EXTENSION AND STRAIN ACROSS VALLES MARINERIS. **Richard A. Schultz**, Geomechanics–Rock Fracture Group, Department of Geological Sciences, Mackay School of Mines, University of Nevada, Reno, NV 89557-0138 (http://unr.edu/homepage/schultz; schultz@mines.unr.edu).

Summary.
Extension and strain are calculated for six traverses across the Martian Valles Marineris troughs. Extension accommodated by the large trough normal faults varies systematically along the length of the trough system, increasing from 5–10 km near the eastern and western termini to a maximum value of 20–30 km near the center, assuming 60° fault dip angles and ±1 km in trough relief. The spatial gradient in extension exceeds reasonable uncertainties in both topography and fault dip, demonstrating an inhomogeneous deformation field along strike, similar to other well documented examples of normal faults and grabens on Earth. Strain also varies with position, typically between 5 and 20%. Smaller values of strain reported for the Valles Marineris region, <2%, that include large expanses of unextended terrain represent spatial averages that may underestimate the magnitude of strain at the troughs.

Introduction and Background.
Troughs in the Valles Marineris system accommodate localized extensional strain of the Martian lithosphere [1–7]. Normal-fault displacements that have been observed at various locations in several troughs [1,4] represent evidence for discrete extensional strain. Previous work showed that extensional strains across multiple sets of shallow grabens in the Tharsis region [8–12] were small, < 1% across a given area. Attempts to calculate regional strains across the large, triangularly shaped quadrant containing Valles Marineris [12] have resulted in relatively low values, 2% or less, despite the large length, depth, and extent of the troughs.

Methods and Results.
Horizontal extension and strain accommodated by trough faults are estimated by measuring vertical offsets of inferred correlative strata such as Upper Hesperian caprock [4] across each major fault and summing these offsets along the traverse which has a deformed (final observed) length L_f. Strain ε is calculated using $\varepsilon = (L_f - l_0)/l_0$, where L_f is the final, deformed length of the faulted area along a given traverse and l_0, the initial, unfaulted length, is given by $l_0 = (L_f - e_T)$ in which e_T is the cumulative extension across the area. An uncertainty of ±10° in fault dip contributes a factor-of-two uncertainty in the amount of extension; the uncertainty in measurement of L_f of perhaps 10%, and that due to a ±1 km uncertainty in relief across each fault, are smaller than that due to fault dip. The topographic uncertainty contributes a 20% variation in extension or strain for a given dip angle.

Extension accommodated by the large faults varies along strike, increasing from 5.8 ± 1.2 km in eastern Coprates Chasma to 27.2 ± 5.8 km in central Melas Chasma, assuming fault dips of 60°. The largest values of extension occur in central Melas Chasma (17.1 ± 3.6 to 39.5 ± 8.4 km, corresponding to 70° and 50° dips, respectively). Perhaps the clearest estimate of extension in the central trough region, determined using unambiguous faults from both western Coprates Chasma [4] and from Candor Chasma, is 20.2 ± 4.1 km for 60° dips, with lower and upper bounds of 12.7 ± 2.5 to 29.4 ± 5.9 km. Extension decreases in magnitude to both west and east, from the central Melas Chasma area, by about a factor of two for a given fault dip angle. Even if faults steepened from 50° at the trough termini to 70° in Melas Chasma, the changes in extension along the strike of the trough system would exceed the uncertainties due to both fault dip and relief. However, it is more likely that the major faults dip at reasonably consistent angles throughout the trough system, rather than varying randomly, making the observed changes in extension with position more significant than some conjectural variation with dip angle.

