RECENT ADVANCES IN MARS TECTONICS. M. P. Golombek and W. B. Banerdt, Jet Propulsion Laboratory, Pasadena CA 91109, USA.

Introduction: Since the publication of the "Stress and Tectonics on Mars" chapter in the Mars book [1] (the last comprehensive summary of our knowledge on the topic) considerable advances have been made in certain areas of Martian tectonics and significant advances are expected with the return of Mars Global Surveyor data. This abstract will summarize the advances in our knowledge of tectonic features and processes on Mars since the Mars book and point towards new areas of research that can be expected from the Mars Global Surveyor data.

Two out of three areas of study that were discussed as future directions of work in the Mars chapter [1] have had significant work directed towards them. One area is the field of structural mapping and understanding the timing of tectonic activity on Mars in the framework of the global stratigraphy [2]. Although the general development and relative timing of the development of the Tharsis province on Mars had been understood for some time, actual placement of mapped tectonic features in a global stratigraphic framework has only recently been completed [3]. The second area of study mentioned in the Mars chapter was the impact of improved topography and gravity on modeling loads and deriving stresses in the Martian lithosphere [1]. Mars Global Surveyor is on the brink of returning vastly improved topographic and gravity fields and these newer data sets can be used to better define the size and shape of Tharsis and to quantify loads and derived stresses in the Martian lithosphere.

Tharsis: The Tharsis province remains the centerpiece of any discussion of Martian tectonics. With the publication of the Mars book it was recognized that the development of the radial grabens and concentric wrinkle ridges that cover the entire western hemisphere of Mars required 2 distinct stress states as calculated from present day topography and gravity [1 and references therein]. Isostatic conditions lead to concentric extensional stresses on the topographic rise and radial compressional stresses around the edge that could account for the radial grabens on the rise and the concentric wrinkle ridges around the edge. However, flexural loading stresses were needed to develop the concentric extensional stresses needed to produce the radial grabens beyond the edge of the topographic rise. Nevertheless, the tectonic record on Mars shows two tectonic events responsible for the development of Tharsis: a Late Noachian-Early Hesperian period involving radial normal faulting on the rise and concentric wrinkle ridge formation at the edge, followed by a Late Hesperian-Early Amazonian period involving radial normal faulting that extended for thousands of kilometers from the center of the rise [4]. A potential resolution of the requirement for 2 distinct, but simultaneous stress states to produce the existing tectonic record led to a model in which isostatic stresses are produced on a detached crustal cap that is separated from a strong upper mantle that yields flexural loading stresses around the edge [4, 5]. A global compressive stress field may have modulated the formation of the concentric wrinkle ridges and perhaps larger thrust structures of lithospheric proportions [6] described south of Tharsis at about the same time when wrinkle ridge formation peaked on Mars [4].

Our general understanding of the timing of tectonic events around Tharsis as a whole has been improved on by placing the major events within the stratigraphic framework as mentioned above [4]. Substantial additional mapping has yielded a detailed picture of individual tectonic events in particular areas of the Tharsis province [e.g., see references in 1-3]. In addition, faulting in these different areas has been tied together into the global stratigraphic framework [3]. This analysis has revealed a complex structural history involving 5 stages of tectonic activity with changes in the derived centers of activity through time and complex faulting in different local centers of Tharsis at the same time [3]. More than half of the structures mapped on Mars are Noachian in age (stage 1), concentrated in exposures of Noachian age crust exposed in Tempe Terra, Ceraunius Fossae, Syria Planum, Claritas Fossae, Thaumasia, and Sirenum. By Late Noachian-Early Hesperian (stage 2) activity was concentrated in Thaumasia and Valles Marineris. Middle Hesperian (stage 3) showed the development of concentric wrinkle ridges concentrated along the edge of the topographic rise [3]. Normal faulting also occurred north of Alba, in Tempe Terra, in Ulysses Fossae, in Syria Planum and Valles Marineris, and in Claritas Fossae and Thaumasia. Stage 4 activity during the Late Hesperian-Early Amazonian was concentrated in and around Alba Patera and Middle to Late Amazonian activity (stage 5) was concentrated on and around the Tharsis Montes volcanoes [3].

In addition to improving our knowledge of the stresses and timing of tectonic activity around Tharsis, substantial progress has been made in deciphering the strain accommodated by tectonic features around Tharsis. Estimates of the extension across the heavily faulted regions of Alba, Tempe, Thaumasia and Sirenum (see summary in [7]) have been combined with new estimates across Valles Marineris based on more detailed mapping and modeling of the structure as a rift [8]. Even given the large uncertainty in the estimates of extension, which mostly derive from the possible variation in normal fault dip, results suggest about 60±45 km total hoop extension or 0.5% strain around a circle of radius 2500 km now expressed at the surface (not accounting for buried structures), which agree to first order with elastic strains derived from the flexural loading model at comparable distances [7].

