TECTONICS OF THARSIS DORSA ON MARS

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Abstract. The tectonics of the Tharsis and adjoining areas is considered to be associated with the convection in the Martian mantle. Convection and mantle plume have been responsible for the primary uplift and volcanism of the Tharsis area. The radial compressional forces generated by the tendency for downslope movement of surface strata, vertical volcanic intrusions and traction of mantle spreading beneath Tharsis were transmitted through the lithosphere to form peripheral mare ridge zones. The locations of mare ridges were thus mainly controlled by the Tharsis-radial compression. The load-induced stresses then contributed on further ridge formation over an extended period of time by the isostatic readjustment which was reponsible for long-term stresses in the adjoining areas. Extrusions, changes in internal temperature and possible phase changes may also have caused changes in mantle volume giving rise to additional compressional forces and crustal deformations.

1. Introduction

The existence of Tharsis-related peripheral ridge pattern is evident (Wise *et al.*, 1979; Chicarro *et al.*, 1985; Watters and Maxwell, 1986) although there is controversy as to its importance and origin (Saunders *et al.*, 1981; Banerdt *et al.*, 1982; Maxwell, 1982; Plescia and Golombek, 1986; Watters, 1986). The disagreement of how to evaluate different aspects of mare ridge formation is derived from the variety of interpretations for their origin. A pure volcanic origin of mare ridges (Fielder, 1965; Quaide, 1965; Strom, 1971; Scott, 1973) can, however, be excluded although volcanic vents are found in conjunction with mare ridges (Colton *et al.*, 1972; Raitala, 1978, 1980) indicating an apparent tectonic control of both mare ridges and adjoining volcanism. The existence of crater chains, sinuous rilles and volcanic domes in conjunction with some ridges may also indicate tectonic control of these structures (Raitala, 1982) rather than volcanic origin of mare ridges (Fielder, 1965; Quaide, 1965).

There seems to be a firm association between mare ridges and tectonics. A variety of tectonic processes have been invoked to explain different characteristics of mare ridges. Lunar mare ridges, located almost exclusively within mare areas, led some scientists to argue that the effects of mascons or basalt load and the compressional environment caused by the mass-induced surface shortening are responsible for mare ridge formation (Phillips *et al.*, 1972; Bryan, 1973; De Hon and Waskom, 1976; Golombek, 1985b). The share of the buried basement structures is emphasized by Baldwin (1963), Colton *et al.* (1972), Phillips *et al.* (1972), Maxwell (1982), Sharpton and Head (1982). The processes by which subsurface topography can produce mare arches and ridges include draping of the basalt lavas over basin bottom heights (Ar-

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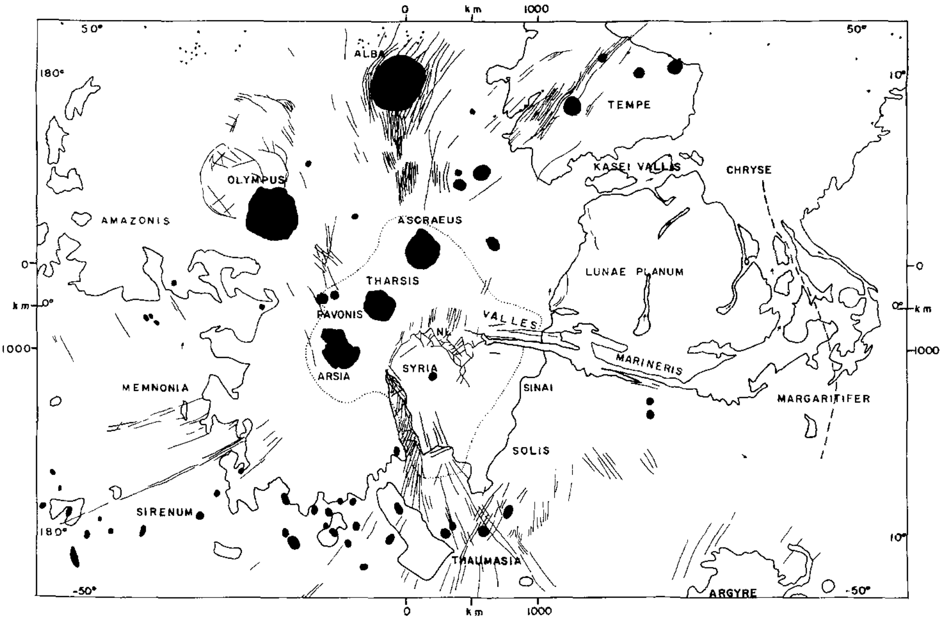

