DISPLACEMENT-LENGTH SCALING OF FAULTS ON EARTH, MARS, AND BEYOND. Richard A. Schultz[1], Chris H. Okubo[1], and Scott J. Wilkins[1,2] [1]Geomechanics–Rock Fracture Group, Department of Geological Sciences/172, Mackay School of Earth Sciences and Engineering, University of Nevada, Reno, NV 89557–0138 (www.mines.unr.edu/geo-eng/geomech; schultz@mines.unr.edu); [2]Now with Shell International Exploration and Production, P.O. Box 481, Houston, Texas 77001.

Summary: Faults on Mars exhibit ~1/5 of the maximum displacement D_{max} of terrestrial faults for any given length L. This systematic shift to smaller D_{max}/L ratios results from the gravity dependence of shear driving stress, yield strength of rock at the fault tipline, and stiffness (modulus) of the surroundings. To first order, the D_{max}/L ratio scales with gravity, so faults of any type on smaller planets and satellites will accumulate smaller displacements per unit length than faults on Earth. This reduction is modulated by the lithology and pore-pressure state of the lithosphere.

Introduction: Precision measurements of the maximum displacement ("offset," D_{max}) and map lengths L of surface-breaking faults on Mars [1,2] and Mercury [3,4] demonstrate that less displacement per unit length is accumulated along faults on these planets than along terrestrial ones. For example, normal faults from Tempe Terra (Mars) and thrust faults from Arabia (Mars) show D_{max}/L ratios of 6.7 x 10^{-3} [2] and 6 x 10^{-3} [3], respectively. Thrust faults from Mercury also show D_{max}/L ratios of 6.5 x 10^{-3} [4]. Typical values for terrestrial faults (normal, strike-slip, or thrust) are ~1–5 x 10^{-2} [5,6]. Data from the literature for normal faults from Earth and Mars are shown in **Fig. 1**.

In this abstract we demonstrate the key role played by *gravity* in displacement-length (*D-L*) scaling of faults and, by implication, other types of fractures such as joints and dikes, on other planetary bodies. We incorporate gravity explicitly into the standard *D-L* scaling relations for faults [7,8] and find that the systematic shift toward smaller maximum displacements for normal and thrust faults on Mars and Mercury is related to the reduced gravity on these planets relative to the Earth.

Background: For an individual fault (having a central well-slipped portion bounded by frictionally stronger end zones: a "Dugdale-Barenblatt" model) [8],

$$\frac{D_{max}}{L} = \frac{2\,(1-\nu^2)}{E}\, C \left\{ \sigma_d - \sigma_y \left[1 - \cos\left(\frac{\pi}{2} \frac{\sigma_d}{\sigma_y} \right) \right] \right\} \quad (1)$$

in which ν is Poisson's ratio, E is Young's modulus (both of the surrounding rock), L is fault length, σ_d is the cumulative shear driving stress on the fault, and σ_y is the yield strength of rock bounding the fault. Plausible values of σ_y/σ_d are 2–3 [e.g., 7,8] so that C = 0.4–0.6.

Equation (1) shows that the D_{max}/L ratio for faults depends on three key factors [7,8]:

- **Driving Stress.** This is the shear stress leading to slip and displacement along the fault, represented as $\sigma_d = (\Delta\mu\, \sigma_n)$, where $\Delta\mu$ is the difference between static and residual (or maximum and dynamic) friction coefficients for single-slip events [7,9], and σ_n is the magnitude of effective (compressive) normal stress resolved from far-field tectonic stresses onto the fault plane. For faults, the relevant quantity is the cumulative shear driving stress [7,10] associated with the total (cumulative) geologic offset along the fault.
- **Rock Strength.** The shear yield strength of unfaulted rock at the fault's tipline modulates fault propagation and hence, the D_{max}/L ratio. Stronger rock requires greater near-tip stresses to break, leading to larger values of displacement along the fault [7,8,11].
- **Rock Stiffness.** The stiffness of surrounding unfaulted rock is given by $S \propto (1-\nu^2)/E$. The various moduli (Young's, shear, and deformation [12,13]) are interchangable here. As modulus increases, stiffness decreases and displacement along a fault decreases.

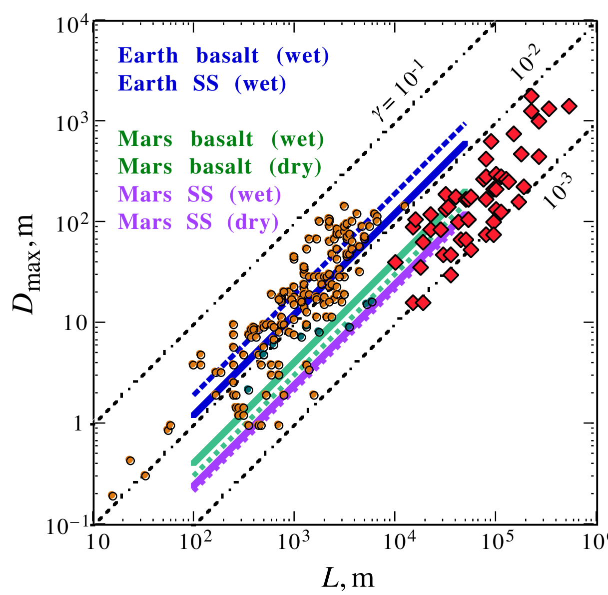

Fig. 1. Displacement-length data from Earth (L < 10 km, small circles, normal faults, after [16]) and Mars (Tempe Terra normal faults, L > 10 km). Upper two curves calculated for terrestrial data; lower four curves calculated for Mars. Curve order (planet, rock type, pore-pressure state) given by caption.

