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Tectonic-structural systems of Mars: Is it possible to use them to reconstruct its thermal evolution?

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RESUMEN

Este trabajo intenta establecer la posible relación entre los esfuerzos corticales evidenciados por fallamientos mapeados en superficie y la evolución térmica del planeta Marte. Para lograrlo, se hizo una clasificación inicial de los sistemas tectónico-estructurales que aparecen en superficie, los cuales fueron detectados por diversas misiones desde órbita. Esta clasificación se basó en la asociación de los rasgos tectónico-estructurales con rasgos geológicos específicos, lo cual permitió dividirlos en cuatro grandes grupos: I) Fosas y fallas normales distribuidas paralela y radialmente al bulbo volcánico Tharsis. II) Sistemas tectónicos asociados a los volcanes que coronan al bulbo Tharsis, a los montes volcánicos de Elysium y a los alrededores de las cuencas de impacto Isidis, Argyre y Hellas. III) Crestas arrugadas que se extienden por casi todo el planeta. IV) Una serie de crestas secundarias asociadas a la dicotomía cortical. Posteriormente se plantea una reclasificación basada en la extensión superficial y en los posibles procesos geológicos que pudieron haber originado las diferentes estructuras tectónicas. Esta última clasificación permite asociar esfuerzos a procesos geológicos específicos y contempla tres grandes grupos de estructuras: deformaciones locales, regionales y globales. Finalmente se sugieren las posibles causas de los esfuerzos, las cuales incluyen: esfuerzos globales debidos a expansión o contracción térmica, esfuerzos regionales o locales debidos a anomalías térmicas en el manto y a cargas litosféricas, esfuerzos producidos por impactos, entre otros. Esto permitió sugerir una posible evolución térmica que plantea un calentamiento inicial por acreción, seguido de un enfriamiento brusco en un tiempo muy corto y un enfriamiento secular posterior, el cual continúa en el presente.

PALABRAS CLAVE: Marte, esfuerzos, deformaciones, crestas arrugadas, evolución térmica.

ABSTRACT

This work tries to establish the possible relationship among cortical stresses evidenced by faults mapped in the surface and thermal evolution on Mars. To achieve it, we made an initial classification of the tectonic-structural systems that appear in surface, which were detected by diverse missions from orbit. This classification was based on the association of the tectonic-structural features with specific geologic features, which allows to divide them in four groups: I) Grabens and normal faults parallel and radially associated to the Tharsis volcanic bulge. II) Tectonic systems associated to the volcanoes that crown the Tharsis bulge, to the volcanic mons of Elysium and the surroundings of the Isidis, Argyre and Hellas impact basins. III) Wrinkle ridges that extend for almost the entire planet. IV) A series of secondary ridges associated to the crustal dichotomy. Later we suggest a classification based on the surface extension and on the possible geologic processes that could have originated the different tectonic structures. This last classification allows to associate stresses to specific processes and it contemplates three groups of deformations: local, regional and global deformations. Finally the possible causes of the stresses are suggested, which include: global stresses due to expansion or thermal contraction, regional or local stresses due to thermal anomalies in the mantle and to lithospheric loads, stresses due to impacts, among others. This allowed to suggest a possible thermal evolution that outlines an initial heating for accretion, followed by an abrupt cooling in a very short period of time and a later secular cooling, which remains in the present time.

KEY WORDS: Mars, stresses, deformations, wrinkle ridges, thermal evolution.

1. INTRODUCTION

Mars has experienced a thermal history. The effects of this evolution are manifested as stresses that have deformed its lithosphere. Causes of the stresses could include: global stresses produced by expansion or contraction due to planetary differentiation (Banerdt *et al*., 1992), regional and local stresses due to thermal anomalies of the mantle and lithospheric loads (Schubert *et al*., 1990; Banerdt *et al*., 1992), and exogenic stresses produced by impacts (Schultz *et al*., 1982). The analysis of these causes of stress could indicate that a very narrow relationship would exists among stresses, faulting and thermal evolution. In order to find which were the causes of stresses in the Mars lithosphere, we treat objectively the surface prints of the events that could have caused stresses in the Mars surface. To do this, the global tectonic map developed by diverse authors (Scott and Tanaka, 1986; Greeley and Guest, 1987; Scott and Dhom, 1990) was used to classify the tectonic structures.