Fig. 1. Map of the Tharsis province of Mars, simplified from Scott and Carr (1978). Rough, cratered and ridged plateau areas and old volcanic materials of the southern hemisphere are separated from northern plains and younger Tharsis formations by a heavy line. Thin line indicates major fossae grabens. Volcanoes are indicated with black according to Scott (1982). The dotted line indicates the 8 km contour. Valles Marineris, adjoining canyon floors and channels are outlined. The broken line indicates the course of the Chryse-Margaritifer trough (Christensen, 1975; Mutch and Saunders, 1976; Saunders, 1979). NL = Noctis Labyrinthus.

thur, 1962; Baldwin, 1963) and uneven relative compaction within areas with thin and thick lava cover (Colton *et al.*, 1972). Activation of bedrock faults may or may not be connected with previous subsurface topography (Sharpton and Head, 1982; Plescia and Golombek, 1986).

The interpretation of the nature of faults connected with mare ridges has varied from horizontal strike-slip movements (Tjia, 1970, 1976; Wilson, 1970) to vertical tectonics (Lucchitta, 1976, 1977) and thrust faulting (Conel, 1969; Hodges, 1973) with adjoining fault-related folding (Howard and Muehlberger, 1973; Greeley and Spudis, 1978; Lucchitta and Klockenbrink, 1981; Watters and Maxwell, 1985; Plescia and Golombek, 1986). Critical for the mare ridge formation seems to be a compressional environment. In the case of lunar Oceanus Procellarum the location and orientation of compressional faults are also controlled by a strike-slip component (Raitala, 1982). The apparent dominance of compressional features may be caused by the layered surface strata and underlying megaregolith which causes strike-slip movements to be attenuated below the surface at a major mechanical discontinuity in the shallow crust between the megaregolith and the underlying bedrock (Golombek, 1985a; Watters, 1986). Accompanying folding is then possible (Saunders *et al.*, 1981; Watters, 1986), but of secondary importance, in explaining mare ridges (Plescia and Golombek, 1986).

This paper deals with the mare ridge tectonics coupled with the Tharsis bulge (Figure 1) and with explanations of how the building up of a major huge volcanic complex and the vertical forces associated with it may have led to horizontal compression and caused the observed dorsa structures.

2. Tharsis-Related Ridges

Tharsis-related Martian ridges are peripheral and roughly concentric to the Tharsis bulge (Wise *et al.*, 1979; Maxwell, 1982) being actually circumferential to Syria Pla-

