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Evolution of the Tharsis Province of Mars: The Importance of Heterogeneous Lithospheric Thickness and Volcanic Construction

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The Tharsis province of Mars is a broad region characterized by anomalously elevated topography, a positive free-air gravity anomaly, and extensive volcanic and tectonic activity. The evolution of this region has spanned up to 4 b.y. of Martian history. The traditional explanation of the Tharsis province is that uplift of the lithosphere caused by a thermal, chemical, or dynamical anomaly in the Martian mantle or crust led to lithospheric fracturing and to the later volcanic emplacement of thin plains units and large shields. By this explanation the majority of the topographic anomaly is due to uplift. The stress field predicted for lithospheric uplift, however, does not match the generally radial trends of observed extensional fractures. Strictly thermal or compositional explanations for the support of the Tharsis rise encounter problems with the magnitude and duration of the required lateral variations in mantle density. For these reasons, we propose a new model for the origin and evolution of the Tharsis province which emphasizes that the topography of Tharsis may be produced largely by construction, rather than uplift. The model is based on the premise that the elastic lithosphere of Mars was laterally heterogeneous early in Martian history; such heterogeneity is discernible later in Martian history from the variable tectonic response of the lithosphere to local surface loads. Stress due to both global and local causes was concentrated in zones of thin lithosphere, including at least a portion of the Tharsis region. As a result, fracturing was also concentrated in such zones and favored localization of volcanism by providing access to the surface for mantle-derived magma. The heating associated with volcanism maintained the lithosphere locally thin, so that further fracturing and volcanism were concentrated in the same area. The Tharsis rise was thus built primarily by volcanic construction. Most visible tectonic features, by this model, were produced by the response of the lithosphere to loading, not by uplift. Early in the history of Tharsis the lithosphere responded to volcanic loading by nearly local isostatic compensation, while later additional loads have been partly supported by the finite strength of the globally thick elastic lithosphere of Mars. This mechanism for the evolution of Tharsis led to permanent topographic and gravity highs and a greatly thickened crust in the Tharsis region. A major advantage of the model is that no anomalous dynamical or chemical properties need to be sustained in the Martian mantle beneath Tharsis for billions of years. The mantle beneath Tharsis would thus play a passive rather than an active role in the regional volcanic and tectonic activity, much like the role of the mantle beneath major midocean ridges on earth. This and other models for the origin and evolution of the Tharsis province can be further tested by establishing the detailed chronology of tectonic features in the region.

INTRODUCTION

The Tharsis province of Mars, by virtue of its large scale and its complex and extended history of volcanic activity [*Carr*, 1974; *Wise et al.*, 1979*a*], is a focal point for discussions of Martian geological evolution. Approximately 8000 km in diameter and occupying an area equal to 25% of the surface area of Mars, the Tharsis region is marked by a broad topographic rise standing as much as 10 km above the surrounding terrain. A positive gravity anomaly coincides with the long-wavelength topographic high [*Christensen and Balmino*, 1979]. Swarms of extensional fractures and graben extend outward from Tharsis for thousands of kilometers in a crudely radial array. The crest and flanks of the Tharsis topographic rise consist generally of volcanic plains, capped by a number of volcanic shields and other constructs. The summits of several of the largest shields stand over 20 km above the local elevation. The duration of faulting and volcanism represented by the tectonic and volcanic features of Tharsis extends over a large fraction of Martian history.

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The traditional explanation for the origin and evolution of the Tharsis province is that uplift of the lithosphere caused by a thermal or chemical anomaly in the mantle or crust led to lithospheric fracturing and to the volcanic emplacement of thin plains units and later of the large shields [*Carr*, 1974; *Wise et al.*, 1979*a*]. The topographic rise, by this view, is regarded as primarily due to uplift rather than to construction. With this explanation, Tharsis is a Martian analog to the 'active mantle' class of terrestrial rifts as described by *Sengör and Burke* [1978]. Evidence cited in support of this uplift model for Tharsis includes the broad domical shape of the topographic high, the large elevation of surface units mapped as relatively old on the basis of the density of craters and fractures, and the generally radial trends to most extensional fractures in and near the Tharsis area. There are, however, several problems with this model. The stresses predicted for lithospheric uplift on the scale of Tharsis do not match the distribution of observed tectonic features. Mantle support involving a strictly thermal mechanism requires unreasonably large lateral variations in temperature. A plausible chemical mechanism for mantle support of the Tharsis rise is depletion of the sub-Tharsis mantle of its basaltic component [*Sleep and Phillips*, 1979; *Finnerty and Phillips*, 1981], but the large volumes of volcanic material required of this mechanism to provide a change in mantle density sufficient to support significant topographic relief make this hypothesis more of a constructional than an uplift model for Tharsis.

As a result of these problems, we have developed an alternative model for the geological evolution of the Tharsis province [*Solomon and Head*, 1980*b*]. In this paper, we summarize the present understanding of the development of the volcanic and tectonic history of the Tharsis region, we describe the models proposed in the literature to account for that history and the difficulties encountered by these models, and we present in detail our alternative explanation for the origin and evolution of Tharsis. Briefly, our explanation consists of three elements:

1. The elastic lithosphere of Mars throughout much of its history has been heterogeneous in thickness (i.e., in temperature). Stress due to both global and local causes was concentrated in zones of thin lithosphere, foremost among which was (perhaps a small fraction of) the Tharsis region. This led to the concentration of fracturing in such areas.
2. Intense fracturing was conducive to localized volcanism. The heating associated with volcanism maintained a locally thin elastic lithosphere, insuring that further fracturing and volcanism would be concentrated in the same area.
3. The topographic relief of Tharsis was produced primarily by volcanic construction. The response of the Martian lithosphere to volcanic loads involved nearly local isostatic compensation by crustal subsidence during the early history of the Tharsis province when the Martian lithosphere was relatively thin. The response of the cooler and thicker lithosphere to later additions of volcanic material involved regional subsidence and global support by lithospheric strength.

By the scenario for Tharsis evolution proposed here, there is no need to postulate a chemical or dynamical anomaly persistent for billions of years in the mantle beneath the Tharsis rise. Tharsis is thus, by this explanation, a Martian analog to the 'passive mantle' class [*Sengör and Burke*, 1978] of terrestrial rifts. Tharsis is seen to be an extrapolation to larger scale of such geological processes as volcanic loading and lithospheric flexure and failure seen in a number of areas on Mars [*Solomon et al.*, 1979; *Comer et al.*, 1980] and on the moon [*Solomon and Head*, 1980*a*]. The distribution of tectonic features and the Tharsis gravity anomaly are both consistent with this proposed model for Tharsis evolution. Among the implications of the model are a volcanic origin for much of the ancient cratered terrain beneath the younger volcanic plains—and in some areas exposed at the surface—of the Tharsis topographic rise and a total thickness of volcanic deposits beneath Tharsis substantially in excess of the present 10 km of broad-scale relief.

GEOLOGICAL EVOLUTION OF THARSIS

As a prelude to a fuller discussion of the processes responsible for the origin and evolution of the Tharsis province, a brief summary is given of the volcanic and tectonic history of the area. The Tharsis region of Mars has experienced a large number of diverse volcanic and tectonic events spread over an interval of time spanning billions of years. Detailed descriptions of aspects of this geologic history have been provided by *Carr* [1974, 1981], *Mutch et al.* [1976], *Schaber et al.* [1978], *Wise et al.* [1979*a*], *Frey* [1979], *Plescia and Saunders* [1979*a*], and *Scott and Tanaka* [1980, 1981*a*]. Only the Elysium region of Mars displays volcanic and tectonic features broadly similar to those of Tharsis, though on a reduced scale [*Carr*, 1973; *Malin*, 1977]. A generalized geological map of the Tharsis province [*Scott and Carr*, 1978] is shown in Figure 1.

The planet Mars may be divided approximately into two hemispheres [e.g., *Mutch et al.*, 1976]: a heavily cratered and generally elevated southern hemisphere containing a number of large impact basins and a northern hemisphere lower in elevation and covered with younger volcanic plains deposits. The areal density and size distribution of impact craters in the cratered uplands of Mars have many similarities to those of craters in the lunar highlands and in the heavily cratered terrain of Mercury [*Wilhelms*, 1973; *Soderblom et al.*, 1974; *Murray et al.*, 1975]. These similarities have led to the hypothesis [e.g., *Murray et al.*, 1975] that all of the terrestrial planets were subjected to a high flux of impacting objects and that this flux ended at the time of formation of the youngest large lunar basins about 3.8 billion years ago [e.g., *Turner et al.*, 1973; *Jessberger et al.*, 1978; *Bernatowicz et al.*, 1978]. The hypothesis is supported by dynamical studies of the possible populations of objects that could have been responsible for such a late heavy bombardment of the inner solar system [*Wetherill*, 1975]. By this hypothesis the large impact basins and the cratered uplands of Mars are 3.8 billion years or greater in age, and the volcanic northern plains are younger in age. The Tharsis province (Figure 1) straddles the boundary between the geologically distinct hemispheres.

Volcanic history. The oldest major geologic units in the Tharsis area with surface features (wrinkle ridges and apparent flow scarps) indicating a probable volcanic origin are the cratered plateau material of *Scott and Carr* [1978], also termed the plateau plains by *Wilhelms* [1974] and by *Greeley and Spudis* [1978, 1981]. Numerous mountainous features in cratered plateau units to the south and southwest of the younger volcanic plains of the central Tharsis region have been identified from Viking images as volcanic constructs by *Scott and Tanaka* [1981*b*]. Cratered plateau units were formed contemporaneously with the end of heavy impact bombardment and postdate the topographically more rugged hilly and cratered material, held by *Scott and Carr* [1978] to be the oldest extensively exposed surface material on Mars. The geological processes forming the hilly and cratered material cannot be discerned through the overprinting of the heavy bombardment. The volcanic cratered plateau material occurs extensively throughout the southern uplands [*Scott and Carr*, 1978; *Greeley and Spudis*, 1978, 1981] and constitutes most of the cratered terrain on the southern boundary of younger Tharsis volcanic units (Figure 1). A few patches of older hilly and cratered material are also included within the Tharsis topographic rise.

The next oldest major volcanic units in the Tharsis region are the ridged plains, which are areally extensive in the eastern and northeastern portions of the Tharsis province (Figure 1). These plains resemble the lunar maria in terms of smaller-scale morphologic features and crater density [*Scott and Carr*, 1978]. Based on high-resolution Viking images and

