissipation of internal heat, but the evidence of massive differentiation in the upper mantle, or of uplifting induced by convection, is still fragmentary or absent.

We use the global tectonic-structural map of Mars developed by several authors (Scott and Tanaka, 1986; Greeley and Guest, 1987; Scott and Dohm, 1990), to infer which thermal processes operated in it. Surface deformations are classified as local, regional or global on the basis of the surface extension of specific features. Considering the very close relationship among stresses, faulting and thermal evolution, we suggest a proposal for the thermo-tectonic history of Mars.

In this proposal, We suggest that the initial stages of the Mars thermal history were dominated by extension stresses around the Tharsis bulge, as suggested by some authors (Wise *et al.*, 1979; Banerdt *et al.*, 1992; Sleep and

Phillips, 1985), and also by compressive stresses produced by large-scale internal cooling.

## 2. TECTONIC AND STRUCTURAL FEATURES OF MARS

Most of the tectonic and structural activity on Mars is closely related to volcanic activity (Scott and Dohm, 1990). This may include the crustal dichotomy.

Figure 1 shows the distribution of tectonic features of Mars due to extensional stresses. We can identify three groups of structural features as follows: **(a)** Large grabens and normal faults forming parallel and radial dense arrangements associated to the Tharsis bulge. The rifts system of Valles Marineris, and the tectonic troughs of Thaumasia, Memnonia, Icaria and Sirenum, stand out. These structures were produced by uplifting and crustal extension associated with the Tharsis bulge (Watters and Maxwell, 1986). **(b)** The tectonic systems associated with the volcanoes of the Tharsis bulge (mainly Arsia Mons, Syria Planum, Alba Patera, Acheron Fossae and Olympus Mons areas), the Elysium Mons volcanic area, and the areas of large impact basins (Isidis, Argyre and Hellas Planitiae). **(c)** A series of secondary ridges associated with the crustal dichotomy (Wise *et al.*, 1979). Where