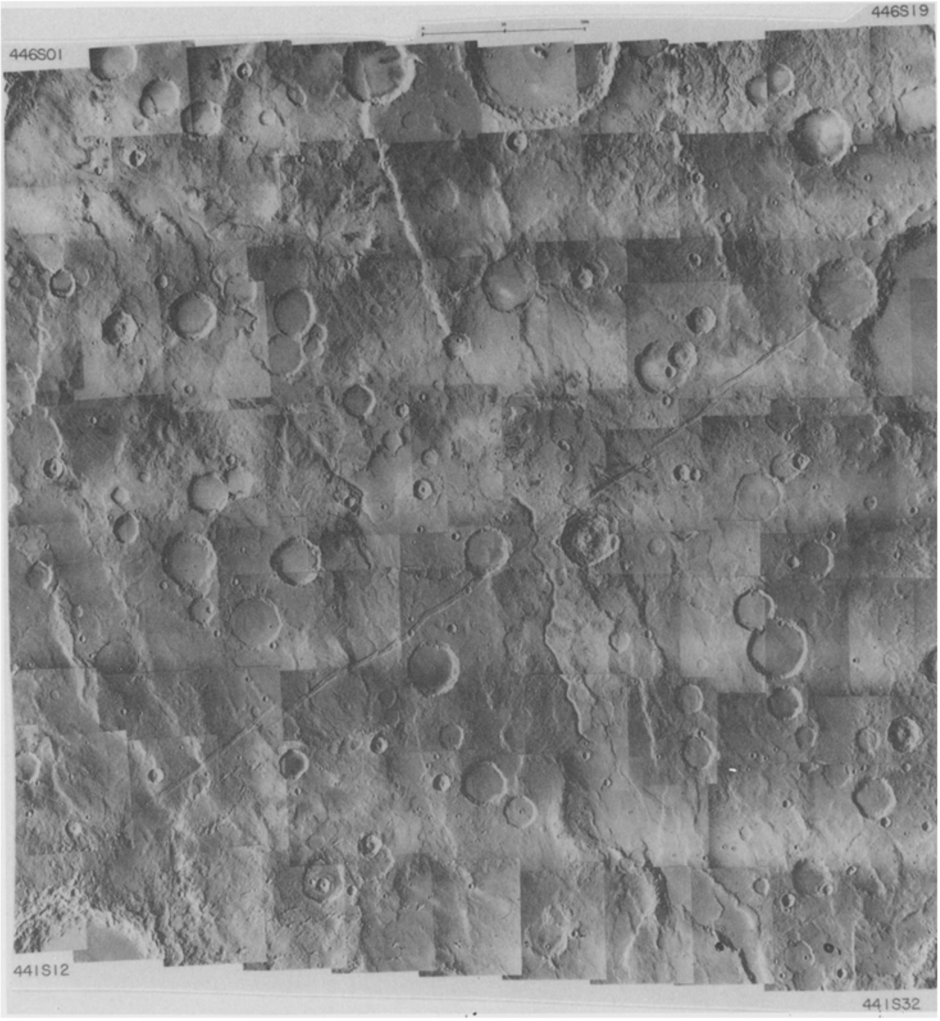

Fig. 2a. Grabens and mare ridges of the northern Memmonia area. Graben with its well-established en echelon pattern is approximately radial to the Tharsis bulge. Wrinkle ridges which in places have a fault-like appearance are roughly perpendicular to the graben and concentric to the Tharsis area. Viking mosaic 211–5950.


East
North
South
West

Fig. 2b. Mare ridges of Lunae Planum on the USGS photomaps I–1303 and I–1305.

num and the Tharsis volcanoes (Plescia and Saunders, 1982; Chicarro *et al.*, 1985; Watters and Maxwell, 1986). The subconcentric mare ridge pattern seems to be consistent with geophysical models (Banerdt *et al.*, 1982; Solomon and Head, 1982; Willeman and Turcotte, 1982; Sleep and Phillips, 1985) but there is still a lack of knowledge of the actual process(es) involved (cf. Watters, 1986). Crosscutting relations between ridges and grabens do not support the idea that compressional ridges are a result of a single lithsphere loading event (Watters and Maxwell, 1983) but rather imply a more complex tectonic development (Plescia and Saunders, 1982; Raitala and Saunders, 1986; Watters and Maxwell, 1986).

The Tharsis dorsa system consists of groups of ridge ranges lying at the marginal low level base of the Tharsis bulge approximately concentrically to it (Carr, 1974; Wise *et al.*, 1979; Maxwell, 1982; Chicarro *et al.*, 1985; Watters and Maxwell, 1986). Ridges are most numerous and largest within Lunae Planum area and southwards from Valles Marineris at the topographic base of the Sinai Planum and Solis Planum area. The N-S ridges of the Memnonia and Sirenum area also have similar main orientation and structural position to the Tharsis bulge than the eastern ridges. There are also tectonically important sets of NW-SE ridges within the southern Icaria area (Figures 2, 3).

