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The Evolution of Volcanism, Tectonics, and Volatiles on Mars: An Overview of Recent Progress

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Among the principal accomplishments of the MEVTV project are several important and widely accepted scientific findings about Mars. The global and regional volcanic flux has been established from systematic geological mapping using Viking images, providing a relative volcanic chronology for most of martian history. Petrologic and chemical analyses of SNC meteorites, inferred to have been derived from Mars, have revealed an abundance of volatile materials, including hydrous minerals (amphiboles), oxidized sulfur, possible carbonates, and various salts; these results provide direct evidence that Mars is likely to be volatile-rich. Geological mapping and temporal groupings of major fault systems have provided strong new constraints on the sequence and timing of martian tectonic events, particularly in the vicinity of the Tharsis region. Substantial progress was also forthcoming on several fundmental but incompletely resolved aspects of martian evolution during the MEVTV program. The origin of the crustal dichotomy on Mars was the subject of intensive investigations, and two classes of hypotheses have emerged: One relates the northern lowlands to the effects of large impact(s); the other calls for tectonic foundering subsequent to subcrustal erosion by mantle convection. The kinematics and mode of formation of wrinkle ridges are the subjects of continuing research. While it is clear that these features represent compressional deformation, whether they are predominantly the expression of buckling or faulting remains problematic, as do the cause and implications of their remarkably straight trends and periodic spacing in some locales. Isotopic and petrologic analyses have revealed significant variations within the group of SNC meteorites that, if these objects come from Mars, suggests heterogeneous sources for the parental martian magmas. Finally, several intriguing new ideas have resulted from project-sponsored research and workshop discussions. A number of tectonic features have been identified as probable transcurrent faults documenting horizontal offsets of at least several tens of kilometers. Such faulting, along with the large extensional strains required to form Valles Marineris, could indicate an early episode of significant horizontal motions of lithospheric blocks. One speculative hypothesis is that such motions were accommodated in a very early episode of plate tectonics on Mars, during which the original lithosphere of the northern lowlands was subducted beneath the Tharsis region and new lithosphere with thinner crust was generated at a now-extinct spreading center. This hypothesis, which remains to be tested rigorously, links the formation of the crustal dichotomy to the formation of Tharsis.

INTRODUCTION

Mars has been the target of a number of ambitious spacecraft missions, including the American Viking orbiters and landers in the late 1970s and, more recently, the Soviet Phobos spacecraft in 1989. Soon after the Viking mission it became clear that data from that mission would constitute a long-term source of important information about the nature and evolution of Mars. In recognition of this potential, NASA established the Mars Data Analysis Program (MDAP) in 1979 to coordinate the funding and the direction of Mars research. The first of several major thematic investigations supported by MDAP was a focused three-year study project entitled "Mars: Evolution of its Climate and Atmosphere" (MECA), initiated in 1984 under the direction of the Lunar and Planetary Institute in Houston, Texas. The success of the MECA project (*Clifford et al.,* 1988a,b) led to a follow-on three-year study project entitled "Mars: Evolution of Volcanism, Tectonics, and Volatiles" (MEVTV), initiated by NASA in 1987, also under the direction of the Lunar and Planetary Institute.

The organization of the MEVTV project was styled after that of the successful MECA project. It combined elements of a project approach and targeted research by independent investigators. Specific goals and objectives were defined from the project perspective, but investigators were funded individually and operated independently within the context of the study. The first meeting of the MEVTV project was held in the spring of 1987, where a science steering committee was chosen and general guidelines for the project were defined. Participation in MEVTV was open to all investigators with research interests encompassed by the goals of the project, regardless of funding source, to ensure broad-based involvement. A program of workshops was organized to provide cohesion to the project and to ensure that the project's objectives would be addressed (Table 1). The MEVTV project provided a rich environment for collaborative efforts between investigators from very diverse fields of investigation, often resulting in new approaches to difficult problems related to the study of Mars.

TABLE 1. MEVTV workshops.

Name Of Workshop	Date
Nature and Composition of Surface Units on Mars	December 1987
Volcanism on Mars	June 1988
Early Tectonic and Volcanic Evolution of Mars	October 1988
Tectonic Features on Mars	April 1989
Tharsis	October 1989
Evolution of Magma Bodies on Mars	January 1990
Special Sessions on Martian Tectonic, Volcanic, Magmatic, and Surface Evolution at LPSC XXI	March 1990

This article reviews the research highlights of the MEVTV study project and discusses some of the important scientific issues that remain unresolved. Detailed treatments of several of the subjects discussed here appear in the papers following this article. Some of the questions brought to the attention of the community through the MEVTV project are now the focus of a new three-year study project entitled "Martian Surface and Atmosphere Through Time" (MSATT), which was initiated by NASA in the spring of 1990.

OBJECTIVES OF THE MEVTV PROJECT

The objectives of the MEVTV project were to outline the volcanic and tectonic history of Mars, to determine the influence of volatiles on martian volcanic and tectonic processes, and to attempt to determine the compositional, thermal, and volatile history of Mars from its volcanic and tectonic evolution.

The scientific rationale for the project was based on the recognition that Mars is the only planet other than the Earth that has had a long volcanic and deformational history that could be studied in detail. The Moon and Mercury became inactive relatively early in their history, and there was then insufficient information to make appropriate comparisons with Venus. Earth's deformational and volcanic history is dominated by plate tectonics, which has tended to obscure and destroy much of its early record. In contrast, plate tectonics was not thought to have occurred during Mars' decipherable history. Volcanic and deformational features on Mars were held to be well-preserved products of the chemistry and long-term dynamics of the relatively deep mantle rather than the result of thin-skinned tectonics. Furthermore, surficial erosional processes have been relatively modest, causing many ancient structures to display only minor degradation. For these reasons Mars was regarded as providing an environment in which volcanic and deformational processes could be studied in a relatively simple tectonic framework in contrast to Earth, where most geologic features are the result of the complex and destructive interaction of many processes.

At the outset of the project, the nature, type, and distribution of martian volcanic and tectonic features had been broadly established. Much work had also been done on the nature of the volcanic activity on the planet. For example, the styles of volcanic activity and possible rheological properties of the erupted lavas had been inferred from studies of the morphology and dimensions of volcanic features. Similarly, the global patterns of deformation were reasonably well understood. The development of the hypothesis that Mars may be the parent body of the SNC meteorites (shergottites, nakhlites, and Chassigny) had been recently developed. Enough was then known about the SNC meteorites to begin to influence our way of thinking about many aspects of Mars, including its bulk composition, oxidation state, differentiation history, thermal history, magma generation capability, volatile inventory (including degassing history), volcanism, weathering, and cratering. What was lacking at the start of the MEVTV project was detailed information on how the volcanic and tectonic activity changed with time (requiring careful analysis of age relations by crater counts and geometric relations); systematic integration of information from the SNC meteorites into studies of martian magmatism and global evolution; and a full understanding of the implications of the volcanic, tectonic, and volatile histories for the evolution of the martian crust and interior.