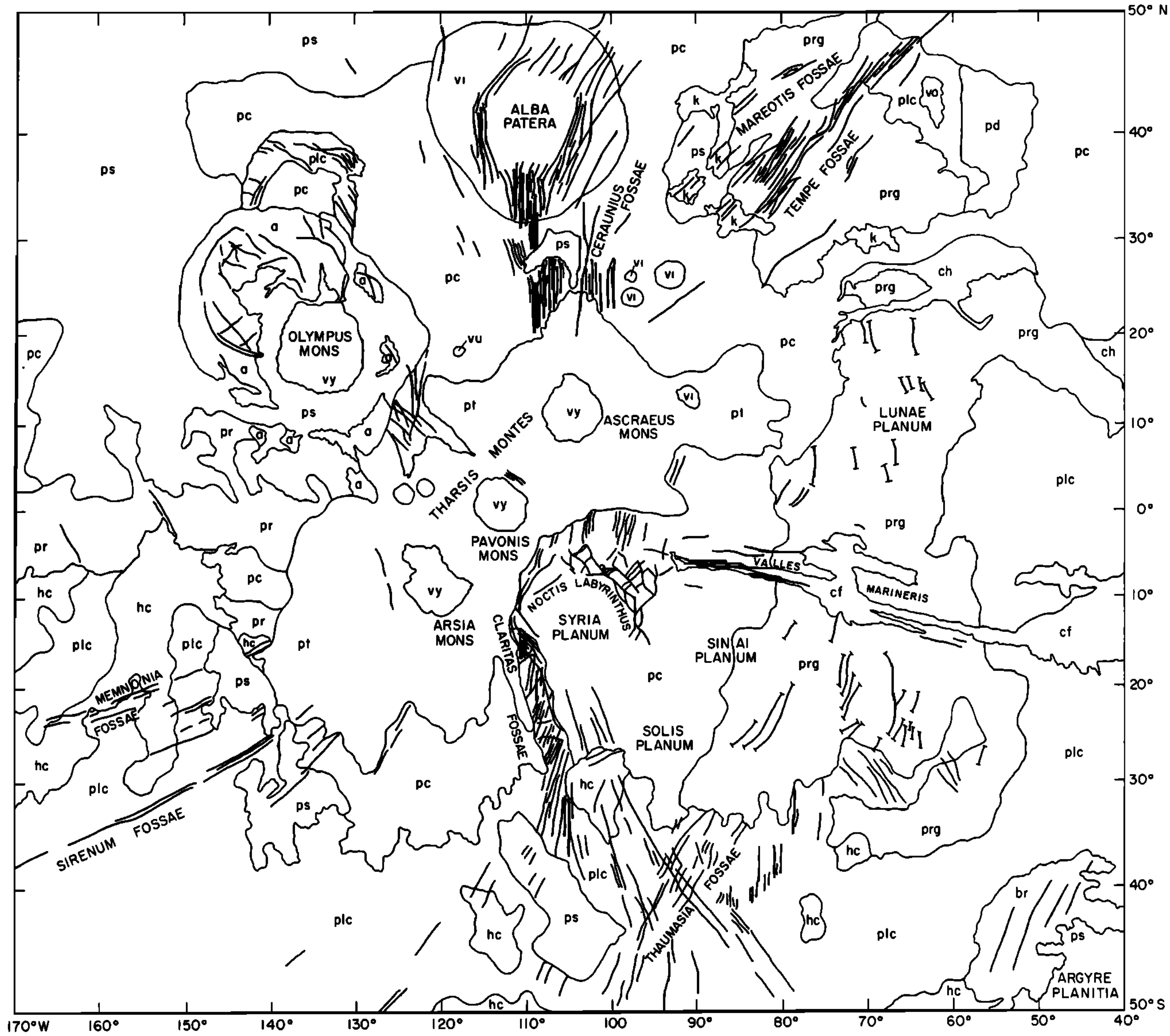

Fig. 1. Geologic map of the Tharsis province of Mars, simplified from *Scott and Carr* [1978]. Heavy lines denote prominent graben and extensional fractures; lines with ticks denote mare-type ridges. Major geologic units, both in this figure and in Figure 6, include hc (hilly and cratered material), br (basin rim), k (knobby material), plc (cratered plateau material), pm (mottled plains), pd (deflated plains), ch (channel material), prg (ridged plains), pst (streaked plains), vu (volcanic material, undivided), vo (old volcanic material), pr (rolling plains), vi (intermediate age volcanic material), cf (canyon floor), a (aureole), pc (cratered plains), ps (smooth plains), pt (Tharsis plains), vy (young volcanic material).

radar altimetry, a number of small constructs of probable volcanic origin have been identified within ridged plains units [*Hodges*, 1979; *Roth et al.*, 1980; *Plescia*, 1981; *Scott*, 1981].

Continued plains formation and the development of the larger volcanic constructs characterized the later volcanic history of the Tharsis region. *Scott and Tanaka* [1980] cite eruptions from Alba Patera and plains formation in the Syria Planum area, near the present crest of the broad Tharsis rise, as the next major volcanic episode following emplacement of the ridged plains; these units correspond approximately to the cratered plains material [*Scott and Carr*, 1978] in Figure 1. Subsequent volcanic events in the region included initiation of the large shield volcanoes of the Tharsis Montes, emplacement of the majority of Tharsis plains units, and further activity in the Alba Patera and Ceraunius Fossae regions [*Scott and Tanaka*, 1980, 1981*a*]. The Olympus Mons shield formed comparatively late in the history of Tharsis. The youngest volcanic flows in the Tharsis region can be traced to the summits and flank fissures of the large shields Arsia, Pavonis, Ascraeus, and Olympus Montes [*Carr et al.*, 1977; *Schaber et al.*, 1978; *Scott and Tanaka*, 1980, 1981*a*].

The absolute ages of surface units on Mars may be estimated, in principle, from the density of impact craters. Such estimates are not completely reliable, however, because of the large uncertainty in the history of the Martian impact flux [e.g., *Wetherill*, 1974]. Even if the flux were known precisely, these estimates would have uncertainties associated with nonvolcanic obliteration processes, such as erosion or eolian deposition [e.g., *Jones*, 1974], and with the tendency for thin surface units to hide only partly the rims of

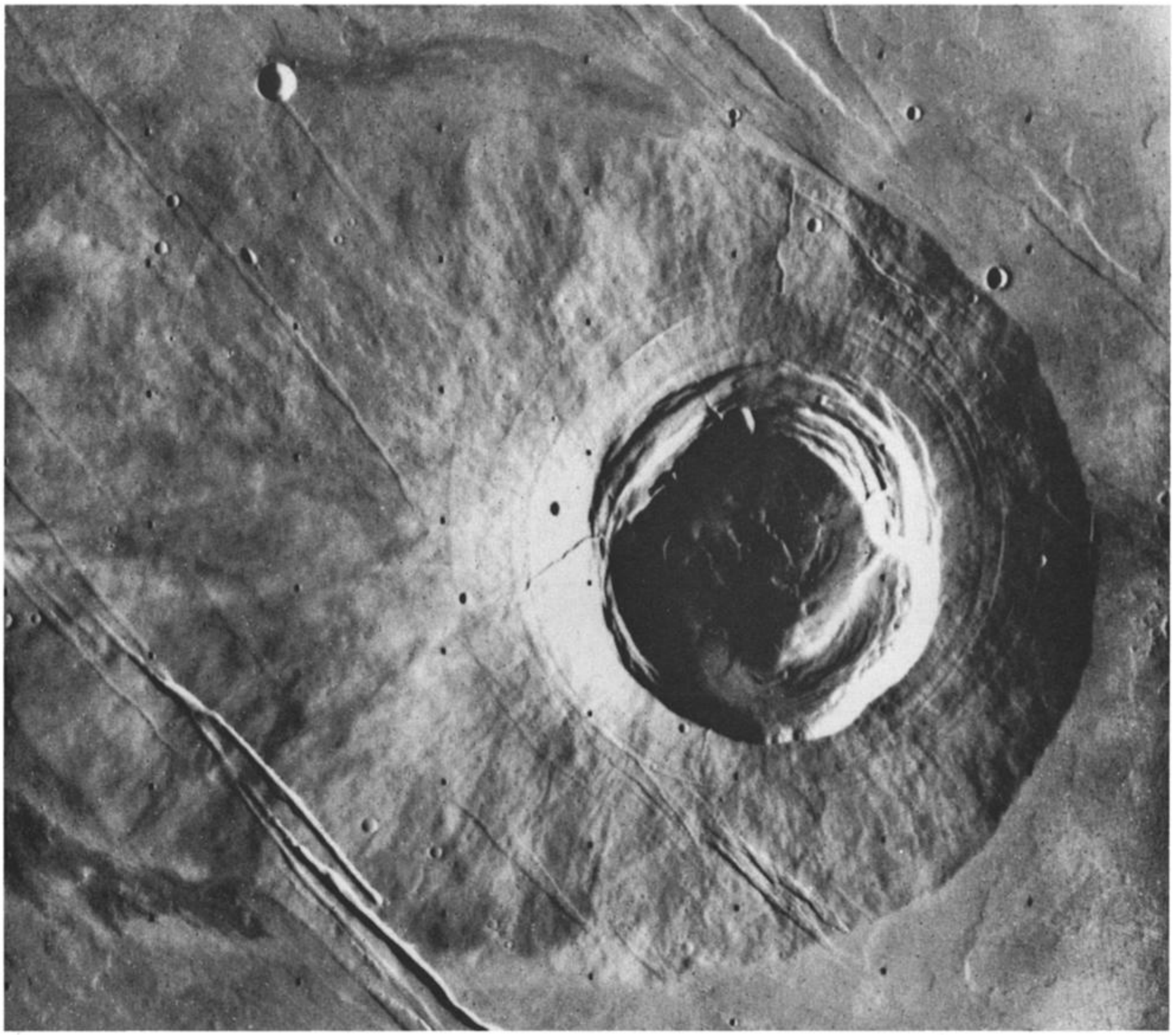

Fig. 2a

Fig. 2. Two Martian volcanoes on the northwest edge of Tharsis Montes partially buried by younger volcanic deposits. (*a*) Biblis Patera (2°N, 124°W). Lava flows from sources other than the central caldera have flooded around the base of the volcano, often truncating the northwesterly trending graben. Viking Orbiter frame 44B50, width 175 km. (*b*) Ulysses Patera (3°N, 122°W). Lava flows also have flooded the base of this volcano, reducing its relative relief. A graben extending across the volcano from the northwest has been flooded at its intersection with the surrounding plains to the southeast. The two central-peaked impact craters on the volcano flank and rim have had their ejecta deposits buried by later lava flows on the exterior flanks of the volcano. Viking Orbiter frame 49B85, width 175 km.

larger craters on underlying surfaces [e.g., *Wise et al.*, 1979*a*]. In spite of these many uncertainties, the low densities of impact craters on the most recent volcanic flows in the Tharsis region indicate geologically young ages by all the current crater chronologies [*Neukum and Wise*, 1976; *Soderblom*, 1977; *Hartmann*, 1977]. The youngest surfaces on Olympus Mons and related flows, for instance, have ages estimated to be in the range 25 to 250 m.y. [*Schaber et al.*, 1978; *Plescia and Saunders*, 1979*b*]. Thus volcanism in the Tharsis area has extended over a time span of almost 4 billion years, or most of the history of Mars.

Important but poorly constrained quantities are the total volume of volcanic material in the Tharsis province and the volcanic flux through time. The volumes of the large shields are known from their topographic relief [*Carr*, 1973; *Blasius and Cutts*, 1976, 1981]. The volumes of a number of prominent flows have been estimated by *Scott and Tanaka* [1980] from the flow areas and an assumed value of 200 m for the average thickness of a flow unit, a value estimated from the observation that craters 5 km in diameter were often incompletely buried by flow units. The thicknesses of major volcanic units in the Tharsis area have also been estimated by *Plescia and Saunders* [1980] and *De Hon* [1981] from the inferred rim heights of partially buried large (10- to 60-km diameter) craters. On this basis, *Plescia and Saunders* [1980] obtain a combined thickness of 0.5 to 0.6 km for the cratered plains and Tharsis plains in southern, southwestern, and northeastern portions of the Tharsis province. The results of *De Hon* [1981] are in agreement for these units; De Hon further inferred thicknesses of 0.7 to 1.3 km for the ridged