3. Building of Tharsis Dorsa

The dorsa ridges are evidently not solely compressional thrusts (Plescia and Golombek, 1986) nor compressional folds (Watters, 1986) but rather indicative for faults (Raitala, 1984), the locations of which were controlled by the peripheral compression raised by the Tharsis bulge phenomena. The orientation and arrangement of dorsa ridges were also controlled by other movements (Watters and Maxwell, 1986). According to Maxwell (1982) there are conjugate NE-SW and NW-SE oriented main ridge directions within Lunae Planum and Coprates Region and the Tharsis effect has only slightly increased the occurrence of ridges orthogonal to the bulge center. The orientation of dorsa ridges and their occurrence in long linear rows with numerous en echelon structures may indicate the possible importance of the strike-slip component in dorsa ridge formation or, in contrast to Maxwell's (1982) interpretation, it may indicate the importance of several active centers within the Tharsis bulge (Plescia and Saunders, 1982; Watters and Maxwell, 1983; Chicarro *et al.*, 1985) and also the extended period of time in ridge formation. Unlike the lunar mare ridges within the Oceanus Procellarum area, the importance of crossing conjugate diagonal ridge zones seems to be of minor importance within the Martian areas. This possibly implies that the compressional component may have been relatively more significant than in the case of lunar mare ridges or that the mechanical discontinuities in the shallow crust of Mars are far more important than on the Moon (Golombek, 1985b; Watters, 1986).

The main point is that the formation and existence of the Tharsis bulge was able to lead to significant horizontal stresses. The major high bulge has resulted in com-