Following are scientific tasks that were identified prior to the MEVTV project as important and achievable with existing data. It was recognized that some progress had already been made on most of these tasks, but most of the effort to that time had involved data reduction more than analysis or synthesis. The general approach adopted was to use available datasets (e.g., photogeology, topography, gravity) to test general models of the volcanic and tectonic history of Mars. The specific tasks were to:

1. Determine the locations and relative ages of volcanic features and trace the history of emplacement of volcanic materials on the surface.

2. Determine changes in the pattern of faulting with time by such means as crosscutting structural relations and crater density statistics.

3. Define and test models of the current state of stress in the martian lithosphere using gravity and topography data.

4. Use fault patterns to infer past states of stress in the lithosphere and how the stresses may have changed with time.

5. Use the stress history within the lithosphere and the volcanic history to place limits on the thermal history of the interior and internal dynamics.

6. Examine the nature and possible causes of the global dichotomy on Mars, with particular emphasis on modeling the topography and gravity.

7. Relate the stress history to the volcanic history and infer how the thickness and other properties of the lithosphere have evolved with time.

8. Assess reasons for the contrasting styles of martian and terrestrial volcanism, particularly the apparent longevity and large size of martian volcanos and the possible role played by volatiles in the eruption process.

9. Compare the vertical deformation and faulting of broad crustal regions of Mars with broad structural uplifts and basins in the interior of lithospheric plates on Earth.

10. Determine to the extent possible the composition of magmas related to volcanic materials, the source reservoirs, and the processes responsible for magma migration to those reservoirs.

11. Investigate the relationship between atmosphere-surface interactions and volcanism during the period of time when surface morphology suggests a substantially different volatile regime.

12. Determine the effect of quasiperiodic (e.g., axial changes) and episodic processes (e.g., volcanism) on the near-surface thermal regime, and on the exchange of volatiles among the atmosphere, regolith, and polar caps.

SCIENTIFIC OVERVIEW OF THE MEVTV PROJECT

The Global Volcanic and Tectonic Evolution of Mars

Important progress was made during the MEVTV project on documenting the geological evidence for the volcanic and tectonic history of Mars. Also advanced during the course of the project were the formulation and testing of models for mantle dynamics, magmatism, and interior evolution consistent with this geological history. While a number of hypotheses for martian evolution have been considerably sharpened as a result of these efforts, it is perhaps not surprising that many fundamental questions remain at best incompletely answered.

The crustal dichotomy. The approximately hemispherical division of the martian surface between the topographically lower and stratigraphically younger northern plains and the heavily cratered southern uplands is often termed the crustal dichotomy. The difference in elevations of the two hemispheres appears to be isostatically supported by differences in average crustal thickness (*Janle,* 1983). The 2.1-km offset of the center-of-figure from the center-of-mass on Mars can be explained by the contributions of a nearly compensated Tharsis rise and an isostatically compensated crustal dichotomy. The direction of this offset, toward 58°S, 94°W (*Kobrick et al.,* 1981), is approximately midway between the centers of the southern highlands and the Tharsis rise (*Roth et al.,* 1981). The ancient age of the southern uplands suggests that the dichotomy was largely established very early in martian geological history, although erosion may have modified the dichotomy boundary over a considerable period of time (*Maxwell and McGill,* 1988).

Two classes of hypotheses have been offered for the origin of the dichotomy. In one class, the northern lowlands are held to occupy one or more large impact basins. In the first discussion of this idea (*Wilhelms and Squyres,* 1984), the largest expanse of lowlands was proposed to result from the formation of a single large impact basin 7700 km in diameter, the "Borealis Basin." This hypothesis was held to account for the approximately circular planform and scarp-like morphology of much of the dichotomy boundary, the concentric massifs and narrow tracts of highlands not related to other basins, the thinned lowland crust, and the heat required for lowlands plains volcanism. A modification of the single-impact hypothesis is that the northern lowlands occupy several large impact basins, on the grounds that the proposed Borealis Basin is much larger than the few next-largest recognized basins (*Frey and Schultz,* 1988) and that high-standing cratered terrain as ancient as the cratered uplands can be found within the proposed basin interior (*Frey et al.,* 1988). Buried topography in the Utopia Planitia region of the northern lowlands indicates the presence of a 3300-km-diameter buried basin (Fig. 1), which is less than half the size of the proposed Borealis Basin (*McGill,* 1989b). The large impact hypothesis, whether single or multiple impacts were involved, has been criticized as inconsistent with the absence of evidence for crust substantially thicker than average beneath the rim and inner ejecta blankets of the postulated large basins, with an early Hesperian peak in global volcanic activity (i.e., substantially after the time of basin formation; *Tanaka et al.,* 1988), and with the fact that stratigraphic units partially filling the lowlands and embaying highland units include nothing older than early Hesperian (*McGill,* 1989a).

In the second class of hypotheses the crustal dichotomy is the product of tectonic processes. According to the first specific scenario suggested (*Wise et al.,* 1979b), the northern regions foundered isostatically after subcrustal "erosion" by a first-degree mantle convection pattern that prevailed prior to core formation. Planetary accretion considerations (*Wetherill,* 1985) and Pb isotope systematics in the Shergotty parent body (*Chen and Wasserburg,* 1986), presumed to be Mars (e.g., *McSween,* 1984; *Bogard et al.,* 1984) as discussed below, now indicate that core-mantle differentiation on Mars occurred very early, perhaps contemporaneously with planet formation. The suggestion has recently been made (N. H. Sleep, unpublished data, 1989) that the lowlands lithosphere was produced during an early episode of plate tectonics on Mars. Such a hypothesis provides an explanation for the large horizontal displacements of the lithosphere inferred from the opening of Valles Marineris and the interpretation of Gordii Dorsum and other related ridges as large-offset transcurrent faults (*Forsythe and Zimbelman,* 1988). It has been speculatively suggested that the Phlegra Montes, centrally located in the northern lowlands, may have been a spreading center that ceased activity by the Late Noachian and that the Tharsis Montes originated by arc-type volcanism at a Noachian subduction zone (*Tanaka,* 1990b; N. H. Sleep, unpublished data, 1989).

