A NEW LOOK AT MARTIAN EXTENSIONAL STRUCTURES: ARE THE FAULTS MORE THAN ONLY SKIN DEEP?

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Summary.

Yes!

Introduction and Background.

Considerable progress has been made on Martian extensional tectonics since the 4th Mars Colloquium in 1989. The intervening decade has seen significant advances in the understanding of how extensional structures in general work—both terrestrial and planetary—along with a remarkable convergence of opinion on the polygenetic history of the Valles Marineris. The new imaging and topographic data currently streaming back from Mars will provide more detailed observations of many Martian structures. Improvements in the analysis and interpretation of terrestrial extensional systems over the past decade will, in concert with the new data, permit a wider range of physically based tectonic interpretations to be made.

In this abstract I touch on some aspects of the three-dimensional nature of extensional deformation on Mars based on surface exposures. Many ideas concerning how normal fault and graben systems work have changed greatly since 1989, resulting in a wealth of new tools that can be applied to planetary structural problems. A few of these tools and concepts are noted here. In particular, the key role that the classic grabens found in Canyonlands National Park, Utah, have played in the development and pedigree of ideas on Martian extensional tectonics will be summarized. While these grabens continue to provide insight into planetary fault systems, they are no longer the universal template that they once may have been. As a result, the "thin-skinned" interpretation of Martian grabens, based on the original Canyonlands analogy [see 1,2], does not appear to be supportable by well-documented examples of terrestrial graben systems for comparable stratigraphic and tectonic settings.

Insights from Canyonlands.

For nearly a quarter-century, the spectacular grabens of Canyonlands National Park, Utah, have provided planetologists with a fundamental template for understanding what planetary grabens should look like and—more importantly—what they imply about the depth variation of extensional strain. *McGill and Stromquist* [1] hoped to invert graben widths for the depth of faulting. By equating this depth with stratigraphic layer thickness and assuming a symmetric graben geometry and plausible values of fault dip angles, grabens provided ready and seemingly reliable probes of the near-surface planetary stratigraphy [e.g., 3–6].

A symmetric graben geometry was also thought to limit the type of structure beneath the graben to either a dilatant ("tension") crack, a décollement, or nothing (see [5] and [6] for rationale). This notion also is at variance with more recent (as well as older) field, experimental, and theoretical investigations of developing grabens (symmetric and asymmetric) from the Earth. The idea of "thin-skinned" extension, and the resulting problem of the likely (and, by construction, different) mechanisms by which strain is accommodated at greater depths, have motivated a variety of formulations of Tharsis tectonics [6].

While reasonable when proposed, many of the initial ideas from Canyonlands faults, as applied to Mars, have not withstood the test of time. Nevertheless, it is still common today to see planetary researchers mapping subsurface horizons using graben widths. We expect planetary grabens to look like those in Canyonlands and—despite the likely lack of thick wet evaporite sequences underlying large regions of post-Noachian Mars—to behave like them.

Work in the 1990s by independent research groups has exploded the legend of symmetric, keystone-collapse grabens in Canyonlands. For example, *Trudgill and Cartwright* [7] and *Cartwright et al.* [8] have demonstrated that the displacements along graben-bounding faults scale with the map lengths and that the displacement maxima are located near the fault-segment midpoints—just like on other types of faults. Why is this important? Because it means that estimates of graben-floor depths, obtained by averaging several measurements made at arbitrary positions along the graben, are only marginally informative because they ignore the fundamental position-dependence of these depth values. The work also demonstrates the necessity of identifying the fault-segmentation lengths appropriate to the observed surface displacements [9], rather than just mapping the aggregate length of an echelon graben array.

Our research group also has been reinvestigating the geometry of Canyonlands grabens geometry. We demonstrated [10,11] that the grabens are *characteristically asymmetric*, rather than the simple, symmetric, keystone-collapse wedges previously thought. We also found that the faults do not necessarily intersect at the base of the faulted layer—as previously inferred—but at perhaps only 2/3 to 3/4 of the layer thickness. Graben formation in this mechanical system is more complex than the symmetric-graben model has supposed [e.g., 12], leading to a poor correlation between graben width, depth of faulting, and faulted-layer thickness [13].