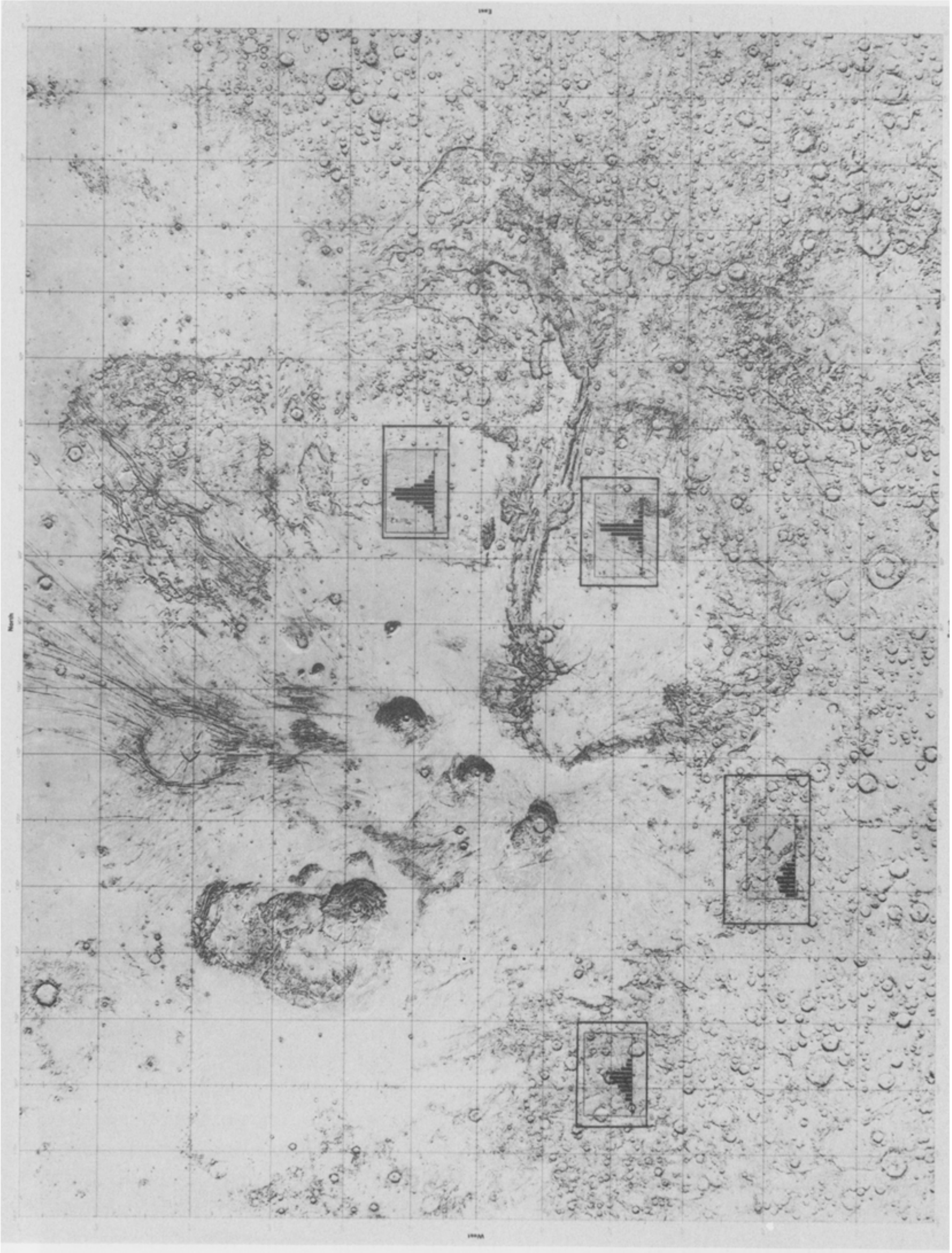

Fig. 3. Strike distribution of mare ridges from four different areas peripheral to the Tharsis bulge. Lunae Planum has a main distribution peak around N5 °W while Coprates has most ridges at N10 ° – 30 °E. Phaethontis and Memnonia have wide northwestern and northern mare ridge histogram peaks, respectively. Base map USGS Mars map I – 1320.

Fig. 4. Major Tharsis volcanoes, and radial graben and valley structures with the 8 km contour. Letters from A through I denote different Tharsis-related block segments. Broken lines indicate the location of cross-sections in Figure 5. Radial compressional stresses against surrounding peripheral areas are indicated by arrowheads.

pressional stresses in the adjacent lithosphere after it developed to form a huge dome and volcanic construction over long-term internal activity center. The dorsa ridges indicating compressional lithospheric environment concentric around the Tharsis bulge and perpendicular to the graben rift zones (Figures 4, 5).

One contribution to the large vertical forces was the mantle plume. However, a plume penetration into the lithosphere was originally weak. An important component was the thinning of the lithosphere and the radial traction force of the outward flowing asthenosphere and the upward doming of the volcanic center which caused some sliding of the surface strata off the crest (Figure 6). The forces from the crest were transmitted through the lithospheric segments driving them away from the bulge crest against the firm and thick highland lithosphere.

At the Tharsis bulge the lithosphere was also uplifted by a mantle plume from below and loaded and built on the top. Due to the volcanic building and heat loss to the surface the crust and lithosphere thickened along the time. The horizontal tectonic forces can be explained in terms of endogenic building. The elevation of the Tharsis bulge and volcanic intrusions led to a bulge push force away from the ridge due to gravitational sliding off the bulge crest. This subsidence-push interaction is an example of how vertical forces can lead to horizontal compressional forces (Turcotte, 1983). The Martian mantle material extruded and intruded to the lithosphere has been dense. The result was the slight gravitational adjustment of the high, volcanic bulge during convection and the decreasing internal activity. During the extensive volcanic phase, volcanic material was, however, extruded more than the bulge, which was also elevated by the convectional igneous activity, was subsided by the increasing load (Figure 5).

The partial relaxation of the Tharsis dome was responsible for a push force against the surrounding lithospheric blocks. Because even small changes in temperature can result in large thermal stresses (Turcotte, 1974), it is possible to suggest, that the cooling of the Martian interior and the decrease in energy transport by convection were also responsible for horizontal stresses around Tharsis. Tharsis area is a dome, surrounded by a highland crust on its eastern, southern and southwestern side. The surface blocks have deformed when moving down the bulge elevation and towards the more rigid and thick lithosphere. The horizontally transported stress from the Tharsis bulge has been responsible for the compressional features of dorse (Figures 4, 5).