Martian volcanic flux. The volcanic flux on Mars as a function of space and time provides a critical constraint on models of mantle dynamics, global thermal evolution, mantle melting, and crustal growth. While the relative chronology of large-scale surface units on Mars was reasonably well established on the basis of stratigraphic and crater density relationships inferred from Mariner 9 images (*Carr et al.,* 1973; *Scott and Carr,* 1978), detailed analysis of the tens of thousands of higher-resolution Viking orbiter images has led to a new global geological map of substantially improved stratigraphic resolution (*Tanaka,* 1986) and unit definition (*Scott and Tanaka,* 1986; *Greeley and Guest,* 1987; *Tanaka and Scott,* 1987). From this analysis, several noteworthy characteristics of the history of emplacement of volcanic material at the martian surface have been documented (*Tanaka et al.,* 1988; *Tanaka,* 1990b). The global rate of volcanic resurfacing generally declined from levels near 1 km^2/yr in the Middle Noachian to on the order of 0.01 km^2/yr in the Amazonian (Fig. 2), presumably reflecting a general cooling of the martian mantle from an initial state sufficiently hot to permit very early differentiation of core and crust. Superimposed on this gradual decline, however, was an apparent peak in volcanic resurfacing rate in the Early Hesperian, with the strength of the peak a function of the uncertain rate of production of impact craters over the past 3.5-4 b.y. and the uncertain proportion of Noachian volcanic material (Fig. 2). Most of the Early Hesperian peak consists of the areally extensive ridged plains units, thought to have

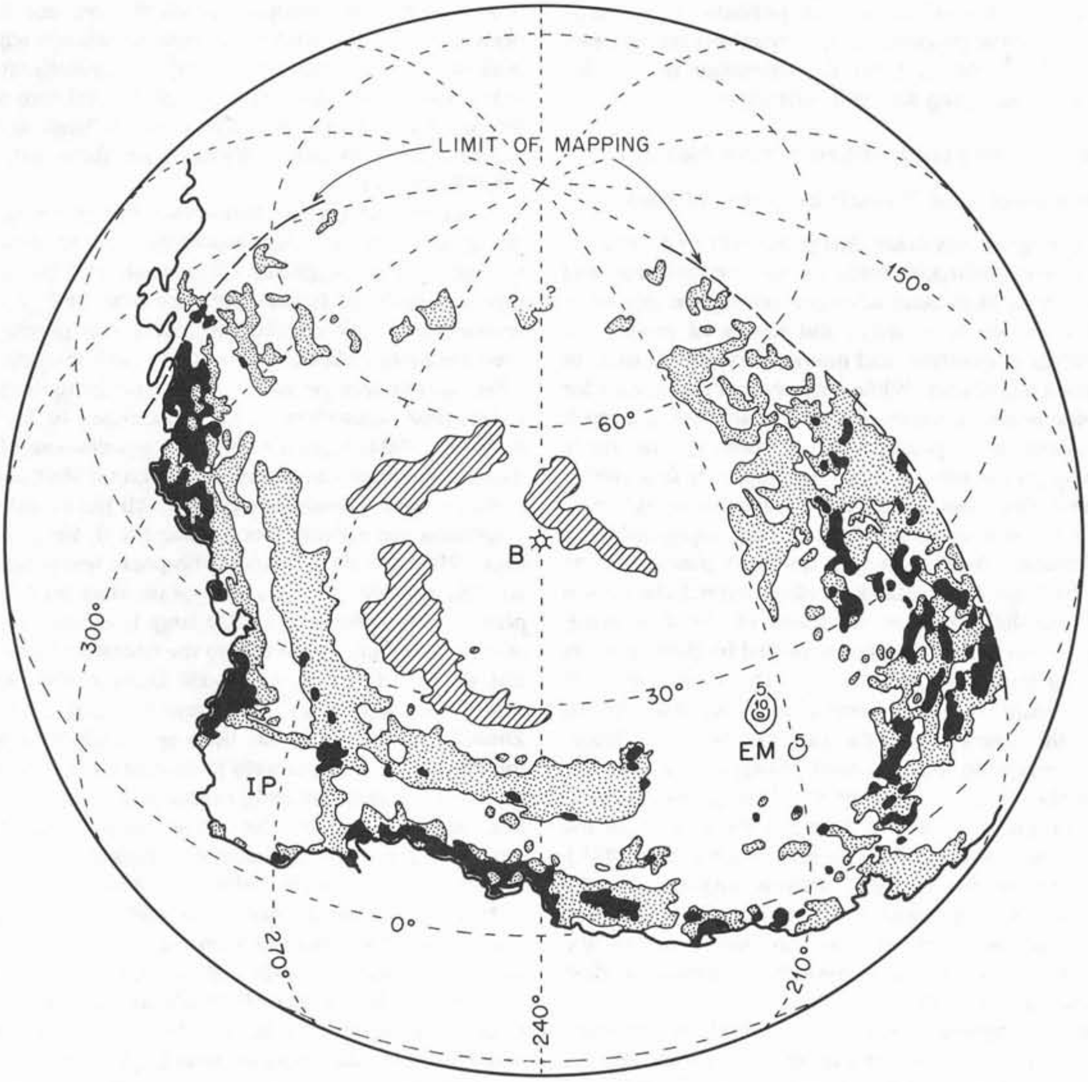

Fig. 1. Distribution of knobs indicating the presence of a buried impact basin in Utopia Planitia (from *McGill,* 1989b). Solid shading, abundant knobs and mesas; stippled shading, scattered knobs; diagonal shading, polygonal terrain. IP, Isidis Planitia; EM, Elysium Mons; B, estimated center of Utopia Basin. The heavy solid line is the boundary between the southern cratered highlands and the northern lowlands. (Figure reproduced with permission of American Geophysical Union.)

formed by the voluminous eruptions of low-viscosity, mafic lavas (*Greeley and Spudis,* 1981). At the end of the Early Hesperian, the spatial pattern of volcanism changed dramatically from one of globally dispersed activity to regionally concentrated plains formation and large shield construction focused in the Tharsis and Elysium areas. Igneous and tectonic activity in these major volcanic provinces apparently led to breakouts of debris flows and catastrophic floods that carved the outflow channels in adjacent lower lying terrain, discharges that eroded extensive areas of highlands, contributed to the resurfacing of the northern plains, and redistributed a significant fraction of subsurface water on the planet (*Tanaka,* 1990b).

Accounting for this history of volcanic flux with quantitative models of martian thermal evolution and interior dynamics remains a topic of ongoing effort and controversy. *Stevenson and Bittker* (1990) have drawn attention to the potential for the extraction of basaltic melt from the martian mantle to stabilize convection because of the strong reduction in the density of the mantle residuum, which they argue would likely reside in an upper boundary layer. These authors suggest that such a stabilizing effect could lead to long intervals in which volcanism is modest to absent while the interior warms and distinct layers develop in the convecting mantle. Gradual merging of convecting layers would lead to an episode of widespread volcanism; extraction of significant melt from the

