STRAIN ACCOMMODATION BENEATH STRUCTURES ON MARS

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A recent review of tectonic features present on Mars (1 and references therein) shows that most of their subsurface structures can be extended, with confidence, only a few kilometers deep (exceptions are rifts, in which bounding normal faults penetrate the entire brittle lithosphere, with ductile flow at deeper levels). Nevertheless, a variety of estimates of elastic lithosphere thickness and application of accepted failure criteria under likely conditions on Mars suggest a brittle lithosphere that is many tens of kilometers thick. This raises the question of how the strain (extension or shortening) accommodated by grabens and wrinkle ridges within the upper few kilometers is being accommodated at deeper levels in the lithosphere. In this abstract, we first briefly review the non-rift tectonic features present on Mars, their likely subsurface structures, and present some inferences and implications for behavior of the deeper lithosphere.

Simple grabens are the most common type of extensional tectonic feature on Mars. Most of these structures are bounded by two inward dipping normal faults that have had the same amount of slip (equal scarp heights). Their simple geometry at the surface (untilted - flat floors and shoulders at equal elevations) argues for a simple subsurface structure, with both faults terminating at their point of mutual intersection (2). Observations of faults bounding grabens in canyon walls on Mars indicate an average dip of about 60° (3), indicating that faults bounding simple grabens on Mars only penetrate the upper few kilometers of the lithosphere (about the width of the structure, 1-5 km). As a result, it is not obvious how the extensional strain taken up by slip on the graben bounding faults in the upper few kilometers is accommodated at deeper levels in the brittle lithosphere.

Some extension of rocks beneath the graben-faulted layer may be accommodated by elastic expansion without fracturing. For example, where narrow simple grabens are spaced 100 km apart, each having about 100 m of extension (4), the total extensional strain is about 10^{-3}. Laboratory measurements of Young's modulus, based on the propagation of elastic waves in homogeneous samples, for likely basement materials on Mars (e.g., basalt) are 4×10^4 to 10^5 MPa (5). In addition, seismic velocities from basement rocks at Apollo 17 indicate a Young's modulus of about 10^4 MPa (6 and references cited therein). As a result, rock beneath the grabens will experience a tensional stress of 10 MPa, which is well below the strength of likely basement rocks on Mars at a few kilometers depth, even if the rocks are prefractured with no tensile strength (7). For elastic expansion to occur a detachment must separate the faulted and unfaulted rocks so that the extension accommodated by the grabens is distributed over the entire underlying basement. If basement rocks on Mars have some tensile strength as is likely in current models (7), elastic expansion of basement rocks without failure is possible beneath simple grabens on Mars that are spaced more than about 25 km apart and where faulted rocks are detached from underlying rocks. For many regions on Mars where grabens are spaced closer than about 25 km, the basement is likely to fail under the extensional strain as described below.

The simple subsurface geometry of grabens only allows vertical tension cracks or dikes beneath them. If one of the two shear faults did extend to a deeper level more slip would be expected on the deeper, master fault than the antithetic fault, which would result in an asymmetric or tilted structure, which is not observed. As a result, dikes or tension cracks could underlie grabens. Accepted failure criteria applied to Mars indicate that the formation of tension cracks can occur to substantial depths beneath graben bounding normal faults (7), particularly when driven by fluid (water or magma) pressure in the forming crack. Their individual widths on Mars could be up to 200 m, about twice that on the earth (8) and multiple intrusions are possible. The total width of the dikes would likely equal the extension in the overlying graben. Terrestrial analogs show that dike intrusion at depth is linked to graben formation at the surface in Iceland and Afar (9). In these areas, grabens are a few kilometers wide and are underlain by dikes that extend kilometers in depth and tens of kilometers laterally (scales comparable to martian examples), and did not erupt on the surface. In addition, dikes are known to feed fissure eruptions on the earth, so their common association with grabens and volcanic regions on Mars (such as Tharsis) supports the model linking dike intrusion at depth with graben formation near the surface. The common association of grabens with pit chains on Mars (e.g., 7) also supports underlying dikes or mechanically similar hydrofractures (fluid driven tension cracks) to provide the space at depth for the inferred subsurface drainage of material and pit chains have been observed in grabens in Iceland and above fissures in Hawaii. In this subsurface structural model, the dike does not have to intrude directly beneath graben, but could be offset, provided that a subsurface detachment allows horizontal slip between the dike and graben. The maximum depth that underlying dikes or hydrofractures could extend is limited by the driving pressure of the fluid and so, mechanically could extend to tens of kilometers depth. Hydrofractures could extend to a depth where the fracture toughness exceeded the extensional strain, below which the lithosphere expanded elastically. Dikes could link with subsurface magma chambers or zone of melt production (upper mantle?) and thus accommodate the extension throughout the brittle crust beneath the grabens.