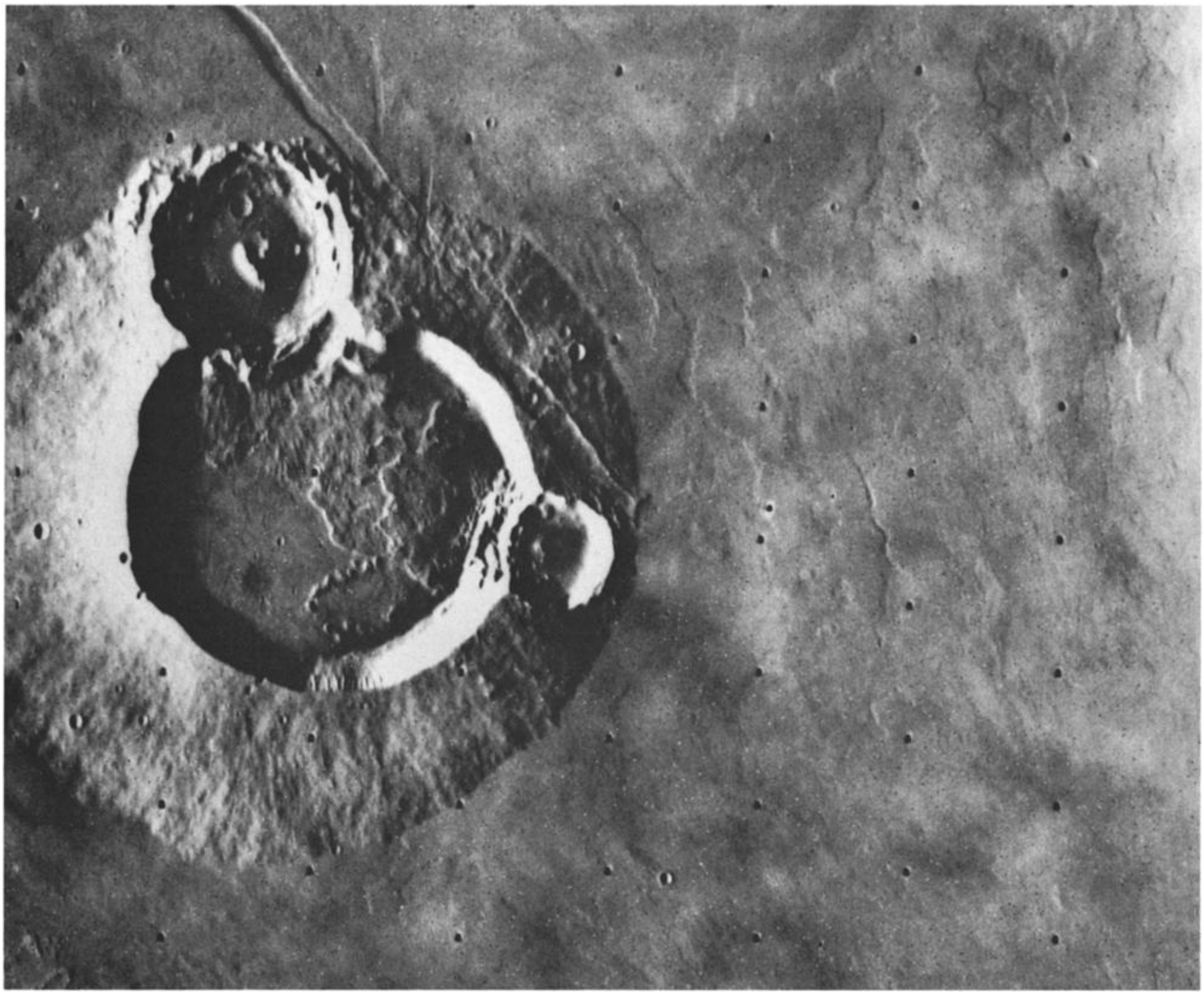

Fig. 2*b*

plains on the eastern flank of the Tharsis rise. The total thickness of volcanic plains material postdating the time of heavy impact bombardment in the central portions of the Tharsis province has been estimated by simple extrapolation from these results; *Plescia and Saunders* [1980] and *De Hon* [1981] estimate that this thickness does not exceed 2 to 5 km. The thickness of volcanic plains units may be estimated independently from the dimensions of partially buried volcanic constructs (Figure 2). A number of the minor paterae of the Tharsis region have been interpreted as partially buried shield volcanoes [*Plescia and Saunders*, 1979*b*; *Greeley and Spudis*, 1981; *Blasius and Cutts*, 1981]. *Pike and Clow* [1981] have estimated that if the visible dimensions of each patera are extrapolated to yield a buried edifice with dimensions similar to those of the Martian montes, then the depths of burial of these paterae are 10–15 km. Pike and Clow, however, rejected these values in favor of the hypothesis that the unburied paterae are smaller than the montes.

Tectonic history. The Tharsis region is the site of the greatest density of large-scale tectonic features on Mars (Figure 1). A great many prominent graben and smaller-scale linear rilles and extensional faults radiate outward from central Tharsis (Figure 3), including the great Valles Marineris canyon system. These features are the product of horizontal extensional stresses that were of largest magnitude in directions generally concentric to the Tharsis topographic rise [*Carr*, 1974; *Blasius et al.*, 1977]. Wrinkle ridges similar to lunar mare ridges also occur in the Tharsis area [*Lucchitta and Klockenbrink*, 1981; *Saunders et al.*, 1981], notably on the ridged plains on the eastern flank of the Tharsis topographic rise (Figure 4). Mare ridges have generally been interpreted as tectonic features resulting from horizontal compressive stresses [*Howard and Muehlberger*, 1973; *Muehlberger*, 1974; *Lucchitta*, 1976, 1977; *Sharpton and Head*, 1981]. The orientations of ridges on the Tharsis ridged plains are generally concentric to the center of the topographic rise [*Wise et al.*, 1979*a*]. Thus the stress field at the time of ridge formation was characterized by horizontal compression, with the greatest compressive stress oriented radially with respect to Tharsis.

At least four major episodes of large-scale extensional faulting in the Tharsis area have been identified on the basis of preserved tectonic features. These tectonic episodes may partially overlap in time and are all closely associated with contemporaneous or nearly contemporaneous volcanic activity. The earliest tectonic episode produced a set of linear faults oriented radially with respect to a center near 40°S, 90°W, in the Thaumasia region [*Frey*, 1979; *Wise et al.*,

Fig. 3. Linear rilles or graben structures in lava plains of the Tharsis region of Mars (38.2°N, 81.3°W). These graben, part of Tempe Fossae, show a variety of widths and orientations, although the major trend is radial to the Tharsis rise. Viking Orbiter frame 627A15, width 75 km.

1979*a*; *Plescia and Saunders*, 1979*a*]. Whether this early fracturing predated or was contemporaneous with formation of the ridged plains units, such as Lunae Planum, is uncertain [*Frey*, 1979; *Wise et al.*, 1979*a*].

The next episode produced a system of extensional fractures generally oriented radially with respect to a center at about 10°S, 100°W, in Syria Planum south of Noctis Labyrinthus, although the majority of preserved fractures formed at this time have approximately north-south strikes [*Plescia and Saunders*, 1979*a*]. This system of faults includes Ceraunius Fossae, the fractures north of Noctis Labyrinthus, portions of Claritas Fossae, and additional faults in Thaumasia and Memnonia. These fractures postdated formation of the ridged plains and were approximately contemporaneous with portions of the cratered plains in the Tharsis area [*Plescia and Saunders*, 1979*a*]; the fractures predated the emplacement of Syria, Sinai, and Solis Planum in southeastern Tharsis and many of the early plains units identified with eruptions from Alba Patera in the north [*Plescia and Saunders*, 1979*a*; *Scott and Tanaka*, 1981*a*].

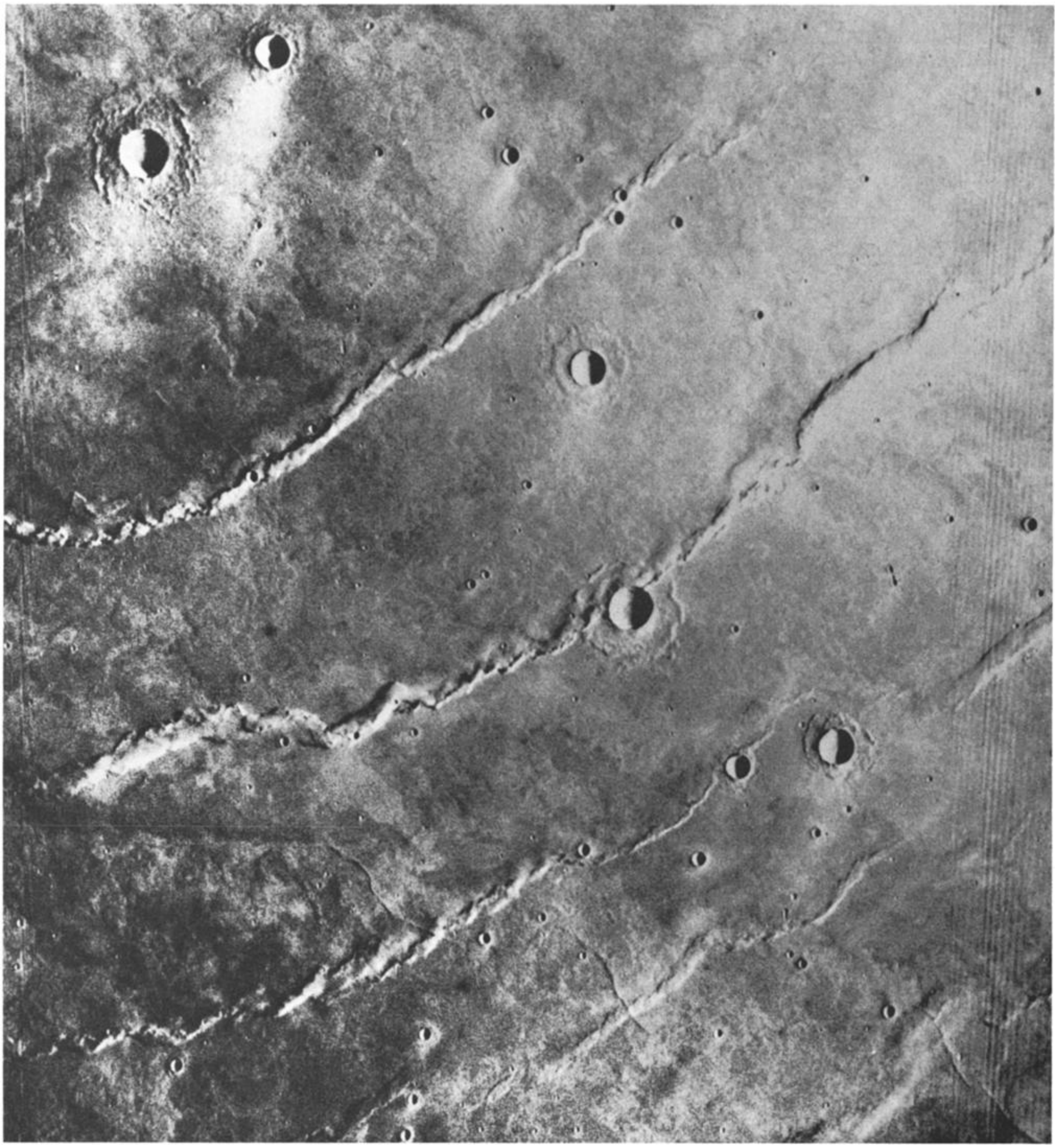

Fig. 4. Mare-type ridges on lava plains in the Tharsis region of Mars (24.9°S, 82.3°W).The geologic unit shown is ridged plains material in eastern Solis Planum. Viking Orbiter frame 608A43, width 225 km.

The third major tectonic episode produced a set of extensional fractures oriented radially with respect to a center at approximately 0°S, 110°W, near the present southeast flank of Pavonis Mons [*Plescia and Saunders*, 1979*a*]. Faulting in this episode produced the Tempe-Mareotis Fossae, most of the Memnonia-Sirenum Fossae, and additional tectonic features in Solis Planum and the Claritas-Thaumasia Fossae region. Formation of the main canyons of Valles Marineris may have also occurred at this time [*Frey*, 1979; *Wise et al.*, 1979*a*; *Masson*, 1980]. The predominant orientation of fractures in this system is northeast-southwest; presumably fractures formed during this episode helped to control the locations of the shield volcanoes of Tharsis Montes [*Wise et al.*, 1979*a*; *Plescia and Saunders*, 1979*a*].

Emplacement of the Tharsis plains was followed by the final episode of extensional tectonic activity [*Plescia and Saunders*, 1979*a*; *Scott and Tanaka*, 1980]. This stage included limited reactivation of faulting on Pavonis-centered graben and formation of additional graben concentric to each of the major volcanic shields. The latter set of faults is the result of loading of the lithosphere by individual volcanic constructs [*Solomon et al.*, 1979; *Comer et al.*, 1980] rather than of the regional stress field of the Tharsis province.

The time of formation of wrinkle ridges, presumably indicative of horizontal compressive stresses, in the Tharsis region is uncertain. These ridges are most prominent on the older ridged plains units in eastern Tharsis [*Saunders et al.*, 1981]. These ridges have been assigned ages both contemporaneous with the main extensional fracture systems of Tharsis [*Wise et al.*, 1979*a*] and prior to the time of most fractures [*Watters and Maxwell*, 1981]. *Sharpton and Head* [1982], however, have shown that many of the ridges may postdate the period of extensional tectonics. *Lucchitta and Klockenbrink* [1981] have also documented the occurrence of young ridges in the Olympus Mons caldera and in situations where cross-cutting relationships indicate that an extended period of time elapsed between plains emplacement and formation of a ridge on the plains unit. We consider the relative ages of ridges and graben uncertain at present; we shall return to the importance of this question below in connection with models for regional stress in the Tharsis area.