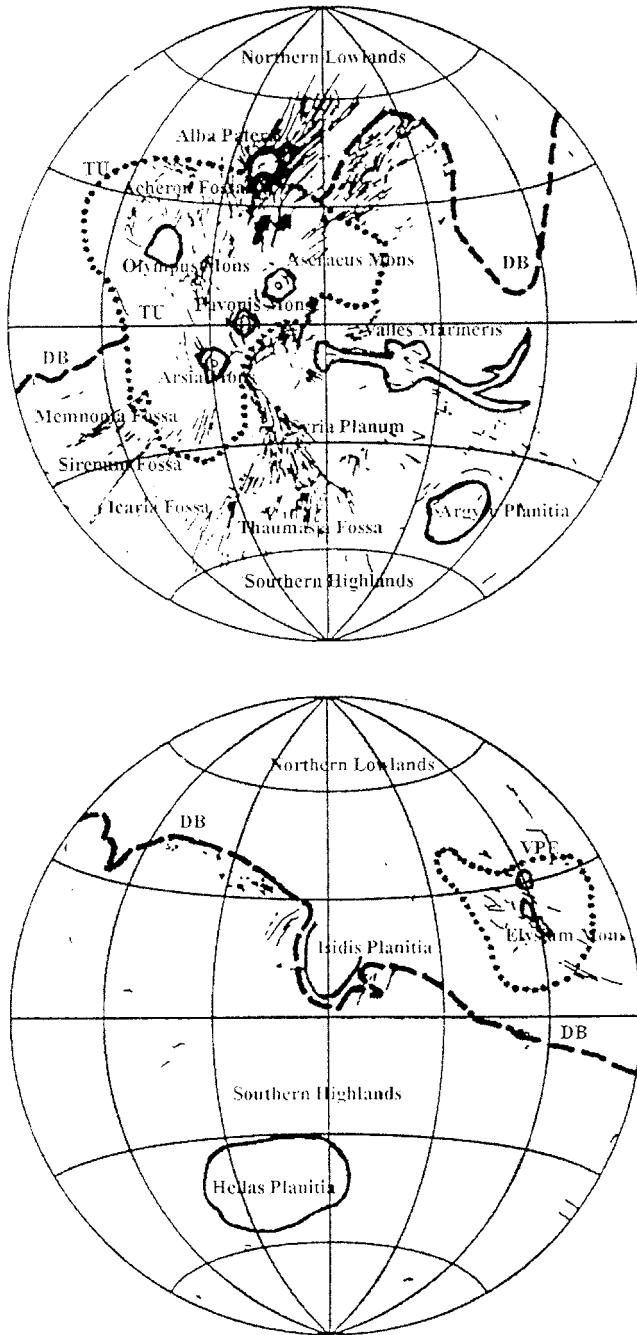


Fig.1. Grabens and fault scarps of extensional origin. The grid interval is 30° in a Lambert equal area projection. VPE = Volcanic province of Elysium and TU = Tharsis uplift, both in dotted lines. DB = Crustal dichotomy boundary, in dashed line. Volcanoes (Mons) and impact craters (planitia) in continuous line. Modified from Scott and Tanaka (1986), Greeley and Guest (1987) and Scott and Dohm (1990).

the Tharsis bulge borders the crustal dichotomy, it is difficult to determine which structures were due to the processes that originated the dichotomy and which were produced by the Tharsis uplift.

Figure 2 shows deformations due to compressional stresses, such as the wrinkle ridges due to compression (Chicarro *et al.*, 1985; Zuber and Aist, 1990). These subsurface structures extend over most of the planet. The most significant are the concentric structures around the Tharsis bulge, which appear to be of tectonic origin (Watters and Maxwell, 1986).

The Martian tectonic and structural systems are mainly associated with volcanic centers, and in a secondary way with impact basins and the crustal dichotomy boundary.

### 3. THERMAL EVOLUTION OF MARS FROM SURFACE TECTONIC FEATURES

The tectonic features and deformation processes on Mars have been discussed by Banerdt *et al.*, (1992), Melosh (1980), Schubert *et al.*, (1990) and others. We use the following structures to reconstruct the thermal history: Tharsis and Elysium volcanic bulges, Hellas and Argus impact basins, the crustal dichotomy, and the wrinkle ridges. Volcanism, cratering and planetary differentiation may focus stress and heat over particular areas of the lithosphere, thus producing tectonic patterns at different scales. Interpreted appropriately, these patterns may indicate processes of cooling and contraction, subsidence, uplifting and isostatic adjustments. Surface tectonic features from Figures 1 and 2 were grouped as follows:

#### 3.1 Deformations due to local processes

In this group we have grabens and faults associated to isolated and relatively small features, such as the Hellas and Argus impact basins and the volcanoes of the Tharsis and Elysium bulges. Comer *et al.*, (1985) used the position and width of fractures arranged concentrically around Isidis basin and Tharsis and Elysium Mons to constrain the position and width of radial extensional stresses. These constraints were inverted to produce elastic lithosphere values. The best estimates were made for Alba Patera and Ascraeus, Pavonis, Arsia and Elysium Mons. A crustal thickness of 20 to 50 kilometers was found.

These features suggest different ages and different thermal lithospheric gradients (Solomon and Head, 1990). There is no a simple decrease of thermal gradient with time. Variations in thermal structure under these features are superimposed on the progressive cooling of the lithosphere. The younger volcanic features show crustal thinning with respect to the older features (Zuber *et al.*, 2000), suggesting that the thermal evolution of Mars has not ended yet, and that recent surface manifestations are restricted to very local areas. In these areas, faults and fractures are distributed concentrically and radially with respect to the main eruptive centers.