Plate Tectonics?: The most original new idea in Martian tectonics to be pursued since the Mars book is that of plate tectonics [9]. Sleep [9] suggested that a well understood way (on the Earth) to produce a crustal dichotomy between the northern lowlands and the southern highlands is the process of plate tectonics (previous explanations include one or more impacts and subcrustal internal activity [see review in 1]). In this model, the northern lowlands are underlain by thinner, denser oceanic crust. Unfortunately little photogeologic evidence supports the suite of features that would be expected to be observed at the various plate tectonic boundaries defined in Sleep's plate tectonic model [10] and other internal models for the formation of the northern lowlands continue to be proposed [11]. Recent topographic data find a crustal dichotomy boundary that has been suggested and interpreted to be similar to passive margins on Earth [12].

Local Loading: Much of the localized tectonics on Mars is associated with local surface loads, primarily large volcanic constructs. The early analysis of these structures used simple thin plate loading models to infer the mechanical properties of the lithosphere, such as thickness and strength [1, and references therein]. In the absence of detailed topographic measurements, the flexural deformation was inferred from the locations of circumferential extensional structures. Until recently, advances over this early work were primarily in improving the fidelity of the models (largely motivated by studies of Venusian volcanoes rather than those of Mars), including such effects as volcano growth and thick plate behavior [13, 2], moat filling [14, 3], superposed regional stress fields [15, 4], and failure mechanics [16, 5]. With the new MOLA elevation data, it is now possible to more accurately define the size and extent of the load and to search for the topographic signature of flexure. Preliminary results from aerobraking include the possible identification of flexural bulges adjoining Olympus Mons [17, 6] and the northern polar cap [18, 7], and the realization that Alba Patera is much more areally extensive than previously thought, placing the extensional grabens well up on the flanks rather than just off the edifice [19, 8].

Geometry and Kinematics of Structures: Other recent work in Martian tectonics have revolved around trying to gain a better understanding of the geometry and kinematics of different structural features. One area that has received some attention is the interpretation of the subsurface structure of long narrow simple grabens, which are the dominant type of tectonic feature on Mars. The observation that some grabens have lines of pits down their centers has led to suggestions that tension cracks or dikes may underlie the grabens [4, 20]. Additional evidence and arguments suggest that many Tharsis grabens are the surface manifestation of dikes fed by plumes [21] and that Valles Marineris is underlain by a massive dike (many kilometers wide) that could have triggered the outflow channels [22]. Other work on the grabens has centered on trying to better understand Martian structures in terms of scaling relationships that have been derived for faults on the Earth. On Earth, fault slip during earthquakes is observed to follow moment magnitude relationships in which the area observed to rupture appears to follow certain length and/or width relations and slip is observed to vary from a maximum near the center of the rupture to a minimum at the edges of the ruptured surface [e.g., 23]. This relationship was used on Mars to derive the seismic moment release through time and present day seismicity using moment frequency relations [24]. Similar relationships have been derived for the estimated maximum displacement and length of faults on the Earth [25] and these relations have been derived for structures on Mars [26].

Initial results from the Mars Orbiter Laser Altimeter (MOLA) and Mars Orbiter Camera (MOC) are beginning to show some of the details of graben and rift structure on Mars. Extensive photoclinometry of simple grabens and scarps on Mars indicated that the scarps have extremely low slopes [see 7 and references therein]. Average simple graben scarps were measured to be 8.7°, which is substantially lower than the angle of repose. One possible suggestion on how to get such low slopes on fault scarps that originally were steeply dipping is that they have accumulated and trapped significant deposits of windblown sand and dust [27]. Systematic measurement of fault scarps covered in early MOLA tracks across Tempe Terra confirms that the scarps are this shallow and that on average rift scarps have similar shallow slopes [28], (contrary to the steeper slopes assumed in [7]). High-resolution MOC images reveal a surface considerably affected by windblown sand and dust and that graben interiors have a muted appearance with extensive smooth deposits banked against the edges of the grabens [29], consistent with the low slopes of the scarps resulting from the accumulation of aeolian sand and dust [27].

Future Directions: Further data from Mars Global Surveyor will considerably add to our knowledge of Mars tectonics. Improved gravity and topography will result in much higher resolution modeling of surface loads and derived stresses. In the Tharsis region this should allow discrimination of more local affects in addition to the province wide stress fields already derived. We anticipate extending our calculations of stresses due to isostatic conditions as well as flexural loading to further investigate the relation between the present day gravity and topography with the tectonic record mapped at the surface and to look for variations in the orientations of the calculated stresses with faulting associated with local centers of activity. Improved MOLA topography will also provide better constraints and tests of the local flexural loading calculations that are underway. In addition, detailed imaging and elevations across structures should help in our understanding of the geometry and kinematics of structures on Mars. In addition to further studies of grabens and rifts, MOLA data should be able to discriminate between competing interpretations of wrinkle ridges. As discussed and referenced in the Mars chapter [1], wrinkle ridges have been alternatively interpreted as being the result of thin-skinned folding of a surface layer only [30] or of thick-skinned faulting involving much of the lithosphere [31, 4]. MOLA tracks should be able to measure elevation offsets across the structures (on the plains on either side of the structures) that would result from the thick skinned interpretation, versus no elevation offset for the surface folding only interpretation.

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