Topography and gravity. The topographic and gravity anomalies of the Tharsis province are important elements of the regional geological history. These anomalies, it should be emphasized, reflect only the present structure of the Tharsis province and have likely evolved over geologic time. Topographic maps for Mars have been produced by the U.S. Geological Survey (USGS) from a combination of data from earth-based radar altimetry, spacecraft occultations, Mariner 9 ultraviolet and infrared spectrometers, and spacecraft imaging [*Wu*, 1978]. These maps are traditionally referenced to an equipotential surface of fourth order and degree; this surface has 2 km of relief along the Martian equator, with the highest elevation centered on the Tharsis province [*Wu*, 1978]. For purposes of discussion and quantitative analysis of Tharsis topography, the proper reference surface should be the ellipsoid of hydrostatic flattening, rather than the USGS datum. Subsequent to the preparation of the USGS maps, new earth-based radar observations of the Tharsis region and elsewhere on Mars have been reported by *Roth et al.* [1980], *Simpson et al.* [1982], and *Downs et al.* [this issue]. The new altimetry data for northern latitudes, in particular, indicate that the northern half of the Tharsis rise may be several kilometers lower in elevation than previously inferred [*Downs et al.*, this issue]. These developments warrant a thorough reanalysis of the topography of Mars and of Tharsis in particular. In the absence of such a new analysis, we note only that the total relief of the Tharsis rise (exclusive of the individual volcanic constructs) is presently about 10 km and that the highest elevations are in the area of Syria Planum and Noctis Labyrinthus.

The Tharsis province of Mars is marked by a broad positive free-air gravity anomaly that is reflected primarily in the harmonics of order 2 and 3 in the Martian gravitational potential; the adjacent Chryse and Amazonis Planitia regions are the sites of corresponding free-air gravity lows [*Phillips and Saunders*, 1975; *Phillips and Lambeck*, 1980]. The Bouguer gravity anomaly over Tharsis is negative and large in magnitude, indicating at least partial compensation of the Tharsis topographic rise [*Phillips et al.*, 1973; *Phillips and Saunders*, 1975]. Complete compensation by an Airy isostatic model (variations in crustal thickness) does not occur, particularly at the longest wavelengths [*Phillips and Saunders*, 1975; *Lambeck*, 1979]. Models with complete local isostasy are possible if the compensation involves both crustal thickness variations and mantle density variations to depths of several hundred kilometers [*Sleep and Phillips*, 1979]. At shorter wavelengths, there are also prominent free-air gravity highs associated with the large shield volcanoes of the Tharsis region [*Sjogren*, 1979], indicating that these constructs are incompletely compensated and continue to exert substantial loads on the Martian lithosphere.

UPLIFT MODELS FOR THARSIS

There are several ways to distinguish among the models proposed to account for the geological evolution of the Tharsis province, including the deep regional structure and the nature of the isostatic compensation of topographic relief. The most straightforward distinction is based on the origin of the broad topographic rise. Most models for Tharsis fall into two classes in this regard. In the first class of models, the topographic rise is produced primarily as a result of uplift of the surface by processes in the crust or mantle, and the rise is currently supported by an underlying column of anomalously low density material. In the second class of models, the topographic high is principally the result of volcanic construction, and the rise is partially supported by lithospheric strength. Models invoking a combination of uplift and construction, of course, may also be postulated. We discuss the uplift model first, because all published geological discussions of Tharsis evolution have been based either explicitly or implicitly on variations of this model. Below we shall argue that volcanic construction of the majority of Tharsis topography, including the lithospheric response to the emplacement of volcanic material, fits the available geological and geophysical observations for Tharsis better than models in which topography has been produced primarily by uplift.

In its traditional form [*Carr et al.*, 1973; *Phillips et al.*, 1973; *Hartmann*, 1973; *Carr*, 1974; *Mutch et al.*, 1976; *Wise et al.*, 1979*a*, *b*], the uplift model for Tharsis involves several principal elements, illustrated schematically in Figure 5. Domical uplift of ancient crust, according to the model, is a consequence of a thermal, chemical, or dynamical anomaly in the Martian mantle or crust. As a result of this broad uplift, fracturing of the lithosphere produces the radial systems of graben and extensional faults. Fracturing is followed by volcanic emplacement of plains units that have a total thickness in central Tharsis that is small in comparison with the magnitude of the uplift. The large shield volcanoes form during, and perhaps toward the end of, the period of plains emplacement.

Key pieces of evidence cited in support of the uplift model are the radial pattern of extensional fractures and the roughly domical shape of the broad topographic rise [*Carr et al.*, 1973; *Hartmann*, 1973; *Carr*, 1974]. Carr and Hartmann compare Tharsis to terrestrial examples, generally of smaller scale, of rifted domes or swells initiated by uplift associated with a heating event, a diapir, or an underlying region of upwelling mantle flow.

Additional evidence given in support of uplift, rather than volcanic construction, of Tharsis topography is the presence of hilly and cratered material exposed at the surface of the topographic rise [*Phillips et al.*, 1973; *Mutch et al.*, 1976] and the occurrence of degraded large craters protruding through the younger plains deposits [*Wise et al.*, 1979*a*]; see Figure 1. An implication of this line of argument is that the heavily

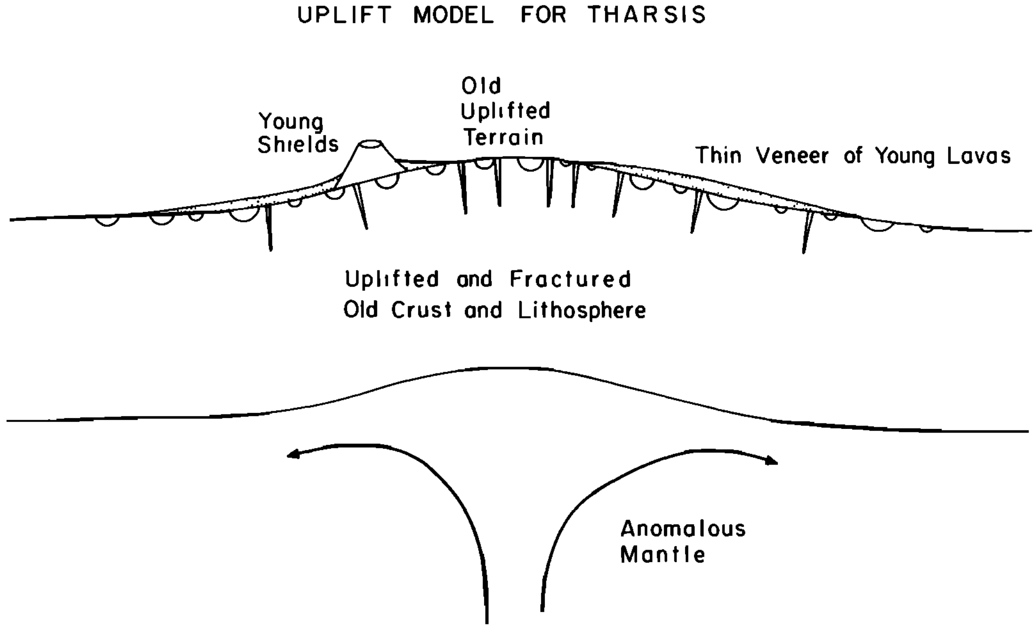

Fig. 5. Schematic view of the uplift model for Tharsis. Ancient lithosphere is uplifted as a result of a thermal, chemical, or dynamical anomaly in the Martian mantle. This uplift leads to fracturing at the surface, volcanic emplacement of thin plains units, and construction of isolated shield volcanoes.

cratered terrain within and surrounding Tharsis either is not of volcanic origin or is a product of geological processes and events which ceased prior to initiation of the tectonic and volcanic activity that contributed to the anomalous character of the Tharsis region [*Wise et al.*, 1979*a*, *b*; *Scott and Tanaka*, 1980; *Plescia and Saunders*, 1980].

A variety of mechanisms have been proposed to produce and to sustain broad crustal uplift in the Tharsis region. Both *Carr* [1974] and *Hartmann* [1973] invoked a mantle plume, or region of convective upwelling, which also provided the heat necessary to fuel the long-lived volcanic activity. *Wise et al.* [1979*a*] postulated that the Tharsis region was uplifted as a result of the underplating of the crust with material subcrustally eroded from the northern lowland plains region of Mars; fracturing occurred during uplift, in their model, by partial detachment and gravity sliding of a surficial brittle layer; the high temperatures and possibly high concentrations of heat-producing elements in the underplating material, according to this scenario, led to surface volcanism following uplift and fracturing. *Wise et al.* [1979*b*], in an elaboration on the underplating idea, suggested that this underplating was localized by the overturn of the Martian mantle during the late segregation of a dense core.

A locally isostatic model to support the Tharsis topographic rise was proposed by *Sleep and Phillips* [1979]. In their model, which accounts only for the present state and not for the origin of the Tharsis high, the topographic relief and an additional subsurface excess mass required by the gravity data are compensated by a low-density mantle extending to depths of at least 300 km. The subsurface excess mass in the model of Sleep and Phillips is assumed to be the result of thinning of crust beneath the Tharsis rise by 50 to 100 km, although volcanic and plutonic emplacement of high-density crustal rocks is a possible alternative to crustal thinning. The required lateral density variation in the Martian mantle, about 0.2 to 0.3 g/cm^3 and sensitive to the thicknesses assumed for the crust and for the low-density mantle layer, may be produced by temperature differences, chemical variations, or both. Possible explanations for chemical differences include variable depletion of the mantle of a basaltic component, incomplete segregation of core material, or variable removal of mantle volatiles [*Sleep and Phillips*, 1979; *Finnerty and Phillips*, 1981].

ASSESSMENT OF THE UPLIFT MODELS

Any physical model for the origin and evolution of the Tharsis province must account for the geological history of the region. In particular, the model must be consistent with the ages and distribution of volcanic units and tectonic features as well as with the present topographic and gravity anomalies. While this information is not sufficient to specify a unique scenario for the development of the Tharsis province, it is sufficient to demonstrate several difficulties for the uplift model as a primary explanation for the history of Tharsis. We discuss these difficulties under three categories: (1) the stress distribution associated with uplift and its relationship to observed fault patterns, (2) the consequences of a thermal mechanism for crustal uplift, and (3) the consequences of a compositional mechanism for crustal uplift.

Stress. As was noted above, the radial pattern of extensional fractures centered on the Tharsis rise has been one of the principal pieces of evidence cited in support of the uplift model, on the basis of similar fracture patterns associated with terrestrial domes [*Hartmann*, 1973; *Carr*, 1974]. Terrestrial uplifts, however, provide poor analogs to Tharsis because of their typically much smaller scale compared with the planetary radius. At such small scales, the stress field produced by lithospheric uplift is dominated by bending stresses. For the long wavelengths of the Tharsis topographic and gravity anomalies, particularly the large anomalies represented by the spherical harmonies of order 2 and 3

[*Phillips and Saunders*, 1975], membrane stresses in the spherical lithospheric shell of Mars dominate the stress field [*Turcotte et al.*, 1981; *Willemann and Turcotte*, 1981]. Lithospheric uplift at the scale of Tharsis leads to membrane stresses of different geometry and sign than the associated bending stresses, and predictions of lithospheric stress based on the lithospheric uplift model are at variance with the observed tectonic features in the Tharsis region [*Willemann and Turcotte*, this issue; *Banerdt et al.*, this issue].

In the calculations of *Willemann and Turcotte* [this issue], the Martian lithosphere is modeled as a thin elastic shell subjected to loads applied from above or below. Tharsis is approximated by a circularly symmetric structure, zonal spherical harmonics are superposed to represent the applied load, and stresses are calculated at the top of the shell beneath the base of the load. Willemann and Turcotte find that if the Tharsis region exerts a radially inward load on the Martian lithosphere, with the magnitude of the load and the thickness of the elastic lithosphere constrained by the amplitudes of the topographic and gravity anomalies over Tharsis, then the calculated stress field would predict extensional fractures radiating from the center of Tharsis over a substantial distance range, consistent with the observed distribution of tectonic features. Uplift of the elastic lithosphere from below, however, would lead to the opposite pattern of stresses, including the prediction of radial compressive features, contrary to observations. A loading model is preferable to a lithospheric uplift model, therefore, as an explanation of the radial extensional fractures of the Tharsis region.