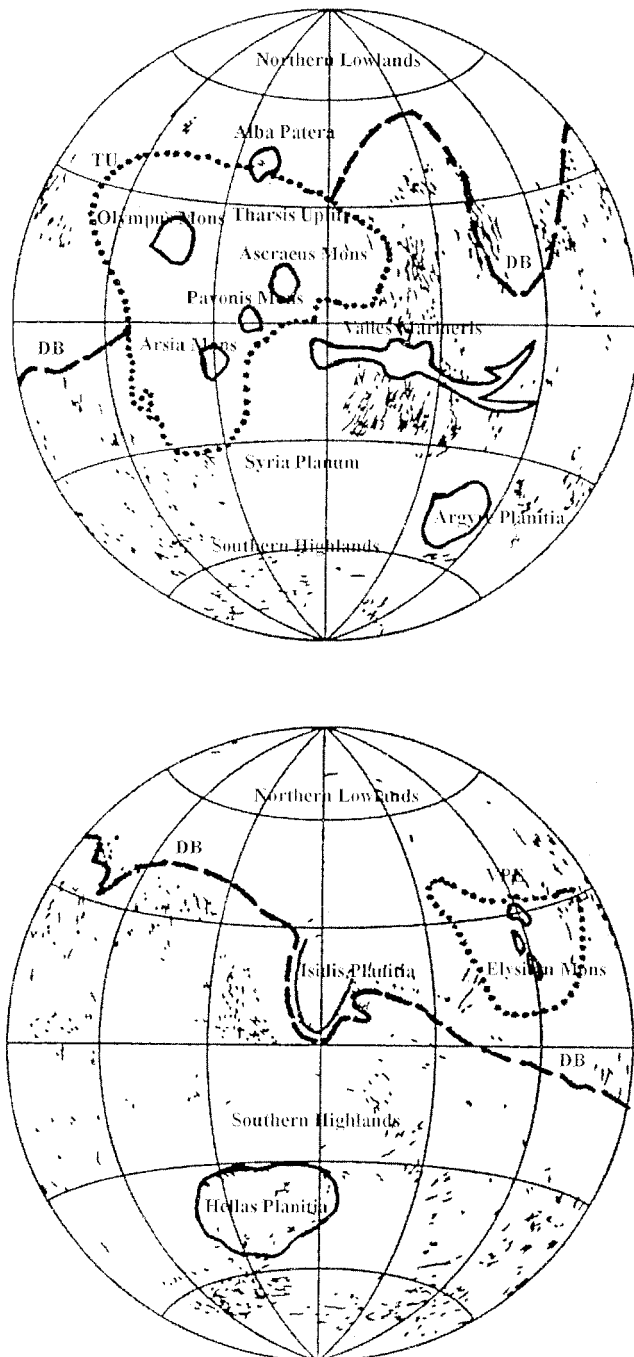


Fig. 2. Wrinkle ridges of compressional origin. As in Figure 1.

### 3.2 Deformations due to regional processes

In this group we have the fault scarps that define the crustal dichotomy, and the radial tectonic troughs (including Valles Marineris) associated with the Tharsis uplift. In many areas the dichotomy boundary has regional scarps, with vertical dimensions larger than 4 km over distances of 300 to 1300 km (Smith *et al.*, 1999). Recent topographical and gravimetric data from the MGS mission suggest that the northern

Lowlands contain structures interpreted as large buried channels, suggesting transport of water from the southern Highlands before the end of the formation of the dichotomy (Zuber *et al.*, 2000). This observation supports the theory that the dichotomy was originated by internal processes instead of by large impacts, which would have destroyed the channels.

The Tharsis volcanic province is of variable crustal thickness. The southern part of the bulge is supported by crustal roots while the northern part, including the main volcanic centers, is a topographical dome without a root (Zuber *et al.*, 2000). Thus volcanism may be an important cause of elevation in the province. This is in agreement with the deficit of mass under Tharsis, as evidenced by gravitational anomalies reported by the MOLA-MGS experiment (Smith *et al.*, 1999).

We conclude that the faults and fractures associated with the dichotomy and the uplift may suggest thermal processes of subcrustal erosion due to convective flows in the upper mantle (in the case of the dichotomy) and a component of thermal support of the topography due to flotation of magmatic chambers (in the case of the bulge). Formation of the core (Wise *et al.*, 1979) may be responsible for concentrating the internal heat and the stresses of the planet almost entirely in the Tharsis area.

### 3.3 Deformations due to global processes

This category includes the globally distributed wrinkle ridges of compressive origin (Chicarro *et al.*, 1985). Four possible global processes have been proposed for Mars:

- Planetary despinning (Melosh, 1980) due to tidal dissipation, with decrease of polar flattening. The resulting stresses could form a global system of fractures (Strom, 1964). However, we believe that this process was not important in Mars, because the moons Phobos and Deimos are small, and the tidal forces on Mars are moderate.
- Polar wandering involves reorientation of the lithosphere with respect to its spin axis. This may produce a characteristic fracturing pattern, due to the repositioning of the equatorial bulge. Any excess of mass near the surface of the planet (e. g., the Tharsis bulge) will tend to reorient it in such a way that the mass moves towards the equator. Grimm and Solomon (1986) calculated the patterns of stress from polar drift caused by the load of the Tharsis bulge. However, they found little support for their predictions from the Mars tectonic record.
- The moment of inertia constrains the crustal fracturing processes, and has strong implications for the composition and internal structure of Mars. The mass distribu-

tion in the crust affects the moment of inertia, which is important because the inhomogeneities in temperature gradients and lithospheric thickness may influence the tectonic processes. At present there is no accepted value for the moment of inertia of Mars. More information on the Mars internal structure is needed.