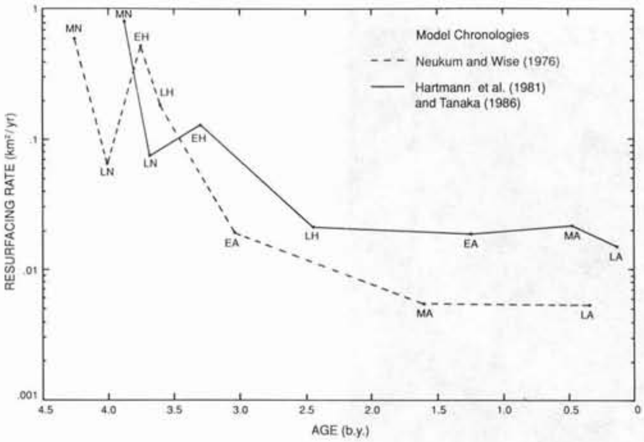

Fig. 2. Average resurfacing rates for volcanic plains corresponding to each martian epoch (modified from *Tanaka et al.,* 1988). Rates are based on the reconstructed areas of volcanic plains for two crater chronologies. Note the corrected resurfacing rates (reduced by a factor of 1000) from those of *Tanaka et al.* (1988). Martian epochs: MN, Middle Noachian; LN, Late Noachian; EH, Early Hesperian; LH, Late Hesperian; EA, Early Amazonian; MA, Middle Amazonian; LA, Late Amazonian.

mantle during this episode would initiate a new cycle. This viewpoint has been challenged by *Turcotte and Huang* (1990), who assert that the residuum remaining after melt extraction would be well mixed into the convecting mantle, leading to a "marble-cake" structure rather than a stably layered system. In their models and in other parameterized convection calculations (e.g., *Schubert et al.,* 1990b), global heat flow, mean mantle temperature, and the average rate of addition of magma to the crust all decrease monotonically with time. The general history of volcanism on Mars is one of a gradually decreasing flux (*Tanaka et al.,* 1988), consistent with the predictions of parameterized convection models, but the apparent peak in flux during the Early Hesperian may be an example of mantle warming of the type predicted by the *Stevenson and Bittker* (1990) scenario.

Accounting for the localization of volcanic activity on Mars to a few major volcanic provinces after the Early Hesperian remains a challenge to theoretical models. The long duration of activity and the excess heat flux implied by the thinning of the elastic lithosphere in the center of major volcanic provinces (*Solomon and Head,* 1990) indicate that the excess heat is being supplied from the underlying mantle, presumably in the form of localized regions of enhanced upwelling, or mantle plumes. Numerical calculations of three-dimensional convection in a viscous spherical shell have been recently carried out by *Schubert et al.* (1990a) to simulate possible convective planforms in a martian mantle heated both from within (by radiogenic heat) and from below (by core cooling). These calculations support the view that the most prominent form of convective upwelling in the martian mantle is the cylindrical plume, but the models yield a large number of plumes (more than 10) unless both an unreasonably large fraction of heat is supplied from the core and the core radius is considerably smaller than inferred from the present martian moment of inertia (*Bills,* 1989; *Kaula et al.,* 1989). While some aspects of these results may be consequences of the assumptions required in current three-dimensional convection codes (constant viscosity mantle, Rayleigh numbers no more than about 100 times the critical value), the concentration of sustained volcanic activity in Tharsis and Elysium may have arisen from the focusing of multiple plumes beneath each province, perhaps as a result of thinning and fracturing of the lithosphere by earlier tectonic activity in each region.

Martian tectonic history. The Tharsis province of Mars, by virtue of its large scale and its complex and extended history of activity (*Carr,* 1974; *Wise et al.,* 1979a), dominates the discussion of martian tectonic 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 (*Phillips and Saunders,* 1975). Swarms of extensional fractures and graben extend outward from Tharsis for thousands of kilometers in a crudely radial array (*Plescia and Saunders,* 1982). There are also important compressional features located in the ridged plains of Tharsis and oriented approximately circumferential to the center of activity (*Wise et al.,* 1979a). The duration of faulting and volcanic activity represented by the tectonic and volcanic features of Tharsis span a large fraction of martian history. The long-wavelength gravity and topography of the region are not consistent with complete isostatic compensation by a single mechanism, such as crustal thickness variations (*Phillips and Saunders,* 1975). Complete local isostasy is possible, however, if a combination of Airy (crustal thickness variations) and Pratt (mantle density variations) mechanisms act in concert, but only if the crust is relatively thin (or is pervasively intruded by high-density plutonic material) beneath the Tharsis rise and substantial density anomalies persist to several hundred kilometers depth (*Sleep and Phillips,* 1979, 1985; *Finnerty et al.,* 1988). Alternatively, a portion of the high topography of Tharsis can be supported by membrane stresses in the martian elastic lithosphere (*Banerdt et al.,* 1982; *Willemann and Turcotte,* 1982).

These compensation models can be used to predict long-wavelength lithospheric stresses for comparison with the observed distribution of tectonic features. The situation at the outset of the MEVTV project was that the isostatic model for Tharsis predicted stresses in approximate agreement with the distribution and orientation of extensional fractures in the central Tharsis region and of compressive wrinkle ridges, while the model involving lithospheric support of a topographic load predicted stresses generally consistent with the more distal extensional features (Fig. 3) in regions adjacent to the Tharsis rise (*Banerdt et al.,* 1982; *Sleep and Phillips,* 1985). An evolution in the nature of the support of Tharsis topography was suggested (*Banerdt et al.,* 1982; *Solomon and Head,* 1982), though it was recognized that a sequence of distinct support models depends upon the distal and proximal tectonic features having different ages. If the distal features were older, then viscoelastic relaxation of stresses associated with an early episode of lithospheric loading might have led to an essentially