Wrinkle ridges are morphologically complex linear topographic highs. Most recent work has suggested two compressional kinematic models involving folding and faulting. The thick-skinned model suggests that faults beneath wrinkle ridges extend through the entire lithosphere (10). If wrinkle ridges do involve thrust faulting of most of the lithosphere, then there is no problem reconciling the compressional strain accommodated by the wrinkle ridges in the upper few kilometers of the crust with that in the rest of the lithosphere. If, however, wrinkle ridge formation involves only a thin surface layer (faulting and folding extends only a few kilometers deep), in the thin-skinned model (11), then some explanation must be provided for how the compression in the ridges is accommodated deeper in the lithosphere. The compressional strain across lunar and martian wrinkle ridges and lunar basins has been estimated at 10^{-2} to 10^{-3} (10, 11, 12). For the values of Young's modulus discussed earlier, this strain indicates a stress of tens to hundreds of MPa, which exceeds the compressional strength of low cohesion materials. Low cohesion rocks on Mars are stable to failure for stress differences under compression of 35 MPa per kilometer of depth. As a result, wrinkle ridges could be expected to involve faulting down to 10 km depth if they accommodate compressional strain of order 10^{-2}. In this model, thrust faults propagate to a depth below which the imposed compressional strain was less than the elastic strength of the lithosphere.

Possible differences in strength of surface units on Mars could augment this effect and control certain aspects of wrinkle ridge formation. The strength of brecciated highland rocks is controlled by the frictional resistance to sliding on preexisting fractures, with no cohesive strength. As a result, lower stresses would be required to produce faulting in breccia than if the rock had cohesive strength. This might lead to small thrusts in highlands breccia that initiated at the surface and propagated into the shallow subsurface. In contrast, volcanic flows could possess substantial cohesive strength (30-50 MPa; 5), thereby requiring much greater differential stresses to initiate faulting in surface rocks. These higher stress levels could lead to initiation of faults at greater depths, perhaps at a mechanical discontinuity between the base of the strong volcanics and the weak underlying breccia (e.g., 6). Faults would propagate down in the ejecta until the greater strength of the volcanics was exceeded. In this scenario, faults would propagate deeper than if the entire shallow crust had the same strength as the volcanics. Thus faulting beneath wrinkle ridges in cohesive volcanic flows could involve more of the lithosphere, leading to each ridge accommodating greater shortening on fewer structures resulting in the wide spacing observed between large ridges on the ridged plains. This model is capable of explaining the observation on Lunae Planum (13) in which large, widely spaced ridges with great shortening are found in the thicker plains to the west than the smaller, more closely spaced ridges with less shortening found in the thinner plains to the east.

References: (1) Banerdt, Golombek & Tanaka 1991 Stress on Mars, UA Chapter Mars. (2) Golombek & McGill 1983 JGR 88, 3563. (3) Davis & Golombek 1990 JGR 90, 14231. (4) Tanaka & Davis 1988 JGR 93, 14893. (5) Hand. Phys. Const. GSA Mem 97, 1966. (6) Golombek 1985 JGR 90, 3065. (7) Tanaka & Golombek 1989 19th PLPSC, 383. (8) Wilson and Parfitt 1990 LPSC XXI, 1345. (9) Rubin & Pollard 1988 Geology 16, 143. (10) Golombek et al. 1989 LP Sci Con XXI, 421. (11) Watters 1988 JGR 89, 10236. (12) Bryan 1973 4th PLSC, 93. (13) Plescia 1991 LP Sci Con XXII this volume.