Unraveling the Complex Tectonic History of the Memnonia-Sirenum Region: A Window into the Early Formation of the Tharsis Rise.

R. C. Anderson[1], J. M. Dohm[2], A. Siwabessy[1,3], and J. F. Schroeder[1] ; [1]Jet Propulsion Laboratory. California Institute of Technology, Pasadena CA, 91109. [2]Dept. of Space Exploration & Discovery, Univ. Museum, Univ. Tokyo, Tokyo, Japan, 113-0033; [3]Department of Physics and Astronomy, California State University Long Beach, 90840.

Introduction: A detailed reconstruction of the tectonic history of the Memnonia-Sirenum region of Mars (15°S to 40°S, 190°E to 230°E) is presented here through a 1:5,000,000-scale USGS map. From the detailed mapping of the Memnonia-Sirenum region, stratigraphic and crosscutting relations among rock materials and structures displays a significant interplay among tectonic, magmatic, and aqueous activity within this region, especially with respect to the development of Tharsis. Detailed analysis of the tectonic structures and the stratigrpahic units in this region provided an excellent window into the tectonic processes that operated from the Early Noachian through Middle Amazonian phases of Mars [1].

Graben Analysis: From the cross-cutting relationships between mapped stratigraphic units and structures, graben were divided into groups based on the youngest stratigraphic units each cut. Using a young lava deposit (AHThv-Fig. 1) as a stratigraphic marker unit, three trends emerged: 1) N56°W trend, which graben project radially to the Arsia Mons volcano, 2) N73°W trend, which graben radially project to the Stage 3 center (Syrtis NW) defined by Anderson et al. [1], and a minor N83°W trend, which the graben project radially to the Stage 1 (Claritas) center defined by Anderson et al. [1].

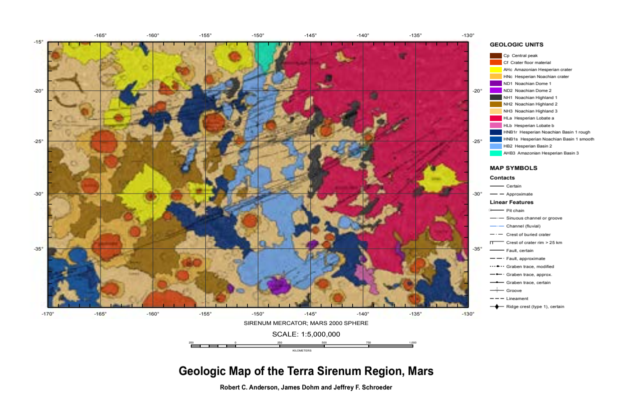

Fig. 1. 1:5M-scale Geologic map of the Memnonia-Sirenum region of Mars showing stratigraphic units overlaid by mapped faults [Anderson et al., USGS review].

In order to delineate the spatial distribution of the mapped graben, we further subdivided the graben into distinct geographic groups based on the following criteria: 1) stratigraphic relationships between structures, 2) orientation of the structures (azimuth angle), and 3) geographic location of each graben. Base on the above criteria, five different geographic groups were identified (Fig. 2). Two groups of graben appeared prior to the emplacement of AHThv, subsequently three groups of graben where identified that occurred after the deposition of AHThv.

From Groups 1 and 2 (Fig. 2), two additional subgroups of graben were identified: 1) Group 1a and 2a graben trend in