One prominent and persistent byproduct of the Canyonlands model of graben faulting was the correlation of fault-intersection depth with the thickness of the *megaregolith* on terrestrial planets. An attractive layer-cake model of planets such as Mars—faulted basement, megaregolith, capping veneer of lava flows and other stuff—has motivated many interpretations of Martian and planetary tectonics [e.g., 6,14,15]. Recent high-resolution images of Valles Marineris trough walls and other slope faces have been unable, however, to identify either the megaregolith or its basal contact with the fractured bedrock below [e.g., 16,17]. Previous searches using Viking data have also been unsuccessful in locating this contact [18]. It now appears [16,17,19] that the ideal three-layer scenario is far too simplistic to describe much Martian geology and stratigraphy. As a result, the Canyonlands model may be of limited applicability to describe the 3D deformation and strain in Martian terrains underlain by thick sequences of layered rocks.

What about Valles Marineris?

One major result of the 4th Mars Colloquium was a chapter in the Mars book on the Valles Marineris trough system [18]. That work summarized the thinking on this important and perplexing region through that time. Since then, work by several independent research groups has refined the geologic and structural sequence significantly [9,20–28].

We now recognize that the region is likely underlain by dike swarms [29] that fed the Lower Hesperian ridged plains flows that, in turn, have resurfaced much of the region. The ridged and smooth plains units may now represent the *last phase* of a long-lived volcanic resurfacing period—as suggested by 5–10 km thick layered sequences imaged by MOC [16,17,19]—rather than a pulse of volcanic activity. Igneous dikes may thus be quite common in regions underlain by such layered sequences. The dikes may have contributed to the quasi-linear fabric implied by alignments of pit-crater chains [28,29] and troughs [9]. Downward displacement of large crustal blocks, in general association with chaotic terrain and fluvial outflow channel development, preceded the formation of the structural troughs that clearly overprint this earlier assemblage [18,23,27]. The improved geologic sequence now provides a less confusing context for studies of planetary rifting [30], while studies that ignore the geologic context do so at their peril [31].

Conclusions and Implications: Where Do We Go Now?

Martian graben arrays clearly represent only the surface expression of a 3D network of crustal extension. New observations of Martian stratigraphy may require a re-evaluation of megaregolith-based, “thin-skinned” tectonic models. Similarly, popular concepts of Martian grabens as symmetric grabens—and therefore as easy probes of faulted-layer thickness and crustal stratigraphies—are no longer supported by terrestrial analogs or data and may require some revision. On the other hand, considerable work has demonstrated that *faults are faults*, whether Martian or terrestrial. This gives us powerful tools for extracting fault mechanics, strain, and rheology from Martian extensional fault arrays that largely did not exist 10 years ago. Further, the flat-floored Canyonlands grabens provide a timely and relevant analog to many sediment-filled Martian grabens—now observed in MOC images—and a basis for understanding the fault kinematics.

The available work demonstrates that the structural troughs of Valles Marineris, like the second set of Tharsis-radial grabens, are *young*—perhaps Amazonian in age. Because the Valles Marineris Extensional Province exhibits a clear polygenetic history that is unique in the Tharsis region, the recent extensional strain field leading to grabens was superimposed onto a previously special region.

The next several years will likely see the re-evaluation of Martian graben arrays using non-Canyonlands models. Studies of fault-segment linkage and displacement distributions will permit clearer statements about the downward continuation of these fault arrays. Similarly, mechanical modeling of faults in the Valles Marineris can address the outstanding problems in crustal thickness, lithospheric structure, and the evolution of the system. Data from MOC and MOLA will provide critical observations against which the new structural and tectonic models will be tested.

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