2. MARS TECTONIC-STRUCTURAL FEATURES

Mars tectonic-structural systems have been determined from features recognized in radar images from several missions. All these structures have been assigned to a stratigraphic age (Scott and Dohm, 1990), which has allowed to determine that the Mars tectonic activity is closely related, both in space and time, mainly to the volcanic activity. Figure 1 shows the distribution of Mars tectonic features. We classify this features, based on the association of the tectonic-structural features with specific geologic features, which allows to divide them in four main kinds of structural groups: I).- Large grabens and normal faults distributed in parallel and radial dense arrangements associated to the Tharsis volcanic bulge. The Valles Marineris rifts system and the Thaumasia, Memnonia, Icaria and Sirenum tectonic troughs stand out. II).- Tectonic systems associated to the volcanoes of the Tharsis bulge (mainly in Arsia Mons, Syria Planum, Alba Patera, Acheron Fossae and Olympus Mons areas), to the Elysium Mons' volcanic area and to the surroundings of the Isidis, Argyre and Hellas impact basins. III).- Wrinkle ridges extended for almost the entire planet. In the Valles Marineris area, they seem to be concentric to the Tharsis volcanic bulge. IV).- A series of short secondary ridges associated in a parallel way to the crustal dichotomy boundary. In the contact of the Tharsis bulge with the crustal dichotomy, it is very difficult to determine which structures are due to the processes that originated the dichotomy and which are product of the Tharsis uplift. From previous classification, it is possible to see that the tectonic-structural systems are mainly associated to volcanic centers, and in a secondary way to impact basins and to the crustal dichotomy boundary.

3. SURFACE STRESSES AND THERMAL EVOLUTION

Structures associated to the volcanoes of the Tharsis bulge, to the volcanic province of Elysium, to the Hellas and Argyre impact basins, to the wrinkle ridges distributed globally and to the crustal dichotomy boundary, can be very useful to study the Mars thermal history. The classification of these tectonic features, based on the processes of deformation that have been proposed (Banerdt *et al.*, 1992; Melosh, 1980; Schubert *et al.*, 1990), could be useful to infer a Mars thermo-tectonic history. When carrying out this classification, we considered that the processes of volcanism, craterism and planetary differentiation (Solomon and Head, 1990), can have the capacity to focus the stress and the heat in particular areas of the lithosphere, producing diverse-scales tectonic patterns. If these patterns are interpreted appropriately, they could be indicating processes of cooling and contraction, subsidence, uplifting and isostatic adjustments. We consider that we can identify the thermal processes through the inspection of the surface prints, so we reclassify the surface tectonic features of Figure 1 in three groups, based on their surface extension and on the possible geologic processes that could have originated the different tectonic structures. This allowed to associate tectonic structures to specific geologic processes. Thus, deformations represented in Figure 1 were grouped as follows.

3.1 Deformations due to local processes.- Grabens and faults associated to isolated features as the large impact basins and the volcanoes of Tharsis and Elysium bulges form this group. In these areas, the strength goes up, generating tensional stresses that produce faults and fractures distributed in a radial way regarding the Arsia, Pavonis, Ascraeus and Elysium eruptive centers.

3.2 Deformations due to regional processes.- Fault scarps that define the crustal dichotomy boundary and the large radial tectonic troughs (included Valles Marineris) associated to the Tharsis uplift form this group. In this features the force points down, giving place to tensional stresses associated to the process that originated the crustal dichotomy and the Memnonia, Icaria, Sirenum and Thaumasia tectonic troughs.

3.3 Deformations due to global processes.- Inside this group are the wrinkle ridges of compressive origin (Chicarro *et al.*, 1985). These are subsurface structures extended for almost the entire planet. In the Valles Marineris area they are concentric to the Tharsis volcanic bulge. It has been suggested a planetary phenomenon to explain them (Chicarro *et al.*, 1985).

4. DISCUSSION

From previous classification of deformations that appear in the tectonic maps, we consider it is possible to discern the main thermal processes that have operated in Mars. These processes have operated at different scales and their surface manifestations indicate thermal phenomena of diverse intensity and magnitude.

Local deformations would indicate tensional stresses in eruptive centers as Alba Patera, Ascraeus, Pavonis, Arsia and Elysium Mons. These structures were produced by the uplifting and crustal extension that gave origin to such volcanoes (Watters and Maxwell, 1986). These features show different ages and different thermal lithospheric gradients (Solomon and Head, 1990), which have allowed to evidence a lack of decreasing of the thermal gradient with the time in