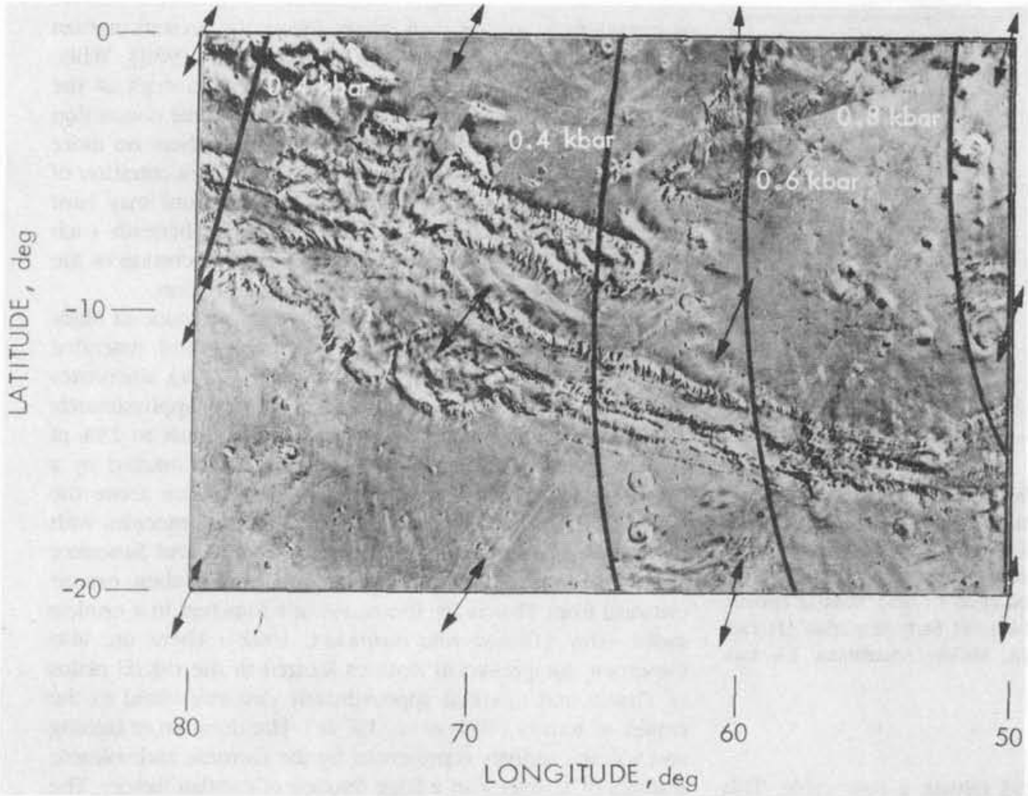

Fig. 3. Prediction of surface stress trajectories in the Valles Marineris region from a Tharsis flexural loading model (after *Banerdt et al.,* 1982). The greatest extensional stress is horizontal and approximately orthogonal to Valles Marineris. Contours of stress magnitude are in kilobars.

isostatic state at present; if the distal features were younger, then a progression from local isostasy to lithospheric support as the Tharsis rise was constructed might have been the natural consequence of global interior cooling and lithospheric thickening (*Sleep and Phillips,* 1985).

Recent geological mapping and detailed studies, as part of the MEVTV project, of the history of faulting in the Tharsis province and surrounding areas have provided a wealth of new constraints on possible evolutionary models for the region. The earliest recognized set of faults, dating from the Early Noachian, are east-west trending normal faults and graben in the Claritas Fossae region (*Tanaka and Davis,* 1988). These faults are among the few tectonic features in the Tharsis province that are orthogonal to extensional stress directions predicted by flexural uplift models for Tharsis (*Banerdt et al.,* 1982) and support an early episode of large-scale uplift of the region (*Tanaka and Davis,* 1988; *Phillips et al.,* 1990). During the Noachian and Hesperian, major systems of extensional fractures and graben formed in patterns predominantly radial but also concentric to a series of areas within central Tharsis (*Wise et al.,* 1979a; *Plescia and Saunders,* 1982; *Tanaka and Davis,* 1988). The principal episode of formation of wrinkle ridges, oriented generally concentric to Tharsis (*Wise et al.,* 1979a), occurred shortly after ridged plains emplacement in the Early Hesperian (*Scott and Tanaka,* 1986). Because the major episodes of faulting during the Late Noachian to Hesperian involve nearly contemporaneous formation of features both distal and proximal to central Tharsis, neither the isostatic nor the lithospheric flexure models of *Banerdt et al.* (1982) provide an adequate fit to the full distribution of faulting during any single tectonic episode.

Several promising directions have been identified to improve on existing models for the tectonic evolution of Tharsis and of Mars in general. First, it is important to distinguish faulting associated with localized centers of uplift and subsidence from that associated with the long-wavelength stress distribution across Tharsis, and ongoing mapping efforts provide a basis for such a separation (*Tanaka and Davis,* 1988). Second, it is necessary to explicitly include global thermal stress. The Early Hesperian age for most major ridged plains units (*Tanaka,* 1986) and the contrast between the widespread occurrence of wrinkle ridges in the ancient cratered uplands and their spotty occurrence in volcanic plains younger than Early Hesperian (*Chicarro et al.,* 1985) suggest that ridge formation may have been concentrated in a comparatively early stage in martian evolution (*Watters and Maxwell,* 1986), perhaps dominantly in the Early Hesperian (see below). Examination of crosscutting relations between ridges and graben also supports the view that most ridge formation in the Tharsis region was restricted to an early time period (*Watters and Maxwell,* 1983). Martian thermal histories calling for a hot initial state and rapid cooling concentrated within the period

3-4 b.y. ago (*Schubert et al.,* 1990b; *Turcotte and Huang,* 1990) are most consistent with an Early Hesperian episode of global contraction and widespread wrinkle ridge formation.

Finally, it appears that lateral variations in heat flux and crustal thickness across Tharsis have led to pronounced horizontal variations in the mechanical properties of the lithosphere (*Solomon and Head,* 1990) that can have a significant effect on stress models (*Banerdt and Golombek,* 1990). Specifically, the thicker crust and higher heat flow in the central Tharsis region may act to decouple the crust in that region from the underlying strong layer of the upper mantle. In such a situation the strong upper mantle layer will deform as part of the globally continuous elastic lithosphere shell, some 100-200 km thick (*Banerdt et al.,* 1982; *Willemann and Turcotte,* 1982; *Solomon and Head,* 1990), while the comparatively thin layer of strong upper crust in central Tharsis will deform as a spherical cap with a lubricated lower surface and a periphery fixed to the global shell. Preliminary models (*Banerdt and Golombek,* 1990) suggest that the central area will respond primarily to isostatic spreading forces and increases in radius of curvature induced by subsidence of the lower lithosphere, leading to radial extensional structures in central Tharsis, while outside of the central region of crust-mantle decoupling the faulting will generally follow the predictions of the earlier flexural models for the formation of distal radial extensional fractures (Fig. 3). Horizontal radial compression, leading to the formation of concentric wrinkle ridges, is likely to be concentrated near the boundary between the two regions (*Banerdt and Golombek,* 1990).

Martian Magmas and Their Weathering Products

A primary goal of studying volcanic materials is to place constraints on the composition and the physical conditions of the source magmas. As noted above, a unique group of basaltic achondrites, known collectively as the SNC meteorites, may represent samples from the volcanic plains of Mars (*Wood and Ashwal,* 1981). While this hypothesis has not been conclusively proven, the evidence in support of a martian origin for these meteorites is very compelling. Analyses of the SNC meteorites provide clues to the composition of the martian mantle and the sources of volcanic activity on Mars. In particular, conclusions obtained from meteorite analysis have interesting implications for the observed characteristics of martian volcanos and the interaction of volcanic materials with volatiles in the martian environment.

Inferences from SNC meteorites. Return of a documented sample from Mars will provide the first conclusive compositional information about the red planet, but until that occurs, the SNC meteorites (Fig. 4) will remain the most likely examples of martian volcanic material. None of the SNC meteorites are older than 1.3 b.y. (*Wood and Ashwal,* 1981; *McSween,* 1984, 1985), and isotopic evidence suggests that the shergottites contain an igneous component that is both quite young (<200 m.y.) and mantle-derived (*Jones,* 1989). These ages are much younger than those of all other dated meteorites (>4.4 b.y.; from *Sears,* 1978) and are difficult to reconcile with a parent body smaller than the size of Mars. The very close match between the gases trapped in the glassy portions of the SNC meteorites and atmospheric measurements made by the Viking landers on Mars strengthens the case for a Mars origin, particularly since both sets of results are distinct from any other sampled region of the solar system (*Bogard et al.,* 1984; *Becker and Pepin,* 1984; *Pepin,* 1985). If one assumes that the SNC meteorites are from Mars, then the martian mantle can be modeled using the SNC chemistry and the assumption of a chondritic bulk composition, opening the martian interior to both experimental and petrochemical techniques (*Holloway,* 1990).