The main parts of the Tharsis-related lithosphere may have acted as stress guides. There is a lack of deformation structures within large areas indicating that the lithosphere has been able to transmit stresses over large distances during a long time period (Saunders *et al.*, 1981; McAdoo and Sandwell, 1985; Watters, 1986; Watters and Maxwell, 1986; Raitala, 1987). The process may have been similar to that suggested by Turcotte (1982) where upper parts of the lithosphere with temperatures less than about 400 degrees C can transmit kilobar level stresses through the elastic lithosphere while stresses were relaxed by solid state creep processes deeper in the lithosphere where the temperature is higher.

The tectonic forces which caused the compressional environment of the dorsa formation were primarily applied to the Martian lithosphere at central active Tharsis areas. Due to the hot-spot-like volcanism of the Tharsis bulge, hot mantle rock reached the surface and near-surface areas within the bulge crest (Raitala, 1987). Intrusions and extrusions cooled to form a volcanic bulge and made it thicker along the time. Around Tharsis, the Martian crust and lithosphere was shortened and compressed to form mare ridge (Bryan, 1973; Battistini, 1984) structures, located on peripheral plateau areas. The compressional body forces were transmitted through the lithosphere down to those areas where a rigid thick highland lithosphere, unaffected by the mantle impingation, uplift and traction forces, was met with. The lithosphere thinned below and the crust thickened by igneous materials, both due to the impinging mantle plume, leading to tension on the crest of the central ascended area. Adjoining sliding of the lithosphere and crust away from the crest was the result of the gravitational downhill slide, volcanic push, crest load, and outward mantle traction (Saunders *et al.*, 1981; Turcotte, 1983; McAdoo and Sandwell, 1985; Watters, 1986; Watters and Maxwell, 1986; Raitala, 1987). These processes caused compression at the slope base while loaded at the higher end. Horizontal compression was caused by a dome crest phenomena acted in the adjacent lithosphere (Turcotte, 1982). Dome building caused the existence of compressional environment (Raitala, 1982, 1984) and wrinkle ridges of the Sinai-Solis area can be considered to be