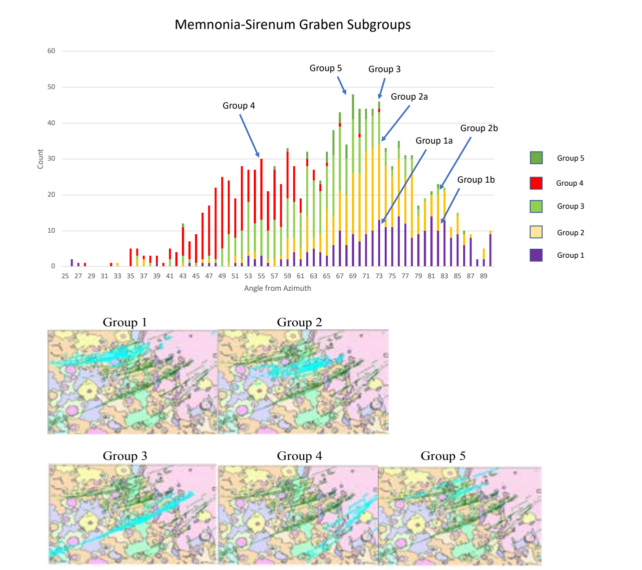

Fig. 2. (*Upper*) Graben subdivided into geographic five different geographic subgroups were identified. (*Lower*) Graben Group locations.

a N73°W direction and project radially to the Stage 3 (Syria NW) Center identified by Anderson et al. [1]; Group 1b and 2b graben have a graben trend of N83°W and radially project to the Stage 1 (Claritas) center of Anderson et al. [2001]. Although there is no overlap in the Group 1 and Group 2 graben, they both appear to be contemperous, cutting the same stratigraphic units, and both groups may have resulted from the same tectonic event. It appears by the presences of the radial graben, that both the Claritas center and the Syria NW center [1] were active during this time prior to the emplacent of AHThv (before 3.64 Ga).

Group 3 graben also display similar trends to Groups 1 and 2 with the dominate trend being N73°W (Stage 3 Syria NW center). The number of graben assoicated with the N83°W trend (Claritas center) have declined in the number of new graben forming. Because Group 3 grabens are observed before and after the deposition of the lava flow AHThv, it appears the Syria NW Center was active when the young AHThv lava was emplaced; whereas the decrease of graben associated with the Claritas center after the deposition of AHThv may indicate that this center is no longer active except for minor reactivation of existing graben.

Group 4 graben are dominated by the appearance of a new trend N56°W. These graben are located in the southern portion of the mapped area and project radially to the Arsia Mons volcano. Minor reactivation of the Group 1, 2, and 3 graben can also be identified associated with the formation of Group 4. Group 5 graben appear to have resulted from the reactivation of the Group 1a, Stage 3 (Syria NW) center graben.

Basin Analysis: Deformation of the Early Noachian heavily cratered crustal materials in the Memnonia-Sirenum mapped region marks an early phase of Mars evolution. Early to Middle Noachian tectonism is interpreted by 1) stratigraphic units displaying high densities of impact craters and magnetic signatures; 2) a set of largely northeast trending prominent faults; and 3) structurally controlled basins (widths vary from kilometers to hundreds of kilometers) displaying evidence for water enrichment in the substrate.

Correlative in time with the deposition of the Early to Middle Noachian highland units was the formation of northeast trending basins (Trend 1 - N25ºE) and associated ranges (~3.87 Ga), which included major extensional forces similar to what has been identified for the Basin and Range province of the western United States [3]. In order to investigate the temporal timing of the northeast trending basins (Trend 1 - N25ºE) and the northwest trending set of basins (Trend 2 - N35ºW), we compared the models developed by Banerdt et al. [2] for predicting the stresses that should be associated with the formation of Tharsis (external loading, flexural uplift, and isostatic [2; Figs. 5 and 6] to features mapped in the Memnonia-Sirenum region to determine if the fomation of Tharsis could be responsible for the formation of the basins. Using the Stage 3- Syria center (4ºS; 107ºW) identified by Anderson et al., 2001) as the starting center as reference, superimposing the external loading case does predict the presence of extensional stresses in this map region. But a closer examination of the strain direction from this model predicts a northwest (~N10ºW) extensional direction for the basins, not a northeast (N25ºE) direction as mapped for basins in this region.

For flexural uplift model, a similar pattern in the predicted stress derived from the flexural uplift model (~N10ºW) as was seen with the external loading case. The major difference in this model is that the flexural uplift case predicts more compressive stress in area of the northeast trending basins (~-20ºlatitutde; 215ºlongitude), not extensional as observed. All of the modelled predicted extensional features lie to the west of the observed basins (~-40ºlatitutde; 195ºlongitude). It was interesting to note that the external loading case does predict compression in the area where the Trend 2 ridges were identified. Although both the external loading and the flexural uplift models predicted extension in the area of the basins, neither adequately explain the predicted azimuthal stress direction for the basins identified from the mapping in this region.