Experimental and thermodynamic constraints on the bulk composition give a mineralogy for the martian mantle, at a pressure of 30 kbar, of approximately 50 wt% olivine, 25 wt% orthopyroxene, 15 wt% Ca-pyroxene, and 10 wt% garnet (although the Ca-pyroxene/garnet ratio is highly variable), a composition quite similar to that of the Earth's upper mantle (*Bertka and Holloway,* 1989; *Holloway,* 1990). Garnet is stabilized at lower pressures in Mars than in the Earth (*Holloway,* 1990) and Mars appears to have a lower mg# [= atomic Mg/(Mg + Fe)], which could affect the partitioning of rare earth elements between the source region and the primary magmas (*Holloway,* 1990). The measured viscosity of a generalized SNC parent magma ranges from 10-200 poise over a temperature range of 1250°-1350°C at 1 bar pressure (*Spera and Stein,* 1990), only slightly higher than the 1-3 poise viscosity of the magma at 1450°C and 23 kbar pressure (*Bertka and Holloway,* 1989).

Synthesized glasses with the approximate bulk composition of various SNC meteorites have been used to determine the position of phase boundaries and crystal/liquid tie lines (*Longhi and Pan,* 1989). All these materials could have fractionated to produce the pyroxenes observed in Shergotty

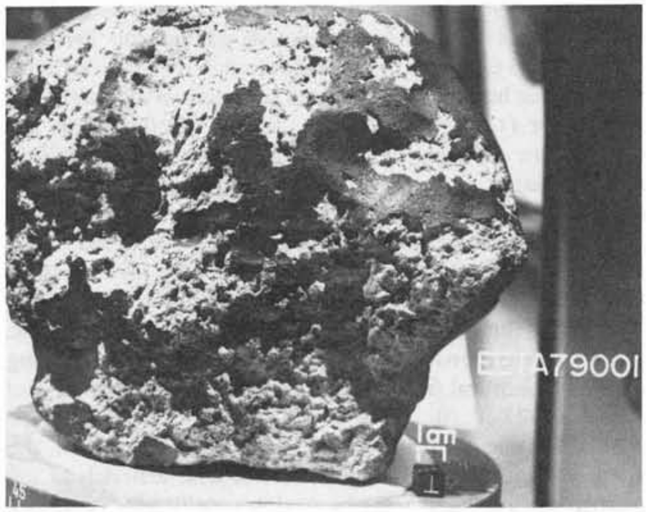

Fig. 4. SNC meteorite EETA 79001, found in Antarctica in 1979. Gases trapped within the glassy portions of this meteorite have isotopic abundances very similar to the atmosphere of Mars, as measured by the Viking spacecraft.

and Zagami (a shergottite). The calculated parent magma compositions have low aluminum contents and vary widely in the concentrations of a calcium-rich component (*Longhi and Pan,* 1989). These results require either that the source region was dominated by augite, which should be accompanied by a small negative Eu anomaly that is not observed, or that CO_2 fluxed the melt at pressures >25 kbar (*Longhi,* 1990). Thus the martian mantle may have interesting characteristics that distinguish it from volcanic source regions on Earth.

Volcanic materials and volatiles. The volcanic products derived from SNC primary magmas have important implications for volcanic features observed on the martian surface. Primary magmas derived from a volatile-free mantle at 25 kbar would resemble an iron-rich, picritic, alkali basalt at low degrees of partial melting (*Bertka and Holloway,* 1988). With an increase in the degree of melting, the primary magmas will trend toward iron-rich komatiites (*Bertka et al.,* 1990), consistent with field observations of komatiite flows that may be analogous to long lava flows observed on Mars (*Treiman,* 1987). Flow dimensions have been used to estimate rheologic properties for martian flow features (e.g., *Hulme,* 1976) but with varying degrees of uncertainty (*Baloga,* 1988). Application of photoclinometric techniques to images of martian lava flows have led to refinements in some estimates (*Moore and Davis,* 1990), which tend toward the low viscosities that should accompany flows derived from a SNC parent magma. A new method for estimating eruption rates from considerations of the temperature distribution throughout an active flow (*Crisp and Baloga,* 1990), rather than the equivocal interpretation of levee heights, should provide an independent check on martian lava properties derived from images.

The confirmed presence and abundance of volatiles in SNC meteorites have important implications for possible explosive volcanism on Mars. The high H_2O content documented for the Chassigny and Shergotty parent magmas (*Treiman,* 1985; *Johnson et al.,* 1990), coupled with the very low solubility of CO_2 at low pressures for SNC parent magmas (*Pan and Holloway,* 1990), indicate that some erupting lavas on Mars could include a significant explosive component. Tyrrhena Patera (Fig. 5), one of the oldest volcanos on Mars, includes deposits that have been interpreted to include a substantial ash component (*Greeley and Spudis,* 1981). Whether these ash deposits are products of phreatomagmatic volcanism is presently a matter of some debate (*Greeley and Crown,* 1990; *Robinson,* 1990). Ash deposits also have been identified on or around Hecates Tholus (*Mouginis-Mark et al.,* 1982), Alba Patera (*Mouginis-Mark et al.,* 1988), and near Elysium Mons (*Zimbelman and McBride,* 1989). Exsolution of juvenile volatiles in the erupting magmas may have driven explosive stages of eruptions of these volcanoes without requiring extensive chemical fractionation, as discussed by *Francis and Wood* (1982).

Volatiles should have an important effect on both the chemistry and physical condition of volcanic materials at the martian surface. Sulfur was observed in considerable quantities at the Viking landing sites (*Clark et al.,* 1977), an observation that stimulated consideration of possible mechanisms for its emplacement at the martian surface (*Burns,* 1988) as well as the chemical and weathering effects of iron sulfides on Mars (*Burns and Fisher,* 1990). Oxidized sulfur is present in substantial quantities in several SNC meteorites (*Gooding and Muenow,* 1986; *Burgess et al.,* 1989), strengthening the probable significance of this material to martian chemistry. Other volatile substances reported in SNC meteorites include apparent carbonate carbon (*Carr et al.,* 1985; *Gooding et al.,* 1990), carbon and deuterium of apparent preterrestrial origin (*Kerridge,* 1988), and various salts (*Gooding et al.,* 1988, 1990). Recent observations by the Infrared Spectro-Imager (ISM) instrument on the Phobos spacecraft document a variation in the hydration of martian surface materials (*Bibring et al.,* 1990; *Erard et al.,* 1991), consistent with the high H_2O content of some SNC meteorites (*Johnson et al.,* 1990). While the martian atmosphere contains relatively little water vapor (*Farmer et al.,* 1977), it still holds about as much water vapor as it can under present surface conditions (*Davies,* 1979). Water transported ephemerally through the atmosphere can have a pronounced weathering effect even in extremely cold and arid environments. Slow chemical alteration associated with intermittent, thin ice layers turns fine-grained, nonvesicular basalt in Antarctica into deeply pitted, irregular rocks; a