Results: We find that linear scaling, with $n = 1$ (giving a constant ratio of D_{max}/L as on **Fig. 1** [6,7]) requires constant values of shear driving stress, rock (yield) strength, and stiffness (modulus) across the length scale of the fault population. Our calculations assume a depth of 100 m over which these parameters were averaged; varying the depth interval does not alter the scaling conclusions.

Planetary gravity enters into each of these three factors, but more subtly than simply as a ratio of planetary gravities (e.g., g_{Mars}/g_{Earth}) because the reduction in D_{max}/L exceeds the gravity ratio (**Fig. 1**).

Driving (shear) stress is reduced on lower gravity planets because the resolved effective normal stress σ_n, and the horizontal and vertical far-field stresses (which promote fault slip), are all dependent on $\sigma_v = \rho g z$, in which ρ is average (wet or dry) rock density and z is depth.

Rock strength is calculated from the Hoek-Brown (Mohr) envelope for rock masses [12,13] assuming a Rock Mass Rating (RMR) of 50, appropriate for wet conditions and typical near-surface fracture densities; dry conditions are considered by increasing RMR to 65, following standard practice [e.g., 12]. For the basalt, $\rho = 2900$ kg m^{-3}, $m_i = 22$ and the unconfined compressive strength of the intact rock material $\sigma_c = 250$ MPa; for a weaker rock mass (such as tuff or poorly indurated sedimentary material), the parameters for sandstone are used ($\rho = 2200$ kg m^{-3}, $m_i = 19$, $\sigma_c = 100$ MPa). The yield strength is taken to be the peak shear strength of the rock mass averaged over the 100-m depth interval used. *Rock strength increases with planetary gravity for the same depth range below the surface* and is analogous to the well-known dependence of peak strength and confining pressure observed in experiments.

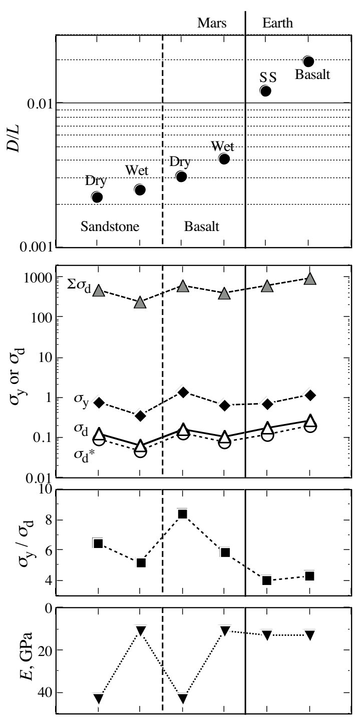

Fig. 2. Parameters for *D-L* scaling from Mars normalized to Earth.

Young's modulus is calculated from the known increase with depth from Earth [14], starting with a value at the surface corresponding to the deformation modulus calculated from RMR [12,13]. Because density and the pore-pressure state of the crust (that modulate E) depend on gravity, *Young's modulus decreases with gravity for equivalent conditions and depth ranges below the surface*.

Values of the main parameters for Mars, normalized by the values for the terrestrial wet basaltic rock mass, are shown in **Fig. 2**. For the same conditions of rock type (e.g., basaltic rock mass) and fluid-saturated crustal rocks (i.e., "wet" conditions), g reduces D_{max} by $g_{Mars}/g_{Earth} = 0.38$ (via the driving stress term). Yield strength in shear scales with gravity, with the Martian basaltic rock mass ~0.5 of the corresponding terrestrial one. Modulus decreases with decreasing g, to a normalized value of ~0.84 for the Martian case. The combined effect of g on all three key factors discussed above (0.38*0.5*0.84 = 0.16) is a reduction in D_{max}/L of about a factor of 5–6, consistent with the data (**Figs. 1 and 2**).

Scatter in *D-L* datasets arises from several sources [e.g., 5,6,8] including mechanical interaction and linkage, which are both found on Earth and Mars [1,15]. Variations in rock type or pore-pressure state appear small in relation to these other factors.

Conclusions and Implications: The systematically smaller values of displacement for faults on Mars and Mercury are *real*—not an artifact of measurement technique or data resolution.

We infer that faults on Venus should accumulate somewhat smaller displacements than their terrestrial counterparts given a ~10% reduction in gravity ($g = 8.8$ m s^{-2}) relative to the Earth. Faults on the icy satellites of Jupiter, Saturn, and beyond should also scale with gravity, with particular values of the D_{max}/L ratio depending on appropriate values of near-tip ice strength and ice stiffness.

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