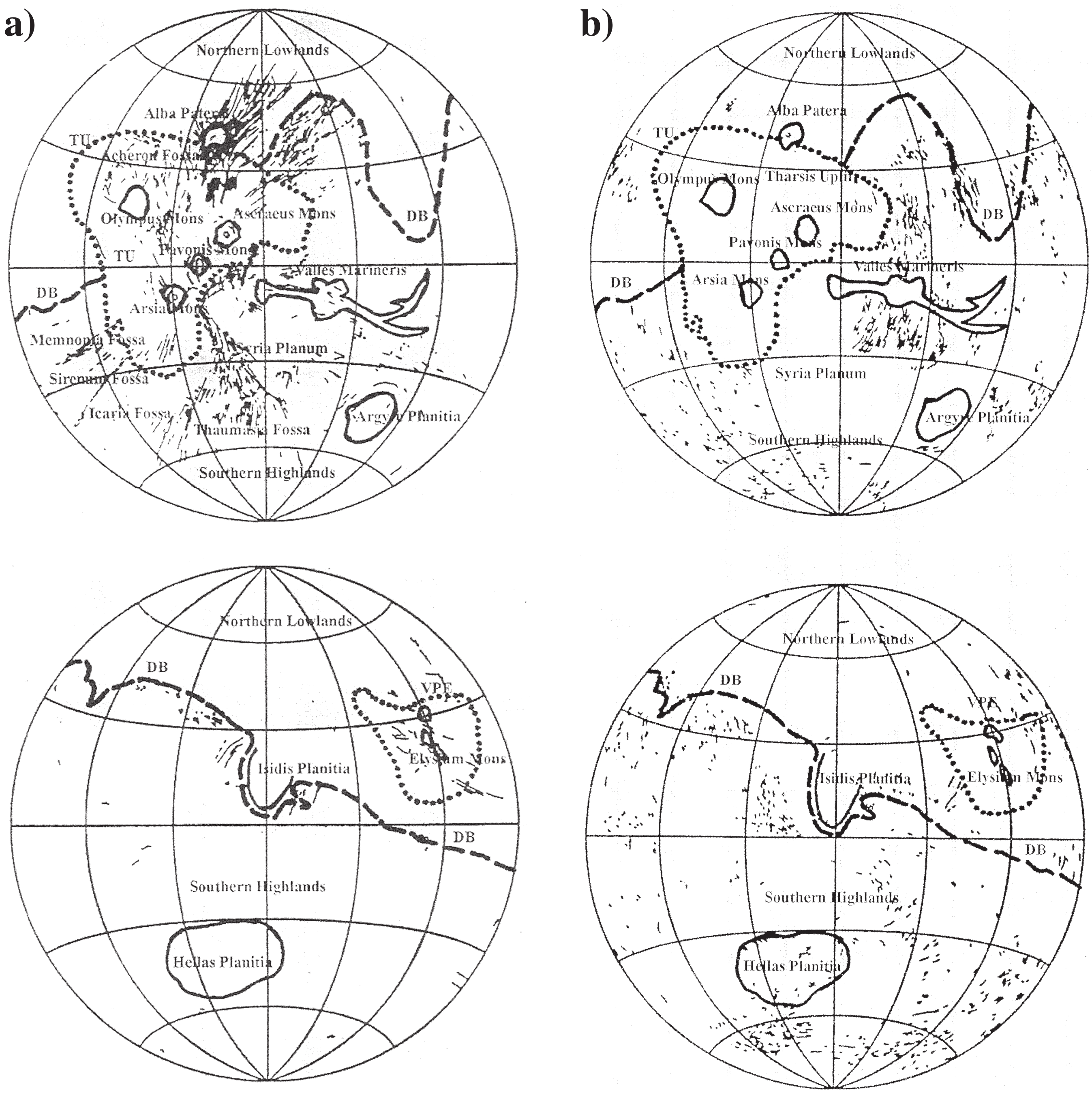

Fig. 1. Maps that show the distribution of the tectonic-structural features on the Martian surface. The grid interval is 30° in a Lambert equal area projection. a) Grabens and fault scarps of extensive origin in western (longitudes 0° to 180°) and eastern (longitudes 180° to 360°) hemispheres. b) Wrinkle ridges of compressive origin in western and eastern hemispheres. VPE = Volcanic province of Elysium, TU = Tharsis volcanic uplift, DB = Crustal dichotomy boundary. Modified from: Scott and Tanaka (1986), Greeley and Guest (1987) and Scott and Dohm (1990).

them. This would imply that the variations in thermal structure under these volcanoes are superimposed in the progressive cooling of the lithosphere. This agrees with the MOLA experiment data, that have evidenced a crustal thinning in the youngest volcanoes regarding the oldest (Zuber *et al.*, 2000). This could be reflecting that Mars thermal evolution has not still ended and that their youngest surface manifestations are restricted to very located areas.