Fig. 5. Tyrrhena Patera, a low-relief volcanic feature in the cratered highlands of Mars that likely includes a significant component of ash. The volatiles involved in the pyroclastic eruption may have been from liquid or frozen groundwater, or juvenile gases that accompanied the rise of the magma, or both. Viking Orbiter frame 87A14; area shown is 280 km across.

similar, slow process may have played a part in forming the pitted rocks abundant at the Viking landing sites (*Allen and Conca,* 1991). Surface conditions in the past were likely very different from present conditions on Mars (e.g., *Toon et al.,* 1980), perhaps allowing liquid water to accumulate in transient northern oceans, causing planetwide climatic effects (*Baker et al.,* 1990). A variable climatic history on Mars will complicate the identification of past weathering processes from present surface materials.

Origin and Distribution of Tectonic Features on Mars

The surface of Mars displays a spectacular array of compressional and extensional features. A long-standing objective of Mars studies is to understand the controls over the orientation, position, and spacing of these features and the constraints they impose on the rheology and state of stress of martian surface units. Considerable attention was directed toward this goal during the MEVTV project, including two MEVTV workshops, one to address questions regarding the early tectonic and volcanic evolution of Mars (*Frey,* 1989), and another to assess the current knowledge of martian tectonic features, including kinematic and mechanical models for their origin (*Watters and Golombek,* 1989). While some fundamental issues remain unresolved, it is clear that substantial progress has been made in several key areas.

Controls over the distribution of tectonic features through time. The distribution and relative ages of major extensional and compressional tectonic features on Mars are now sufficiently documented through detailed mapping that the timing and relative significance of local and regional tectonic controls are well constrained (except for the Thaumasia province of southeastern Tharsis, which is currently being studied; K. L. Tanaka, personal communication, 1990). In addition to the global tectonic influence of the Tharsis rise, discussed above, eight other centers exerted regional control over faults and graben systems on Mars. Five of these centers are volcanic complexes similar to, but smaller than, the Tharsis rise. Listed in order of decreasing influence they are the Syria Planum rise (*Tanaka and Davis,* 1988), Alba Patera (*Rotto and Tanaka,* 1989; *Tanaka,* 1990a), Tharsis Montes, Elysium Mons, and Olympus Mons (*Scott and Dohm,* 1990).

All these volcanic centers are surrounded by regional systems of graben and/or ridges, and several show indications of substantial flank and summit deformation. Recent efforts to understand the tectonic evolution of these large centers have focused on the dramatic suite of surface features on Olympus Mons. *Borgia et al.* (1989) suggested that its prominent and enigmatic peripheral scarp is the surface expression of a fault-propagation fold that formed by gravitational failure and outward spreading of the volcano. Collapse and thrusting associated with magma chamber evacuation could account for the series of terraces on the slopes of Olympus Mons (*Thomas et al.,* 1989). Calculations based on the topography and radial distribution of tectonic features within the Olympus Mons caldera complex predict that this magma chamber was located at a depth of ~15 km (*Zuber and Mouginis-Mark,* 1989). It remains a task for future analyses to determine if these models are compatible with the full range of features observed both at Olympus Mons and on other large volcanos.

The extensive parallel fault systems that bracket and delineate the highlands-lowlands boundary scarp demonstrate that it is a major tectonic influence, regardless of uncertainties over the origin of the crustal dichotomy (*Maxwell and McGill,* 1988; *Scott and Dohm,* 1990). The remaining three tectonic centers are the large impact basins Hellas, Isidis, and Argyre (*Wichman and Schultz,* 1989; *Scott and Dohm,* 1990). The younger plains units flanking these basins are deformed by concentric graben. Thus it appears that these large martian impact basins acted as centers of sustained volcanic and tectonic activity in a manner consistent with that of lunar mare basins of comparable size.

Martian wrinkle ridges, similar in many respects to those on the lunar maria (*Sharpton and Head,* 1987), are typically associated with plains-forming materials interpreted to be lava flows (Fig. 6). Ridges range in age from Middle Noachian to Early Amazonian, but the widely recognized "surge" in ridged plains emplacement occurred in Early Hesperian (*Scott and Dohm,* 1990; *Frey et al.,* 1991). Most of the extensive systems of Early Hesperian wrinkle ridges were formed concentric to the Tharsis rise more than 2000 km away from its center. Generally less pronounced but widespread wrinkle ridges and

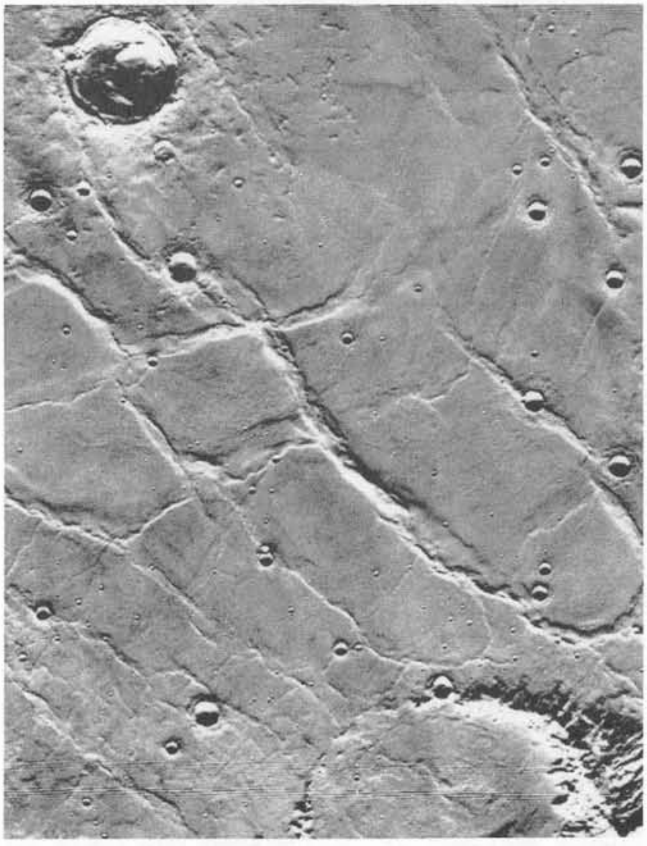

Fig. 6. Wrinkle ridges in the Lunae Planum region of Mars. The morphology of these ridges appears very similar to wrinkle ridges found on the Moon. Viking Orbiter frame 610A22; area shown is 150 km across.

associated scarps formed during the late Noachian, and a few ridges formed during the early Amazonian (*Scott and Tanaka*, 1986; *Chicarro*, 1989).