Projecting perpendicular stress lines from the ridges, using the two ridge trends identified above [1], the perpendicular from the northeast trending ridges (Trend 1 - N25ºE) projects approximately to the Stage 1 (Claritas), whereas the perpendicular stress lines for the northwest trending ridges (Trend 2 - N35ºW) project to the Stage 3 (Syria NW) center identified by Anderson et al., [1] respectively.

Figure 3 is a combination of the flexural uplift predicted stresses projected to the Stage 1 (Claritas-27ºS; 106ºW) center of Anderson et al., [1]. If you further rotate the center of the flexural uplift model to the northeast, parallel to the direction of the Tharsis mountains (~20 degree), the predicted stress patterns correlate very well with the mapped basin structures of Trend 1 (N25ºE). It was interesting to note, that making this slight rotational shift of the center of the stress field to the northeast, you not only get a strong alignment to the northeast trending basins mapped in the Memnonia-Sirenum region, but the model predicts extensional stress associated with all three of the Tharsis Montes volcanoes: Arsis, Syria NW, and Ascraeus. Unfortunately, by adding this rotation to the stress pattern, there is no correlation with the Trend 2 ridges (N35ºW) identified in this study.

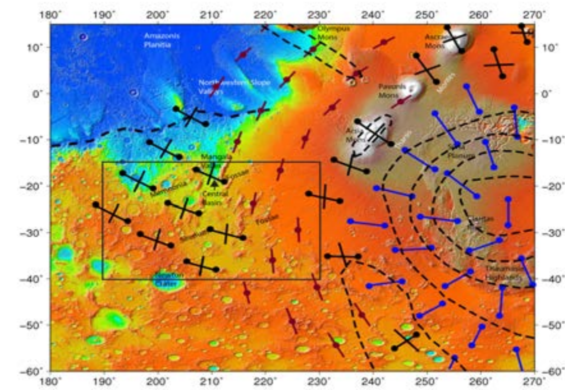

Fig. 3 Composite map of the Flexural Uplift model of Banerdt et al. [2] centered at the Stage 1 center 27°S, 106°W of Anderson et al., [1] and rotated 5º to fit the azimuth direction of the Tharsis Montes. The stress orientation indicators with symbols at each end denote horizontal extesion; those with symbols in the center denote compression. See Fig. 5 of Banerdt et al., [2] for complete explanation.

Conclusion: It appears the older N25ºE trending ridges/basins (Trend 1) appears to be the result of the initial uplift of Tharsis centered at Claritas. This is in agreement with the results of Anderson et al. [1] where the Claritas Stage 1 center was the oldest and appeared before the Syria Stage 3 center; it is therefore apparent that Claritas marks the earliest center for Tharsis identified to date and is responsible for the formation of the NE trending extensional basins by flexural uplift. It also appears that over time, the plume migrated to the northwest towards the Syria NW center, building up Tharsis, and forming the Trend 2 basins (N35ºW) as a result of external loading of the crust and the younger graben sets. This migration no only led to the major buildup of Tharsis, but also to the formation of the young graben sets identified. Combining the results from the flexural uplift model and subsequent external loading of Tharsis following the buildup provides an excellent job of explaining most of the structurallly controlled basins observed in the Memnonia-Sirenum map area.

References: [1] Anderson, R.C., et al., 2001. JGR 10620,563-20,585. [2] Banerdt, W.B., et al., 1992. Stress and tectonics on Mars (book chapter). Mars, H.H. Kieffer, B.M. Jakosky, (eds.), University of Arizona Press, p. 249-297. [3] Karasözen, E., J. C. Andrews-Hanna, J. M. Dohm, and R. C. Anderson, 2016, The Formation of the South Tharsis Ridge Belt: Basin and Range-style Extension on Early Mars, JGR, Vol. 121, Issue 6, pages 916-943, https://doi.org/10.1002/2015JE004936