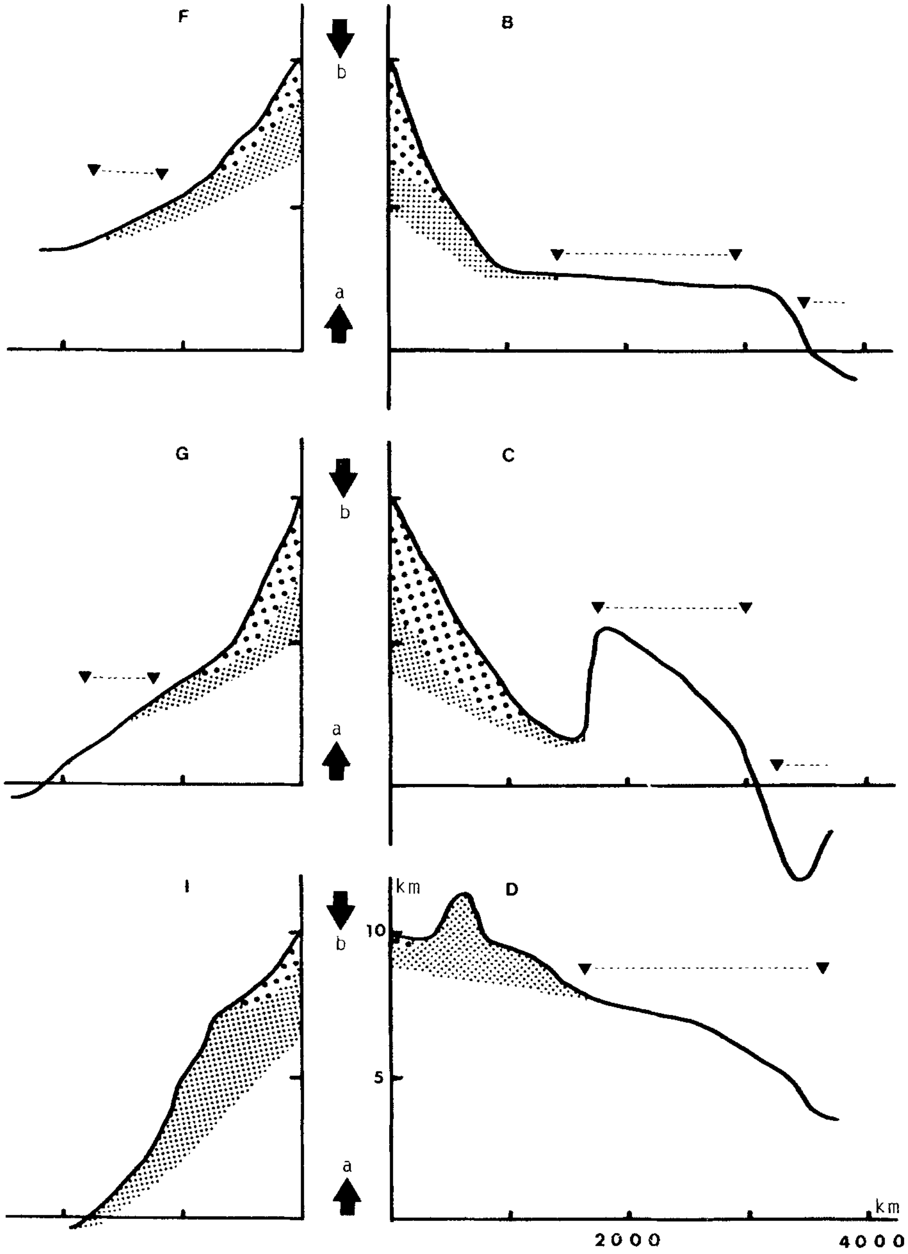

Fig. 5. Low-resolution topographic profiles across the sections indicated in Figure 4. Triangles with broken lines indicate the location of dorsa ridges. Dots indicate volcanic construction. Arrows indicate vertical stresses caused by endogeneous activity (a) and volcanic load (b).

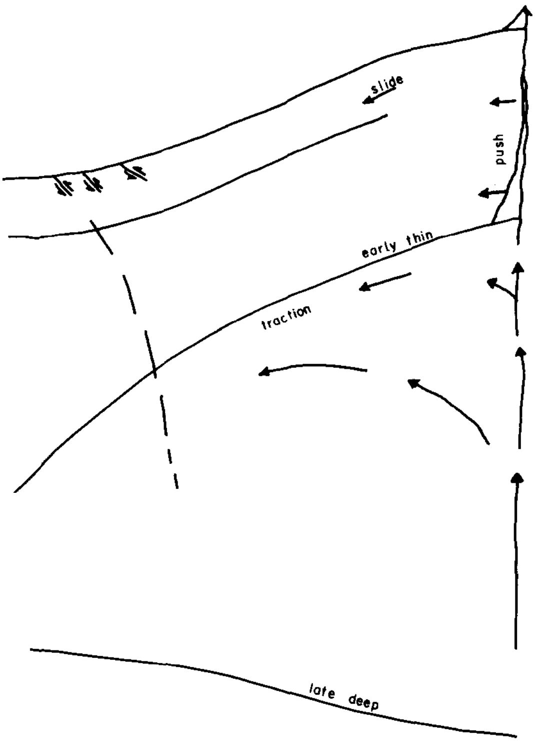

Fig. 6. Sketch of the endogeneous forces which must be inspected more closely when considering to the concentric structures around Tharsis. These forces may have been most active during the early Tharsis' development. Lithosphere thickening has occurred due to the decreasing of endogeneous activity leading also to decreasing tectonic activity. The broken line is hypothetical divide between Tharsis' and highland lithosphere.