Regional deformations are associated to the crustal dichotomy boundary and to the Tharsis volcanic bulge. In the contact of the Tharsis bulge with the crustal dichotomy boundary, is not easy to differentiate the structures associated to the dichotomy of those associated to the Tharsis uplift. Most recent topographical and gravimetric data indicate that northern Lowlands contain structures that have been interpreted as large buried channels (Zuber *et al*., 2000). This suggests transport of water from the southern Highlands, before the end of crustal dichotomy formation. This agrees with an internal process for the crustal dichotomy origin, instead of mega-impacts as suggest Schultz *et al*. (1982), because impacts have would destroyed the channels. On the other hand, the Tharsis volcanic uplift is characterized by a variability of crustal thickness: the south part of the bulge is supported by crustal roots, while the north part is a topographical dome without root (Zuber *et al*., 2000). This observation supports the notion of volcanism as a contributor to the elevation of the bulge, which would explain the deficit of mass under Tharsis uplift, evidenced by the gravitational anomalies reported by the MOLA-MGS experiment (Smith *et al*., 1999). Thus, faults and fractures associated to both, the dichotomy and the uplift, would be indicating thermal processes of subcrustal erosion (case of the dichotomy) due to convective flows in the upper mantle (Wise *et al*., 1979) and a component of thermal support of the topography (case of the bulge) due to flotation of magmatic chambers.

Global deformations are distributed as wrinkle ridges on almost the entire planet. These are subsurface structures and those adjacent to Valles Marineris canyon are concentric to the Tharsis volcanic bulge, which may show their tectonic origin (Watters and Maxwell, 1986). Others have an hazardous distribution. According to some authors (Chicarro *et al*., 1985; Zuber and Aist, 1990) and judging by their almost global distribution, wrinkle ridges are due to compression, although in the 180°-360° hemisphere are covered by more recent lava flows (Chicarro *et al*., 1985). The planetary expansion/contraction implies that a planet warms or cools. In general, the heating causes tensional faulting, while the cooling tends to favor the compressive deformation (folding in this case). When there is a change of planetary volume, in the external part of the lithosphere isotropic stresses are induced, due to the net change of surface area (Banerdt *et al*., 1992). Wrinkle ridges would be indicating a planetary contraction in early stages of the Mars geologic evolution.

5. CONCLUSIONS

Previous observations and classification suggest that Mars didn't only experience a long period of lithospheric extension associated to the Tharsis uplift like suggest Hartmann (1973) and Carr (1974), but rather the wrinkle ridges of compressive origin (Chicarro *et al*., 1985; Zuber and Aist, 1990) could be indicating an initial phase of quick thermal contraction. The formation of the wrinkle ridges has been assigned to the Middle Noachian (Watters and Maxwell, 1986). This suggests that global extension is not necessary to explain the formation of radial grabens around the Tharsis bulge as suggested by Wise *et al*. (1979), Banerdt *et al*. (1992) and Sleep and Phillips (1985), but there exists the possibility that the initial states of the Mars thermal evolution were dominated by cooling.

In this sense, the planetary crustal dichotomy could be related to an early differentiation. Wise *et al*. (1979) suggested that a simple convective cell operated in the Mars interior during the planetary differentiation resulting in both, the subcrustal erosion and the sinking that conformed the northern Lowlands. Considering the early formation of the dichotomy and the Tharsis uplift, as well as the concentration of stresses and internal heat in this last one, it is not difficult to suppose that the convective cell mentioned was finally concentrated, giving origin to the uplifting. This supposition is supported by the fact that the northern Lowlands contain structures in form of large buried channels that indicate transport of water from the southern Highlands, before the end of the crustal dichotomy formation (Zuber *et al*., 2000). These observations support the thesis that the crustal dichotomy was originated by internal processes, that could have concentrated the heat and the stress in the Tharsis area giving origin to the uplifting, since this bulb forms the dichotomy boundary in practically the entire western hemisphere.

Thus, we can say there is a strong correlation between thermal and tectonic histories for Mars. This correlation shows that the Tharsis bulge evolved after the end of the intense meteoritic bombardment, of an isostatic initial state, to one with large-scale lithospheric support, accompanied by dynamic thermal support. This would explain the large gravitational anomaly in the area of the bulge (Smith *et al*., 1999). Later, on the structures associated to the bulge, there was a compressive global strength produced by a large-scale internal cooling, which is evidenced by the wrinkle ridges. The local tectonic features have had a modest influence in the Mars global thermal evolution.

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