In the calculations of *Banerdt et al.* [this issue], the Martian lithosphere is modeled as a thick elastic shell subject to specified boundary conditions. With this formulation, stresses can be calculated everywhere on the Martian surface as well as within the volume of material constituting the lithospheric load. The topography and gravitational potential associated with Tharsis are represented by the corresponding spherical harmonics of degree and order 4 and below. Three models have been considered: (1) lithospheric uplift in response to a distribution of upward forces, (2) the 'isostatic' model of *Sleep and Phillips* [1979], and (3) a 'flexural' model in which the Tharsis topographic rise exerts a downward load on the elastic lithosphere of Mars. Trajectories for the maximum and minimum horizontal stress at the Martian surface for the flexural model were also shown by *Phillips and Ivins* [1979] and by *Phillips and Lambeck* [1980]. Because these trajectories in the Tharsis area were shown to be broadly orthogonal to mare-type ridges and extensional fractures, respectively, this manner of presentation apparently contributed to the mistaken impression [*Arvidson et al.*, 1980; *Carr*, 1981; *Watters and Maxwell*, 1981] that a single stress model for Tharsis could produce ridges and extensional fractures at similar distance ranges from the center of the topographic rise and, in some regions, could produce generally orthogonal ridges and fractures in the same region. Compressional and extensional tectonic features cannot, of course, be produced by shear failure of the lithosphere [e.g., *Anderson*, 1951] at one location by a single fixed stress field, and the stress trajectories of *Banerdt et al.* [this issue] which display the relative magnitudes of the three principal stresses in a single figure should not lead to such confusion in the future.

Banerdt et al. [this issue] find that the predicted surface stresses for the uplift model show virtually no correspondence to observed tectonic features, in agreement with the conclusion of *Willemann and Turcotte* [this issue]. Both the isostatic and the flexural models are found to predict stresses which match subsets of the observed tectonic features: stresses from the isostatic model provided the best fit for faults within 40° of arc (about 2400 km) from the center of the Tharsis rise, whereas those from the flexural model yielded the best match for tectonic features at greater distance. *Banerdt et al.* [this issue] have suggested that the two models are each appropriate to a different period of Tharsis history.

Many of the details of the stress models of *Willemann and Turcotte* [this issue] and of *Banerdt et al.* [this issue] can be questioned on a number of grounds. The assumption of circular symmetry made by Willeman and Turcotte and the assumption of only long-wavelength anomalies made by Banerdt and co-workers may be oversimplifications, but these approximations should not introduce serious errors for the long-wavelength components of regional stress. The new determinations of topographic heights by earth-based radar [*Simpson et al.*, 1982; *Downs et al.*, this issue] will require that the stress calculations be redone to account for the downward revisions in the elevation of the northern Tharsis rise. A more serious problem is that in both calculations the present topography and gravity are used to constrain models of the stress field that produced ancient tectonic features. The present topography and gravity may be appropriate for modeling the youngest faulting in Tharsis, particularly since the present regional slope directions agree with those determined from the directions of the youngest major lava flows [*Mouginis-Mark et al.*, 1982], but are not necessarily appropriate for the extensive fracturing that predated the emplacement of the Tharsis plains and most or all of the cratered plains as well as the construction of the large shields. The cratered and Tharsis plains units may together contribute several kilometers to the present topographic relief of the central Tharsis rise [*Plescia and Saunders*, 1980; *De Hon*, 1981]. The excess masses associated only with the four largest shield volcanoes [*Sjogren*, 1979] may constitute as much as 25% of the total excess mass of the Tharsis province [*Reasenberg*, 1977]. Thus these contributions to the topography and gravity must be removed before calculating stresses for comparison with the oldest tectonic features. The time-dependent stress models of *Banerdt et al.* [this issue] deserve particular scrutiny; even if the present gravity and topography are approximately correct for one of their preferred models, they are not likely to be valid constraints for the second model presumably appropriate to an earlier period of Tharsis history.

Despite these criticisms of details, the essential conclusion of two independent sets of calculations remains: the stresses predicted by the lithospheric uplift model for the origin of Tharsis do not lead to radially oriented extensional fractures as is observed. Downward loading of the lithosphere by the Tharsis rise is required to account for the distribution of many of these fractures, while an isostatic model may be a preferable explanation for other tectonic features.

Thermal effects. Because of thermal expansion, higher mantle temperatures generally result in more elevated surface topography. The best examples of this process on earth are midocean ridges, which stand several kilometers above the level of the ocean basins because of the much higher temperatures in the uppermost 100–150 km of the mantle

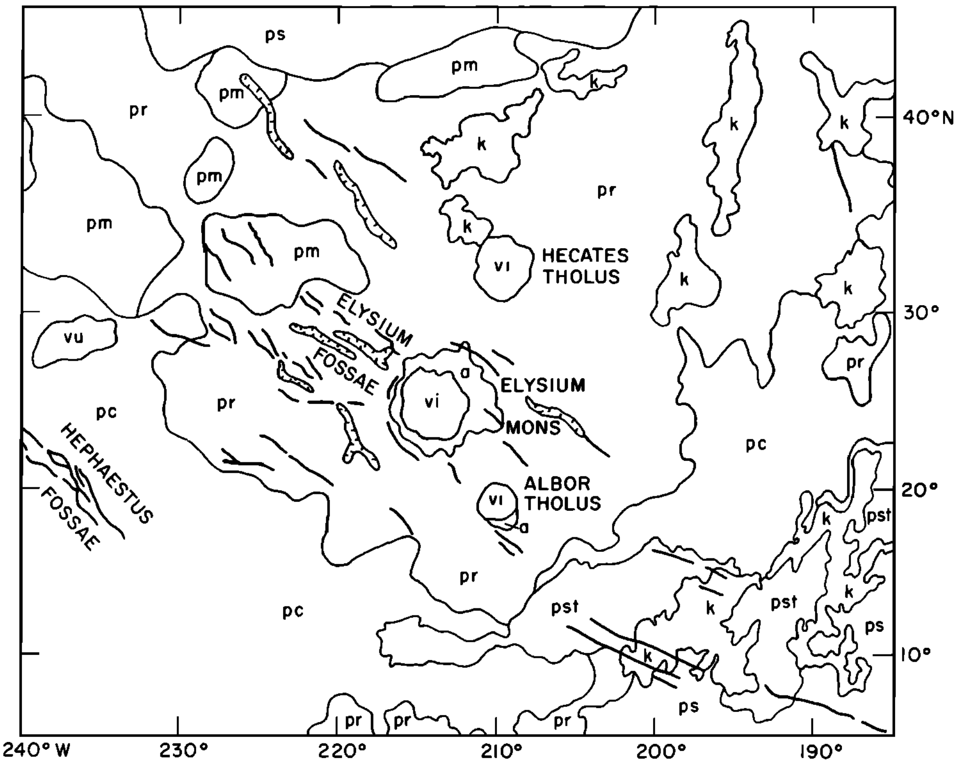

Fig. 6. Geologic map of the Elysium province of Mars, simplified from *Scott and Carr* [1978]. Symbols for tectonic features and abbreviations for geologic units are as in Figure 1. Curvilinear scarps or collapse depressions are shown with inward facing tick marks.

beneath young seafloor [e.g., *Parsons and Sclater*, 1977]. Thermal uplift has similarly been offered as an explanation for the Tharsis rise.

For several reasons, however, heating and thermal expansion are not likely to provide the primary mechanism for the topographic anomaly of Tharsis. Uplift strictly by thermal expansion is essentially an isostatic process, with the elevated topography compensated by the lower density of the underlying mantle [e.g., *Parsons and Sclater*, 1977]. The present gravity anomaly over Tharsis cannot be matched by a model involving only isostatic rise of an otherwise unmodified Martian crust [*Phillips and Saunders*, 1975]; rather a subsurface excess mass is indicated, due either to crustal thinning or to emplacement within the crust of igneous rocks of greater density than the surrounding crustal material [*Sleep and Phillips*, 1979].

If the present Tharsis topographic rise is supported by an underlying mantle of anomalously low density, the required contrast in density with respect to normal mantle may be too large to be strictly a thermal effect. Although the specific density contrast is a function of such details of the model as the thicknesses of the crust and the thermal lithosphere, the lateral contrast is 0.3 g/cm^3 in the model of *Sleep and Phillips* [1979]. Assuming a coefficient of volumetric thermal expansion of 3×10^{-5} °C^{-1}, such a density difference would require a horizontal contrast in the average temperature of the uppermost 300 km of mantle of about 3000°C, a factor of 5 greater than the difference in average temperature in the uppermost 100–150 km of oceanic mantle between midocean ridges and old oceanic lithosphere on earth [*Parsons and Sclater*, 1977], and surely far in excess of that likely to be sustained for billions of years in the mantle of Mars.

Any model for the origin and evolution of the Tharsis province should be considered as well for the Elysium region, the other large volcanic province on Mars [*Carr*, 1973; *Malin*, 1977]. As with the Tharsis region, the Elysium province includes both a topographic rise and a broad positive free-air gravity anomaly [*Sjogren*, 1979]. A series of volcanic plains units spans the province, which also includes several constructs (Figure 6). A number of extensional fractures, many with a northwest-southeast trend, occur within the region. On the basis of crater densities, however, the Elysium province ceased to be volcanically active considerably before the time of the most recent volcanic activity of Tharsis. The Elysium plains are more densely cratered than the Tharsis plains [*Malin*, 1977], and the Elysium volcanic constructs have surfaces older than those of the Tharsis shields [*Plescia and Saunders*, 1979*b*]. While the time of last volcanic activity in Elysium is poorly constrained, the ages of the surfaces of the Elysium volcanoes are similar and are at least 1.0 b.y. according to current competing crater chronologies [*Plescia and Saunders*, 1979*b*]. Despite this great length of time since cessation of volcanism, time during which any thermal anomaly beneath Elysium should have substantially decayed, the topographic rise and the broad gravity anomaly of the Elysium province have persisted. A principally thermal mechanism for the origin of the present topographic rise of Elysium is therefore unlikely.

This discussion does not rule out a limited contribution by thermal expansion to the topographic rise of Tharsis, particularly during the early history of the region. A rough guide to the possible magnitude of this contribution is given by the topographic relief of midocean ridges on earth; in the absence of the oceans, ridges would rise 2 to 2.5 km above the surrounding abyssal plains [*Parsons and Sclater*, 1977]. Because this amount of thermally induced relief on earth requires that near-melting temperatures extend almost to the surface, we regard 2 km as a reasonable limit to the contribution of thermal effects to the relief of the Tharsis rise at any stage in the history of the province.

Compositional effects. Support of the Tharsis rise by density differences between the crust or mantle beneath Tharsis and those of adjacent areas could also be accomplished, in principle, by lateral variations in composition. *Wise et al.* [1979*a*, *b*] have proposed that lighter crustal material from the northern hemisphere of Mars was transported by mantle convective flow to the region over a zone of downwelling initiated by core infall. 'Underplating' of the sub-Tharsis crust, by this scenario, led to a permanent isostatic rise of the Tharsis region. Since isostatic crustal thickening involves simply the replacement of mantle material with a greater volume of crustal material, the subsurface excess mass required by gravity and topographic data [*Phillips and Saunders*, 1975] is not explained by this model.