Wrinkle ridge formation. Little doubt remains that martian wrinkle ridges, like their better-studied lunar counterparts, are produced by compressional deformation. *Scott* (1990) maintains that rare examples of ridge-graben colinearity suggest an extensional ridge origin, but numerous studies have demonstrated that many properties of wrinkle ridges are difficult to reconcile with extensional deformation (*Sharpton and Head*, 1987; *Plescia and Golombek*, 1986; *Watters*, 1988; *Aubele*, 1989; *Schultz*, 1990). The subsurface structure and details of wrinkle ridge formation nonetheless remain the subjects of considerable debate. Detailed understanding in these areas is required before martian ridges can be used confidently as strain gauges (*Golombek et al.*, 1991) or in constraining the mechanical properties of the martian lithosphere (*Saunders et al.*, 1981; *Watters*, 1988; *Zuber and Aist*, 1989; *Watters and Chadwick*, 1990).

A variety of models have been proposed for martian wrinkle ridge formation, ranging from buckling of upper crustal layers (*Watters*, 1988) to deep-seated thrust faulting that leads to near-surface folding (*Plescia and Golombek*, 1986; *Zuber and Aist*, 1990), and a range of planetary analogs have been called upon in support of these models. The failure to resolve the details of wrinkle ridge formation is due in large measure to the lack of imaging and topographic data of sufficient resolution to characterize these features. Photoclinometric profiles of some martian ridges indicate a topographic offset across these structures similar to that associated with some lunar mare ridges. The presence of such an offset has been used to argue against the thin-skinned buckling model for wrinkle ridge formation and in favor of deep-seated thrust faulting (*Golombek et al.*, 1991). This argument can be inverted, however, because it is equally difficult for thrust faulting to explain those ridges that have considerable topographic development unaccompanied by noticeable offsets (*Watters*, 1988). *Sharpton and Head* (1987) have concluded that lunar ridges appear to be polygenetic landforms: The basic morphological properties that identify ridges as a single class of landform reflect their common compressional origin and rheological similarities, but each ridge system is the product of a sustained and variable deformational path that is locally influenced. Some involve buckling and thrusting and others high-angle reverse faulting as compression is accommodated along preexisting basement faults. Only by examination of high-resolution topography and imaging can the details of this process be unraveled for the Moon, and presumably the same holds true for martian ridges.

Valles Marineris. The similarities between Valles Marineris and block-faulted structures on Earth have long been recognized (*Frey*, 1979; *Lucchitta et al.*, 1989). The tremendous size of this system (hundreds of kilometers wide, thousands of kilometers long, and many kilometers deep), although undoubtedly enhanced by severe mass wasting and collapse, points to extensional deformation involving the entire martian lithosphere and prompts comparisons with terrestrial rift valleys. Stress modeling constrained by long-wavelength gravity and topography (e.g., *Banerdt et al.*, 1982) generally predicts extensional stresses orthogonal to Valles Marineris (Fig. 3). One problem in understanding the origin of Valles Marineris is explaining the many closed depressions, such as Ganges Catena and Hebes Chasma, and their relationships to the larger open canyons. A proposed explanation is that these closed depressions are collapse structures over deep-seated fractures, in the manner of pit crater chains (*Tanaka and Golombek*, 1989). *Schultz* (1989a) argues against this mechanism for the origin of large closed depressions, maintaining that, while both features are produced by extensional processes, they are distinctly different in morphology. One problem that all such tectonic explanations face is how to account kinematically for the large amounts of lithospheric extension required to produce the chasmata. *Croft* (1989) presents a novel alternative. He suggests that individual closed features up to $\sim 1000\ km^3$ in volume could be karst features, while larger features are primarily due to tectonic subsidence. While this mechanism may reduce the need for crustal spreading somewhat, considerable extension is still required to produce the larger features.

Possible strike-slip faulting on Mars. In contrast to the attention garnered by both extensional and compressional processes on Mars, strike-slip deformation, until recently, has gone virtually uninvestigated. This is probably because occurrences of clear strike-slip indicators such as offset craters rims, valley walls, or structural trends are not obvious on Mars (*Golombek*, 1985). However, as *Schultz* (1989b) recently noted, such primary strain markers are not always observed in conjunction with major shear zones on Earth either. Near the surface, discrete offsets at depth can be distributed over a broad zone characterized by such secondary features as shear fractures, tear faults, and echelon folds. Echelon structures alone, however, do not necessarily indicate strike-slip faulting; rather they attest to fracture and fold growth through inhomogeneous stress fields (*Schultz*, 1990). Thus, while these secondary features may be more common than primary structural offsets, they are less compelling evidence of strike-slip deformation.

Recent studies of martian surface images have revealed a number of structural elements that resemble the secondary features associated with strike-slip deformation on Earth. *Schultz* (1989b) has noted evidence of limited strike-slip faulting of the ridged plains near Valles Marineris in the form of consistent *en echelon* arrangements of wrinkle ridges.

Transcurrent faulting on Mars at a much larger scale has been advanced by *Forsythe and Zimbelman* (1988, 1989). From their analysis of probable secondary shear indicators in the vicinity of the Gordii Dorsum escarpment and the similarity of this feature to a major terrestrial shear zone, the Dasht-e-Bayez (Iran), they conclude that this escarpment is the surface expression of an ancient left-lateral fault zone of lithospheric proportions (*Forsythe and Zimbelman*, 1988). The width of this shear zone suggests that offsets across this structure could be in the range of tens of kilometers. Horizontal offsets of this scale call for a dramatically different tectonic regime early in the history of Mars, one in which horizontal motion of the lithosphere played a much more significant role than in more recent times. It should be noted that the interpretation of early faulting on Gordii Dorsum requires that portions of the

Medusae Fossae formation be Noachian in age, rather than the Amazonian age indicated by the paucity of impact craters (*Scott and Tanaka,* 1986). While further work is clearly required to substantiate the strike-slip origin of Gordii Dorsum and similar escarpments elsewhere, this hypothesis raises the intriguing possibility that early Mars was, at least tectonically, more similar to the Earth than previously imagined.

A LOOK FORWARD

Research activities encompassed by the MEVTV project have clarified many of the issues relevant to the global evolution of Mars, but the wealth of information revealed by detailed studies of regional problems has raised many new questions. Some of the answers to these questions will be provided by the further analysis of data already available, which is the approach taken in the MSATT study project that succeeds MEVTV. New data from the Mars Observer mission, scheduled for launch in 1992, will aid in evaluating both global and regional problems through a combination of long-term monitoring activities and high-resolution information from selected locations. Several of the problems addressed during the MEVTV project will require geophysical and geochemical measurements from widely dispersed locations on Mars, observations that could be made at multiple lander, rover, and penetrator sites envisioned for missions following Mars Observer. The return of documented samples to Earth will resolve many of the intriguing possibilities raised by the study of the SNC meteorites, as well as providing calibration for measurements made from orbit and from the Earth.

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