The amount of extension at the surface across Valles Marineris is comparable to the values reported for other areas near Tharsis. For example, the extension accommodated by numerous shallow grabens in Tempe Terra, 7–38 km [12], is comparable to the extension across the localized troughs. However, the extension in Tempe is distributed across a larger area, and across many more faults, than that in the Valles Marineris region, which is comparatively narrow and contains fewer but larger faults. Although a single, average value of extension may appropriately characterize regions of distributed faulting such as Tempe Terra, a *gradient* in extension along the troughs is implied by the data. Given these differences, comparable values for extension at the surface in those regions require distinct mechanisms for accommodating the deformation, both at the surface and at depth, as well as differing values for the respective horizontal strains.

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Extensional strain ε also appears to vary along the troughs. Strain across the eastern troughs (Coprates Chasma and Candor Chasma but excluding Ophir Planum) varies from 3–7% to 5–12%, assuming the full range of dip angles, with the increase associated with deepening and widening of the troughs from east to west. Strain across Ius Chasma, in the western region, about 10–20% for 60° dipping faults, is comparable to, or somewhat greater than, that across the eastern troughs. The small value of strain across central Melas Chasma, 3–7%, results from excessive traverse length relative to trough depth. The magnitude of strain along the trough system appears well bounded by $5 < \varepsilon < 20\%$.

In a previous study, Schultz [4] calculated extension and strain across western Coprates Chasma. Assuming fault dip angles of 60°, values of 17 km and 28% were obtained. The value of extension determined in that study agrees well with the present value, but the previous strain estimate exceeds the present one by about a factor of two. The difference can be attributed to the inclusion of Candor Chasma, a relatively broad but shallow trough, in the present, more comprehensive study. Further addition of Ophir Planum, a plateau deformed only by shallow plateau grabens, to this traverse would reduce strain still further from 5–12% to values comparable to those for Melas Chasma, 3–7%. Inclusion of Lunae Planum and Coprates plateau, regions beyond the troughs that have not experienced significant contemporaneous extension, would reduce regional strain still further to the <2% value reported in other studies [11,12].

Differences in traverse lengths considerably affect the calculation of strains. For example, the roughly triangular shape of the Valles Marineris quadrant [10] of Tharsis, across which traverse lengths increase from west to east, requires that a single value of strain cannot be representative of this region. Using an approximate average value of extension of about 15 km (60° dip, range 5–20 km) and estimated traverse lengths for the quadrant (taken perpendicular to trough strike near the "inner", narrow part of wedge-shaped quadrant [10], length 1814 km, and the "outer" part, length 4691 km), the strains are 0.83% for the inner part and 0.32% for the outer part. Although these values could be used as constraints in a Tharsis deformation model, they clearly represent spatial averages that may mask the large inhomogeneities in strain across the quadrant in the direction normal to the trough system (maximum at Valles Marineris, negligible elsewhere).

While the present study was underway, Mège [13] and Mège and Masson[14] independently assessed the magnitudes of extension and stretch across Valles Marineris by using a similar technique. Stretch is defined as L_f / l_0, a dimensionless quantity analogous to strain. Mège and Masson also found that extension increases from ~10 km near trough system terminations to a maximum value of 30–40 km in Melas Chasma (for 60° dipping faults), values comparable to those obtained in the present study. Their larger values for extension may be due to ambiguities in the thicknesses of interior layered deposits and concomitant estimates of fault throws. They also identified an increase in extension in easternmost Coprates Chasma, paralleling our results. The independent work by Mège and Masson, along with the results of the present study, strongly suggest that variations in extension along Valles Marineris troughs are both real and systematic.

Conclusions.

Extension and strain vary systematically with position in the trough system, with extension being greatest in the central trough regions, near western Coprates Chasma and perhaps in Melas Chasma, and smallest near the eastern and western terminations. The results show that extension accommodated by the troughs, 5–30 km, is comparable in magnitude to that reported for other areas around Tharsis, although the average value for strain calculated by previous workers for the Valles Marineris quadrant, <2%, may underestimate the magnitude of strain at the troughs. The strain of 5–20% determined in this study for the troughs provides a new constraint on the amount of near-surface deformation during trough growth [15].

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