The isostatic model of *Sleep and Phillips* [1979], as was noted above, involves a large anomaly in the density of the mantle beneath Tharsis, relative to adjacent regions, and a crust either thinner or denser than average for the planet. The long-term stability of such a lateral density contrast extending to depths of several hundred kilometers against the mixing effects of mantle convective flow has not been addressed. The only compositional mechanism explored quantitatively to date to account for the proposed density model is depletion of the sub-Tharsis mantle of its low-melting-point, presumably basaltic, component [*Finnerty and Phillips*, 1981]. Finnerty and Phillips have suggested, for instance, that removal by partial melting of 30% of the uppermost 140 km of mantle beneath Tharsis would decrease the mantle density sufficiently to produce a 10-km topographic rise. The volcanic extrusives or plutonic intrusives removed from the mantle after such an episode of partial melting would have a total thickness of 40–50 km. The isostatic model by this mechanism cannot therefore be attained until after a vast outpouring of volcanic material, reaching a total thickness far in excess of the present topographic relief. The Finnerty-Phillips model predicts that the crust beneath the Tharsis rise would be thicker than average, in contrast to the thinned crust suggested by *Sleep and Phillips* [1979], unless much of the basaltic component of the mantle beneath Tharsis was emplaced volcanically in regions adjacent to Tharsis [*Phillips et al.*, 1981]. We regard this last suggestion as unsupported by the geological history of the Tharsis province summarized above. Despite the emphasis of *Finnerty and Phillips* [1981] on the support of the Tharsis rise by chemical variations in the Martian mantle, their model has some strong similarities to the model of *Solomon and Head* [1980*b*], elaborated below, in which the Tharsis rise is dominantly a product of volcanism.

Summary. The lithospheric uplift model for Tharsis [*Carr et al.*, 1973; *Phillips et al.*, 1973; *Hartmann*, 1973; *Carr*, 1974] fails to predict lithospheric stresses in agreement with the observed pattern of fractures and ridges. The isostatic model of *Sleep and Phillips* [1979] can account for some of the observed tectonic features [*Banerdt et al.*, this issue], but only if at least a large fraction of the required mantle density anomaly is nonthermal in origin. The only nonthermal mechanism explored quantitatively [*Finnerty and Phillips*, 1981] requires as a first step the emplacement of tens of kilometers of volcanic material in the Tharsis region. A downward load on the Martian lithosphere is necessary to explain at least some of the observed tectonic features in the Tharsis province [*Willemann and Turcotte*, 1981; *Banerdt et al.*, this issue]. Thus areally extensive and voluminous igneous activity is a required element for both a loading model and the Finnerty-Phillips isostatic model. In the next section we show that volcanic construction, lithospheric loading, and lithospheric failure in response to load-induced stresses are widespread and interlinked processes on Mars. We then present a physical model for the evolution of Tharsis in which these same processes largely account for the geological history of the Tharsis province.

LOADING AND LITHOSPHERIC FLEXURE ON MARS

The eruption of volcanic deposits on a planet generates a load on the underlying lithosphere. The flexure of the lithosphere in response to loads of lateral extent small in comparison with the planetary radius is a strong function of the effective thickness of the upper elastic portion of the lithosphere. Stresses generated as a result of such flexure can exceed the strength of brittle lithospheric material, leading to failure. The processes of volcanic loading, flexure, and failure are well known on the earth [e.g., *Walcott*, 1976; *Watts*, 1978; *McNutt*, 1980], particularly in oceanic regions where the apparent thickness of the elastic lithosphere is inversely proportional to the mean thermal gradient in the uppermost tens of kilometers of the oceanic plate [*Caldwell and Turcotte*, 1979; *Watts et al.*, 1980]. These processes are also well documented on the moon, where volcanic deposits in the circular mascon maria have loaded the lunar lithosphere to levels sufficient to produce failure in response to induced bending stresses [*Solomon and Head*, 1980*a*].

Volcanic units similarly exert loads on the lithosphere of Mars. The loads produced by the youngest major volcanic constructs must be at least partially supported by the finite strength of the Martian lithosphere, since these constructs are sites of prominent positive free-air gravity anomalies [*Sjogren*, 1979]. The circumferential graben surrounding many of these constructs (e.g., Elysium Mons in Figure 6) indicate that brittle failure has occurred in response to load-induced stresses, acting to reduce the magnitude of stresses supported by finite strength. The Olympus Mons shield, in contrast, has a gravity anomaly sufficiently large that almost no compensation of the load has occurred in the time since the volcano formed [*Thurber and Toksöz*, 1978; *Comer and Solomon*, 1981].

By combining knowledge of the loads of individual volcanic constructs inferred from measured excess masses [*Sjogren*, 1979] with the positions of circumferential graben in response to those loads [*Scott and Carr*, 1978], we have estimated the thickness of the elastic lithosphere of Mars beneath a number of volcanic features at the time of graben formation [*Solomon et al.*, 1979; *Comer et al.*, 1980]. A map of the inferred thicknesses is shown in Figure 7. The figure presents strong evidence for the existence of lateral variations in the thickness of the elastic lithosphere of Mars. In particular, there appears to have been a dichotomy in lithospheric thickness that was insensitive to load age. Thin (25–50 km) elastic lithosphere is indicated for the regions immediately surrounding large shield volcanoes in the later

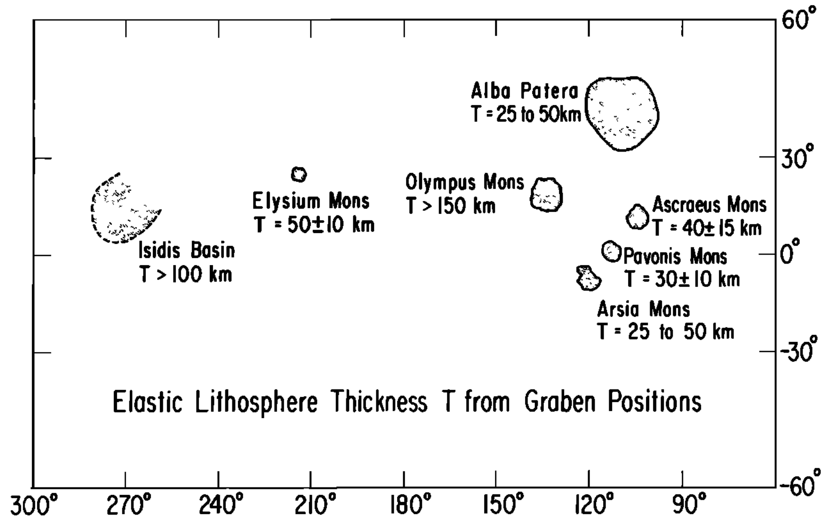

Fig. 7. Estimates of the thickness of the elastic lithosphere beneath major volcanic loads on Mars from the radial distance of prominent circumferential graben, from *Comer et al.* [1980]. The thicknesses shown correspond to the time at which the respective graben formed.

stages of activity in the Tharsis and Elysium volcanic provinces. By contrast, a thick elastic lithosphere (>100 km) is indicated for regions at greater distances from volcanic province centers, including the areas surrounding both the comparatively older Isidis mascon [*Sjogren*, 1979] and the geologically more youthful Olympus Mons shield [*Thurber and Toksöz*, 1978; *Comer and Solomon*, 1981].

The regions on Mars of locally thinnest elastic lithosphere, and by implication of greatest near-surface thermal gradients, are thus also the regions of most recent major volcanic activity and the centers of the best developed fracture systems. The moon similarly displays contemporaneous heterogeneities in lithosphere thickness and near-surface thermal gradients that correlate strongly with tectonic and volcanic activity [*Solomon and Head*, 1980*a*] and, at earlier times, with the extent of ring development in multiring basins [*Head and Solomon*, 1980] and the subsequent viscous relaxation of basin topographic relief [*Solomon et al.*, 1982]. We believe that lithospheric heterogeneity on Mars played an essential role in the development and sustained activity of the Tharsis province.

THARSIS AS A CONSEQUENCE OF LITHOSPHERIC FAILURE AND VOLCANIC CONSTRUCTION

In view of the difficulties encountered by the various uplift models for the origin and evolution of the Tharsis province, we have been led to propose an alternative physical model [*Solomon and Head*, 1980*b*] that is compatible with the geological history of the region, the pattern of tectonic features, and the present topographic and gravity anomalies. We invoke for this model geological processes that are evident in the Tharsis region and elsewhere on Mars, namely, volcanic construction, lithospheric loading, and lithospheric failure caused by load-induced stresses. The unusually large scale and duration of Tharsis volcanic and tectonic activity are attributed to the influence of lithospheric heterogeneity early in the history of Mars. In this section we describe our model for the evolution of the Tharsis region in greater detail. We note several testable consequences of this model, and we refute objections to this model that have appeared in the literature. Finally, we enumerate several advantages of the model presented here that are not all shared by Tharsis evolutionary models previously proposed.

Tharsis evolutionary model. The starting premise of the model is that the effective thickness of the elastic-brittle lithosphere of Mars was laterally heterogeneous early in Martian history, just as it was during the later era represented by Figure 7. Stresses produced on global or regional scales would then be greatest in the regions of thinnest lithosphere, and fracturing in response to those stresses would likewise be concentrated in such regions. Possible sources of stress on global scales include thermal stress associated with planetary warming or cooling [*Solomon*, 1978] and changes in lithospheric shape associated with changes in spin rate [*Melosh*, 1977] or polar wander [*McAdoo and Burns*, 1975; *Melosh*, 1980]. Sources of stress on regional scales include loading [*Solomon et al.*, 1979; *Comer et al.*, 1980] and local thermal stress [*Bratt et al.*, 1981], among others.

In a region of anomalously thin lithosphere, the concentrated fracturing produced by enhanced lithospheric stress would increase the accessibility of mantle-derived magma to the planetary surface. Regions of concentrated fracturing should also therefore be regions of enhanced volcanic activity. Intense igneous activity would serve to maintain anomalously high temperatures at shallow depths and therefore a locally thin lithosphere. The region would continue to be the preferred site for fracturing in response to global lithospheric stress or to the additional local stresses generated by volcanic loading. Thus once a region of locally thin lithosphere develops, fracturing and volcanism can maintain the lithospheric heterogeneity for as long as such activity continues.

We hypothesize that Tharsis was the site of locally thin lithosphere dating from a time before the end of heavy bombardment. Elysium was a similar region of either a lesser horizontal scale or a lesser magnitude anomaly in lithospheric thickness. The concentration of lithospheric stress in the Tharsis and Elysium regions led to extensive

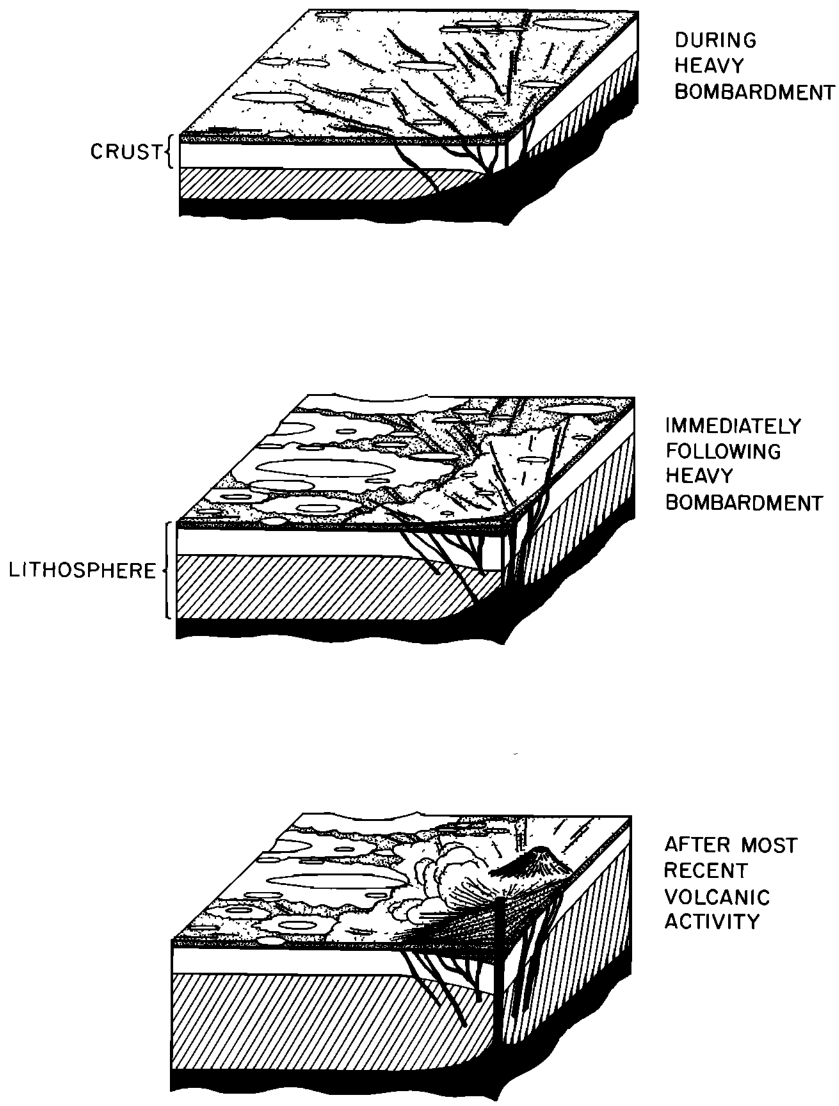

Fig. 8. A schematic illustration of the evolution of the Tharsis province of Mars according to the model presented in this paper. The most ancient crust of Mars is shown as white, the mantle portion of the lithosphere as cross hatched, and the underlying asthenosphere as black. Volcanic units are shown as shaded, except where disrupted by impact craters and basins. Surficial fractures and magma source vents are also sketched. Note that volcanic activity dates from before the end of heavy bombardment, according to the model, and that Tharsis persists as an area of thickened crust and locally thinned but broadly loaded lithosphere for an extended period of time.

fracturing and closely associated volcanism, which served to maintain the lithosphere locally thin by positive feedback. Volcanic deposits contributed successively to the topographic rise in each region. Each episode of widespread volcanic activity altered both the magnitude and the geometrical distribution of the lithospheric load. The stresses generated by each stage of volcanic loading were partially relieved by lithospheric failure and regional subsidence and were partly supported by the finite strength of the elastic lithosphere. A schematic illustration of the evolution of the Tharsis region, according to this hypothesis, is shown in Figure 8.