- (d) The warming or cooling of a planet implies planetary expansion or contraction. In general, heating causes extensive faulting, while cooling tends to favor the compressive deformation. In either case there is a change of planetary volume and isotropic stresses are induced in the external part of the lithosphere, due to the change of surface area (Banerdt *et al.*, 1992). A planetary contraction may have occurred in Mars, judging by the global distribution of wrinkle ridges (Chicarro *et al.*, 1985; Zuber and Aist, 1990).

#### **4. THERMO-TECTONIC EVOLUTION MODEL BASED ON MARINER AND VIKING DATA**

From Mariner 9 and Viking images and assumptions of initial thermal conditions and sources of heat, Toksöz and Hsui (1978) proposed a scenario of thermo-tectonic evolution for Mars.

- 4500 to 4000 million years ago: accretion of the planet, formation of its core and crustal differentiation.
- 4000 to 2000 million years ago: heating, expansion and mantle differentiation.
- 2000 to 1000 million years ago: lithospheric thickening and deepening of the partial melt zone.
- Over the last 1000 million years: secular cooling.

This model assumes that the crust was formed 4600 to 4400 million years ago, before the end of intense meteoritic bombardment and followed by intense volcanic and tectonic activity. The model is consistent with a thermal history characterized by tensional tectonism. The large number of extensive features, particularly in the Tharsis area, have been used to support such a thermal history. However, recent discoveries of the MGS mission may modify this model.

#### **5. A THERMO-TECTONIC MODEL BASED ON MGS DATA**

The size of the core and the differentiation of the mantle are poorly known (Banerdt *et al.*, 1992). Yet some models of the cooling history of Mars have been proposed (Stevenson *et al.*, 1983; Schubert *et al.*, 1990). These models suggest

that during the first ~500 million years of geologic evolution, when the planet was hot and had a vigorous convecting mantle, there was a strong decrease in heat flow. Later came a phase of slow and gradual cooling over most of the geologic history of the planet.

Thus Mars may have experienced a long period of lithospheric extension associated to the Tharsis uplift, as suggested by Hartmann (1973), Carr (1974) and Toksöz and Hsui (1978), but the wrinkle ridges of compressive origin (Chicarro *et al.*, 1985; Zuber and Aist, 1990) might indicate an early phase of rapid thermal contraction, as suggested by these models of Mars cooling. The formation of wrinkle ridges has been assigned to Middle Noachian, 4400 to 3800 million years ago (Watters and Maxwell, 1986). Global extension doesn't seem necessary for the formation of the radial grabens around the Tharsis bulge (Wise *et al.*, 1979; Banerdt *et al.*, 1992; Sleep and Phillips, 1985). We suggest that the initial stages of Mars thermal history may also have been dominated by cooling.

The evolution of the Tharsis uplift was a complex event requiring a combination of large-scale lithospheric support mechanisms in order to explain the general fracturing patterns. Possibly the planetary crustal dichotomy may be related to early Mars differentiation. Wise *et al.*, (1979) suggested that a simple convective cell may have existed in the Mars interior during planetary differentiation, resulting in subcrustal erosion and sinking to produce the northern Lowlands. The time correlation (Lower to Middle Noachian, 4500 to 3800 million years ago) between the crustal dichotomy formation and the concentration of stresses and internal heat in the Tharsis bulge area suggest that the convective cell that originated the Lowlands also produced the uplift. Schubert *et al.*, (1990) suggests that a simple convective system may have occurred with the formation of the core. Zuber *et al.*, (2000) report that the northern Lowlands contain large buried channels that indicate transport of water from the southern Highlands before the end of the crustal dichotomy formation. Both reports agree with our suggestion of an internal origin for the Mars crustal dichotomy.

In conclusion, we suggest that the Tharsis bulge may have evolved after the end of the intense meteoritic bombardment in the Early Noachian (4600 to 4400 million years ago). It evolved from an isostatic initial state to a state with large-scale lithospheric support, accompanied by dynamic (thermal) support. This would help explain the gravity anomalies in the area of the bulge (Smith *et al.*, 1999). Later, in Middle Noachian (4400 to 3800 million years ago), there was a global compressive stress produced by large-scale internal cooling that affected the extensional structures associated to the bulge. Local tectonic features have had a moderate influence on the global thermal evolution over Martian geologic time.

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