responses to this compression. Well developed dorsa patterns on the base of the elevated Sinai/Solis Planum area approximately parallel the topographic contours. The explanation of the dorsa location at the base of the elevated Sinai/Solis Planum area may be in the thickening of the lithosphere farther away from the volcanic center. The dorsa region of compressional tectonics can be referred to as the hinterland (Jordan *et al.*, 1983), resembling a thrust belt. Mare ridges of Lunae Planum, Tempe Terra, Terra Memnonia and Terra Sirenum, also imply the existence of compression due to the stresses generated within the Tharsis bulge (Figures 3, 5).

The transmission of stress through the Sinai/Solis Planum segment against the Argyre NW highland resulted in a quite broad zone of deformation. The broad occurrence of these ridges in the base of the Sinai/Solis Planum area, may indicate the thin Sinai/Solis lithosphere and the slow mantle traction below large areas of this thin lithosphere segment. The development of the Memnonia and Sirenum dorsa to the southwest and south of Tharsis bulge may be of minor importance due to the lower tectonic activity and thicker lithosphere. A broad wrinkle ridge deformation zone also extends through the Lunae Planum and Tempe Terra. The thin-lithosphere explanation is valid there as well. Only difference in NW direction was that the Chryse/Acidalia lithosphere was evidently also thin enough to be affected by compressional ridge-forming tectonics. Embedded within the broad sub-circular mare ridge zone of Tempe Terra, Lunae Planum, Sinai/Solis Planum, Sirenum Terra and Memnonia Terra is the compressional base zone of the major Tharsis bulge (Figure 6).

4. Conclusion

The earliest tectonic structures of the Tharsis area were generated when the initial thermal flux from the Martian interior was big enough to cause convective movements and to raise and hold up the lithospheric dome (Carr, 1974; Frey, 1979; Wise *et al.*, 1979; Plescia and Saunders, 1982). In the case of Martian Tharsis bulge the extensive extrusive (and intrusive) volcanism has also been important (Solomon and Head, 1982; Willeman and Turcotte, 1982). Because the cooling rate has at first been slow and began from the margins, the endogenic activity sustained the middle part of the area, which then froze to form the present bulge. The lithosphere has thickened due to the secular cooling of Martian interiors. The crustal shortening has not been possible within the central areas of the thick lava load but resulted compression in the marginal areas (cf. mare ridges). Major Tharsis bulge is not in isostatic equilibrium (Phillips and Saunders, 1975; Sleep and Phillips, 1979, 1985; Banerdt *et al.*, 1982). The isostatic equilibrium was not reached because of (i) the initial plume, (ii) intensive volcanic building and (iii) relative rapid late decrease in internal activity (Figures 5, 6).

The compression coupled with the dorsa ridge formation may be considered to have been the result of horizontal forces equivalent to a gravitational sliding away from the bulge crest and the horizontal pressure associated with the mantle intrusions and activity within the bulge (Raitala, 1987). If considered as pure compressional structures ridges are a function of these pressures. The horizontal force on the lithosphere around the Tharsis bulge can be illustrated with the aid of Figure 4. Most Tharsis-related ridges are primarily concentric to the Tharsis bulge. All compressional forces have been related to the pluming mantle and wide bulge crest areas. Gravitational sliding of the bulge crest together with intrusions and mantle traction caused compressional stress in the adjacent marginal areas (Raitala, 1987).

There is an analogy between ridges of the Columbian basalt plateau and Martian dorsa (Watters and Maxwell, 1985), between certain earthquake faults and wrinkle ridges (Plescia and Golombek, 1986), and between terrestrial sea-bottom undulations (McAdoo and Sandwell, 1985) and the Martian mare ridge zones. These analogies must, however, not be regarded as a firm conclusion and identity but rather as approaches which are postulated to attain some ideas of the possible continum of the tectonic processes within different terrestrial planets.

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