The thickness of the elastic lithosphere of Mars has increased with time as the planet has cooled. As the lithosphere thickened, the levels of topographic relief and lithospheric load that could be supported by lithospheric strength have increased. During the earliest history of widespread volcanism in the Tharsis province the lithosphere of Mars may have been relatively thin. The response of the lithosphere to volcanic loading would have been that of a thin plate or shell and would have been indistinguishable from local isostatic compensation by crustal subsidence. Later in the history of Tharsis, a thickened lithosphere would have been capable of supporting a fraction of additional volcanic loads by regional flexure and lithospheric strength. The broad topographic rise of Tharsis, according to this scenario, is presently supported by a combination of local compensation by crustal thickening and finite strength of a globally thick Martian lithosphere.

It is important to distinguish between the average thickness of the Martian lithosphere and the locally smaller thickness beneath the central portions of Tharsis (Figure 8). Because the principal wavelengths of the Tharsis topographic anomaly are comparable to the radius of the planet, support of the Tharsis load by finite lithospheric strength involves the global lithospheric shell. Local heterogeneities in lithospheric thickness, even beneath the central portions of the Tharsis rise, affect this global support only slightly [*Willemann and Turcotte*, this issue]. A terrestrial example of lithospheric support of a load in the vicinity of locally thinned lithosphere is the Hawaiian island-seamount chain. Models for the flexure of the Pacific lithosphere in response to the load of the Hawaiian chain provide a better fit to the amplitude and characteristic width of the lithospheric subsidence if the elastic plate is regarded as broken along the axis of the chain [*Walcott*, 1976]. The Hawaiian islands are supported regionally by the finite strength of the Pacific plate despite the break in the lithosphere because the dominant wavelengths in the load are large in comparison with the width of the break. Similarly, a globally thick lithosphere on Mars can support those components of the Tharsis load with wavelengths much larger than the characteristic widths of heterogeneities in lithospheric thickness.

Even beneath the central region of the Tharsis rise, the thickness of the elastic lithosphere increased with time (Figure 8). So, too, did the thickness of the thermal lithosphere, or the depth to sources of mantle-derived magma. This thickening may account for later volcanic shield formation and for the great heights of the youngest shields [*Carr*, 1976].

Although the model presented here emphasizes volcanic construction and the response of an evolving Martian lithosphere to continued volcanic loading, it is worth noting that other processes may also contribute support for the Tharsis topographic rise during the evolution of the province. A thinner lithosphere beneath central Tharsis (Figure 7) implies a thermal contribution of up to 1 or 2 km to the topographic relief, with this contribution probably decreasing with time. If depleted mantle material remains localized beneath Tharsis as suggested by *Finnerty and Phillips* [1981], then there may be an additional chemical component of mantle support for the Tharsis rise after volcanism has progressed to the point where a substantial fraction of basaltic material has been extracted from the upper mantle beneath the province.

A question we are unable to answer at this time is the reason why the locations of the Tharsis and Elysium provinces were sites of anomalously thin elastic lithosphere early in Martian history. Both provinces approximately straddle the boundary between the southern uplands and the northern lowland plains, but the significance of this arrangement, if any, is far from clear. It is noteworthy that the Tharsis province may occupy the site of a large multiring impact basin [*Schultz and Glicken*, 1979], since the formation of such basins involves substantial subsurface heating and lithospheric thinning [*O'Keefe and Ahrens*, 1977; *Bratt et al.*, 1981]. For the arguments presented in this paper, however, the cause of the initial lithospheric heterogeneity is not crucial. Heterogeneities in near-surface thermal gradients have been well documented, as was noted earlier, for the moon during and shortly after the era of heavy bombardment and for Mars at a later stage in its evolution. The model for Tharsis proposed here requires only that laterally heterogeneous thermal gradients also existed on Mars during the earliest history of the planet.

Implications of the model. There are a number of implications of the Tharsis evolutionary model depicted in Figure 8. Several of these may be testable by future measurements of Martian surface properties or subsurface structure.

It follows immediately from the model proposed in this paper that the remnants of ancient terrain preserved on the surface of the Tharsis rise (i.e., the patches of hilly and cratered material in Figure 1) are of volcanic origin. The present surface of such terrain, because of the extensive cratering that has occurred since its emplacement, may consist predominantly of impact breccias and associated soils rather than of volcanic rocks and soils as on the younger volcanic plains, but such breccias should contain igneous clasts diagnostic of an ancient volcanic surface. The literature of Tharsis abounds with terms associating heavily cratered terrain in the Tharsis region with a nonvolcanic origin; *Scott and Tanaka* [1980, 1981*a*, *b*], for instance, refer to 'terra' and 'basement rocks' while *Plescia and Saunders* [1980] use the terms 'cratered basement' and 'nonvolcanic bedrock.' These terms may be rooted in an unstated inference, based perhaps on an analogy to the earth's moon, that the cratered uplands on Mars originated by processes very different from those which produced the younger plains. We do not believe that such an inference can presently be made. To the contrary, the widespread evidence for a volcanic origin for the cratered plateau material [*Wilhelms*, 1974; *Scott and Carr*, 1978; *Greeley and Spudis*, 1978, 1981; *Scott and Tanaka*, 1981*b*] throughout the southern uplands (e.g., Figure 1) supports the hypothesis that the heavily cratered units contained within the Tharsis rise may also be of volcanic origin.

If the Tharsis rise formed primarily by volcanic construction, then the preservation of ancient surfaces within the rise indicates that much of this volcanic construction occurred before the end of heavy bombardment. The Tharsis volcanic flux, by this view, was largest at a very early period of Martian history and had decreased by a time shortly after heavy bombardment. The thickness of volcanic plains postdating heavy bombardment in the central region of the Tharsis province, estimated by *Plescia and Saunders* [1980] and *De Hon* [1981] to be several kilometers, thus represents the product of only this later stage of Tharsis volcanic activity.

Because of subsidence of the Martian lithosphere in response to the Tharsis volcanic load, particularly in the earliest phase of high volcanic flux, the total thickness of volcanic deposits beneath the Tharsis rise is far in excess of the 10 km of large-scale topographic relief. The total thickness may be estimated from gravity and topographic data under one or more assumptions about deep structure. Under the assumption that the Martian crust is of uniform density and variable thickness, *Bills and Ferrari* [1978] derived crustal thickness profiles across portions of Tharsis and Elysium as shown in Figure 9. According to their results, the crust is 35 to 50 km thicker beneath the 10-km Tharsis rise than beneath adjacent areas and 15 to 25 km thicker beneath the 5-km Elysium rise. By the Tharsis evolutionary model of Figure 8, this excess crustal thickness consists primarily of volcanic constructional material, perhaps with a contribution as well from intrusive igneous material. A 35- to 50-km value for crustal thickening beneath central Tharsis compares favorably with the estimate of 50 km for the thickness of the Tharsis load derived by *Willemann and Turcotte* [this issue] from their lithospheric loading model for the same crustal density as assumed in the *Bills and Ferrari* [1978] calculation.

The lithospheric stresses that led to fracturing in the

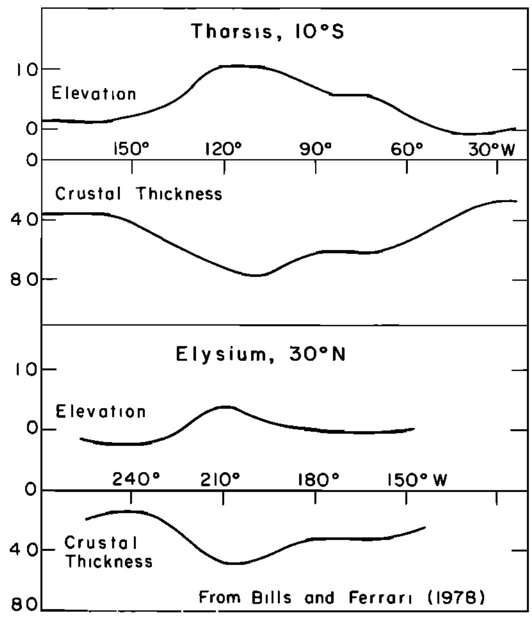

Fig. 9. Profiles of regional elevation and total crustal thickness across Tharsis (along latitude 10°S and Elysium (along latitude 30°N), from *Bills and Ferrari* [1978]. The profiles are taken from their spherical harmonic representation of topography and crustal thickness based on an assumed crustal density of 2.9 g/cm^3, a mantle density of 3.5 g/cm^3, and a global mean crustal thickness of 40 km.

Tharsis region, for the model presented here, are primarily the result of the lithospheric response to loading, perhaps augmented by additional global-scale stresses produced by planetary thermal expansion, polar wander, or spin rate changes. On these grounds the model of Figure 8 is broadly consistent with the loading model of *Willemann and Turcotte* [this issue] and with the isostatic and loading models of *Banerdt et al.* [this issue]. Because the earliest preserved fracture systems, the fractures radial with respect to a center in a heavily cratered region in Thaumasia [*Frey*, 1979; *Wise et al.*, 1979*a*; *Plescia and Saunders*, 1979*a*], either predate or were contemporaneous with nearby ridged plains units, the emplacement of early Tharsis volcanic deposits must have been sufficient to cause lithospheric failure at least by the time of ridged plains formation and possibly earlier. Thus the age of fracturing, in combination with the interpretation that fracturing was a consequence of volcanism, also supports a Tharsis history in which extensive volcanic construction occurred before the end of heavy bombardment.

An important aspect of the model for Tharsis proposed here is the magnitude of shear stresses that must be maintained in the Martian lithosphere. Early in the history of the Tharsis province, we have argued, the response of the lithosphere to volcanic loads was likely that of nearly local isostatic compensation, so that the required shear stresses were only those associated with isostatic support of topographic relief. At present, considerably larger stress differences are required to support the Tharsis rise at least partly by lithospheric strength. *Willemann and Turcotte* [this issue] and *Banerdt et al.* [this issue] have estimated that the lithospheric stress differences predicted by their loading models are about 2 kbar for a 200-km thickness of the present elastic lithosphere of Mars. Such levels of deviatoric stress are thought to be maintained for extended periods of time in terrestrial lithosphere subjected to volcanic loading or bent in the process of subduction, except near the surface where stress is relieved by brittle failure [e.g., *Watts et al.*, 1980; *McNutt*, 1980; *Brace and Kohlstedt*, 1980]. That stress differences of 2 kbar could be maintained for geologically long periods of time in the elastic lithosphere of Mars, except for near-surface regions where shear stresses in excess of brittle strength have been relieved by fracture, is therefore not unreasonable.

The long-wavelength gravity anomalies of Mars are well matched by models, including the one proposed here, in which the Tharsis rise presently exerts a load on the lithospheric shell of Mars [*Willemann and Turcotte*, this issue; *Banderdt et al.*, this issue]. The global response of the Martian lithosphere to the long-wavelength load accounts for the broad flanking gravity lows in Chryse and Amazonis as well as the Tharsis high [*Willemann and Turcotte*, this issue]. An implication of a loading model, in contrast to the isostatic models of *Sleep and Phillips* [1979] and *Finnerty and Phillips* [1981], is that net mass has been transferred to the Tharsis region from the mantle beneath regions elsewhere on Mars. The most likely explanation for such a net transfer of material is that the Martian mantle beneath the lithosphere is subject to solid state convection [e.g., *Young and Schubert*, 1974; *Toksöz and Hsui*, 1978; *Solomon et al.*, 1981]. Because of this mantle convection, the parcel of mantle that provides magma for one volcanic eruption may be well removed from Tharsis at a later geologic epoch when renewed eruptions extract magma from a different volume of mantle. The accumulated result of such convective processes may be the depletion of basaltic magma for Tharsis volcanism from a volume of upper mantle considerably larger than that beneath Tharsis at present. The total volume of volcanic material in the Tharsis province may thus appear gravitationally as an excess mass.

A general observation for the one-plate planets [*Solomon*, 1978] of the inner solar system is that the surface flux of volcanic material was much higher in the early history of a planet than in the later stages of evolution [e.g., *Head and Solomon*, 1981]. This same trend of generally decreasing volcanic flux with time is seen for Tharsis, according to the model proposed here. A volcanic origin for the cratered plateau material and a high volcanic flux for the early Tharsis province are both at least partly consequences of the thermal evolution of Mars from an initial state in which temperatures were sufficiently high in the outer portion of the planet to form a global crust prior to the end of heavy bombardment [e.g., *Solomon et al.*, 1981]. The thickening of the Martian lithosphere with time and the evolving response of the lithosphere to volcanic loads are also consequences of the global thermal history.

Objections to the model. Shortly after the first presentation of this scenario for the evoluation of the Tharsis province [*Solomon and Head*, 1980*b*], the model was criticized by *Plescia and Saunders* [1980], who based their objections on four arguments: (1) color maps of the Martian surface [*Soderblom et al.*, 1978] indicate a pronounced difference between heavily cratered and younger volcanic units within the Tharsis rise but no difference between heavily cratered units in the Tharsis region and similar units elsewhere on Mars; (2) there is no physiographic evidence for a volcanic origin for heavily cratered terrain in the Tharsis area; (3) the Tharsis volcanic region would have been active for an extremely long time and would have been spatially more extensive in its earlier stages than in its more recent stages; (4) there may be a gap in time, on the basis of crater density, between heavily cratered terrain and the mapped volcanic units in the Tharsis province. We do not regard these arguments as valid objections to the model for Tharsis evolution proposed here.

Soderblom et al. [1978] noted distinctive color variations in the southern equatorial cratered terrain which they attributed to local lithologic variations. The color differences between heavily and lightly cratered units within Tharsis may result from differences in volcanic composition or may simply reflect differing degrees of impact breccia formation, regolith formation, or chemical weathering rather than substantive differences in the mode of origin of the units. A volcanic origin for all heavily cratered terrain on Mars, in fact, is not precluded by these data.

The lack of physiographic features diagnostic of a volcanic origin presumably refers only to the hilly and cratered material in Figure 1, since the cratered plateau materials do retain such volcanic features as flow fronts and constructs [*Wilhelms*, 1974; *Scott and Carr*, 1978; *Greeley and Spudis*, 1978, 1981; *Scott and Tanaka*, 1981*b*]. As sufficiently heavy cratering would be expected to obliterate such features, their lack on the oldest surfaces on Mars does not permit the conclusion that volcanic features were never present.

The conclusion that Tharsis volcanic activity, by our scenario, lasted over the exceedingly long time interval from before the end of heavy bombardment 3.8 b.y. ago to as recently as a few hundred million years ago [*Schaber et al.*, 1978; *Plescia and Saunders*, 1979*b*] is valid. We do not regard this conclusion as an objection to our model, however, and we have outlined a sequence of events that can account for such an extended history. The inference that Tharsis volcanic activity in its early stages occurred over an area much broader than that of more recent volcanic plains emplacement is also correct. Rather than an objection to the model, this result is a natural consequence of the waning of the Tharsis volcanic flux and the general thickening of the Martian lithosphere with time following the earliest widespread activity.

The final objection of *Plescia and Saunders* [1980] is based on an apparent gap in the relative surface ages of Tharsis units as measured by crater density. Even if an age gap (i.e., between cratered plateau material and ridged plains material) is real, the length of time represented by such a gap may be short by geological standards. The rate of crater formation decreased very sharply at the end of heavy bombardment [e.g., *Neukum and Wise*, 1976; *Soderblom*, 1977; *Hartmann*, 1977; *Wise et al.*, 1979*a*], so that the density of preserved craters on surfaces formed just before and just after that time would differ substantially. Expressed in terms of the 'crater number,' or the total number of craters of diameter 1 km and greater per 10^6 km^2, *Wise et al.* [1979*a*] give 50,000 and greater for the time of establishment of the hemispherical asymmetry of Mars and 20,000 and less for the emplacement of ridged plains volcanic units. This apparent gap, however, represents a time interval of only 100–150 m.y. according to the various curves of crater density versus age given by *Wise et al.* [1979*a*], and a few surfaces with intermediate values for the crater number are shown in map view by Wise and co-workers for units indicated as cratered plateau material by *Scott and Carr* [1978]. An age difference of 100–150 m.y. is comparable to that between major eruptions in lunar maria [e.g., *Solomon and Head*, 1980*a*] and need not signify a fundamental change in the nature of operative volcanic processes. Similarly, any gap in time between heavily cratered material (much of it volcanic) and the next oldest volcanic units in the Tharsis province may not have been any longer than other subsequent time intervals between major volcanic eruptive episodes.

Advantages of the model. The model for the evolution of the Tharsis province proposed in this paper has several advantages not shared by many or all of the models previously proposed. Because the topographic high associated with the region is primarily constructional and is presently supported by lithospheric strength, the topographic rise and the associated positive gravity anomaly are permanent features, in contrast to models in which uplift is caused by thermal or dynamical anomalies in the Martian mantle. This statement would also apply to the Elysium province if the evolution of that region followed the model proposed here for Tharsis. The concept of stress concentration in an elastic lithosphere locally thinned by elevated near-surface thermal gradients provides a natural explanation for the association and localization of lithospheric fracturing and volcanic activity in distinct provinces. The response of the lithosphere to volcanic loads dominates the stress field and gives rise to the systems of prominent fractures, in agreement with recent calculations [*Willemann and Turcotte*, this issue; *Banerdt et al.*, this issue].

A major distinction between the explanation for the Tharsis province offered here and all earlier explanations [e.g., *Carr et al.*, 1973; *Phillips et al.*, 1973; *Hartmann*, 1973; *Carr*, 1974; *Wise et al.*, 1979*a*, *b*; *Sleep and Phillips*, 1979; *Finnerty and Phillips*, 1981] is that no special or anomalous properties need to be ascribed to the mantle beneath major Martian volcanic provinces for extended periods of time. The location of volcanism on Mars is governed primarily by the sites of easiest access of magma to the surface. In this respect, Tharsis and Elysium may be similar to midocean ridges on the earth. The Mid-Atlantic Ridge and the East Pacific Rise are major planetary volcanic centers and are nearly stationary in a hot spot reference frame [*Morgan*, 1972; *Minster et al.*, 1974; *Solomon et al.*, 1975], yet no anomalous characteristic is attributed to the mantle beneath them. The mantle beneath terrestrial midocean ridges plays a passive rather than an active role [cf. *Sengör and Burke*, 1978]; volcanism occurs at ridges more readily than elsewhere because the lithosphere is locally thin and is subjected to continuing fracture and extension. According to the scenario presented in this paper, the Martian mantle similarly plays a passive role beneath Tharsis. Continued volcanism is a consequence of a locally thin lithosphere subjected to extensional fracturing and not to a chemical or dynamical anomaly sustained for billions of years beneath the Tharsis province.

CONCLUDING DISCUSSION

We have proposed a physical model for the history of the Tharsis province of Mars incorporating zones of locally thin lithosphere capable of concentrating stress and lithospheric failure, closely associated volcanism and fracturing that maintained the lithosphere locally thin by positive feedback, and an evolving topographic construct built by the successive addition of volcanic units and presently supported by a globally thick lithosphere. This model invokes geological processes that are evident at smaller scales in a number of areas on Mars and does not require special chemical or dynamical characteristics to persist in the mantle beneath the Tharsis province for billions of years. The model—which may be applicable as well to the Elysium province—is capable of accounting for the extended history of volcanic and tectonic activity in the Tharsis area, the general distribution of tectonic features, and the presently observed topographic and gravity anomalies.

It should be repeated that even though most of the topographic rise of Tharsis is attributed here to volcanic construction and most of the fracture-producing stress is attributed to the response of the lithosphere to loading, it is likely that some type of uplift mechanism may have also played a contributing role in the evolution of the region. A thinner elastic lithosphere in the central areas of Tharsis and Elysium implies steeper near-surface thermal gradients and therefore a contribution from thermal expansion to the Tharsis and Elysium topographic rises over at least some portions of the history of each province. Further, extraction from the Martian mantle of the large volumes of lava required to build the topographic rises of Tharsis and Elysium will have altered the density of the residual source regions [*Finnerty and Phillips*, 1981], also contributing some amount of uplift for an uncertain length of time.

It is vital at this stage in our understanding of the tectonic and volcanic history of Mars to test as fully as possible the competing models for the evolution of the Tharsis province, including the model proposed in this paper. Several profitable lines of further investigation can be identified. It will be important to build upon the work of *Wise et al.* [1979*a*], *Frey* [1979], *Plescia and Saunders* [1979*a*], and *Scott and Tanaka* [1980, 1981*a*] to determine in detail the relative ages of all major tectonic features and volcanic units. Particularly significant will be ages of the mare-type ridges in ridged plains units (Figure 4) and in areas where ridges and graben are both present [e.g., *Watters and Maxwell*, 1981; *Sharpton and Head*, 1982]. Since ridges and graben cannot be produced by shear failure in one location by the same stress field, a time-dependent stress field is required. The time dependence may be associated with the evolution of Tharsis [e.g., *Banerdt et al.*, this issue] or may be contributed by a superposed time-variable global stress field, such as that associated with planetary thermal stress [*Solomon*, 1978; *Solomon and Head*, 1980*a*].

To predict the stress field due to loading at the time of formation of prominent fracture systems, it will be necessary to remove the contributions of younger loads to the present topographic and gravity anomalies. The work on estimating the thicknesses of individual volcanic units from the rim heights of partially buried craters [*Plescia and Saunders*, 1980; *De Hon*, 1981] or from the dimensions of partially buried volcanoes [*Pike and Clow*, 1981] will be especially valuable in this effort. Once the history of the Tharsis load is estimated, then further stress calculations of the sort reported by *Willemann and Turcotte* [this issue] and *Banerdt et al.* [this issue] should be carried out to test proposed models for Tharsis against the tectonic features formed between times of major changes in the load distribution. It may be necessary to include the effects of lithospheric heterogeneity (Figure 7) in these calculations. Because the Elysium province may share many aspects of its history with the Tharsis province, these tests should be carried out for the Elysium region as well.

The themes of lithospheric heterogeneity, volcanic loading, and vertical tectonics have general validity throughout the terrestrial planets [*Head and Solomon*, 1981]. Only the large horizontal scale and extended duration of activity distinguish Tharsis from most other regions of volcanism and faulting on the moon and Mars and in intraplate areas on earth. An interesting question left to further investigations is whether the physical model for Tharsis proposed here can sharpen the hypotheses for the origin and evolution of such similarly large-scale volcanic and tectonic provinces on other bodies as Oceanus Procellarum on the moon [*Head et al.*, 1980] or Beta Regio on Venus [*McGill et al.*, 1981].

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