CRITICAL FAULT TIP GRADIENTS, YIELD STRENGTHS, AND FAULT PROPAGATION ON EARTH AND MARS. A. T. Polit[1] and R. A. Schultz, Geomechanics-Rock Fracture Group, Department of Geological Sciences/172, Mackay School of Earth Sciences and Engineering, University of Nevada, Reno, NV 89557-0138, [1]polita@mines.unr.edu.

Summary: We demonstrate that a critical fault tip gradient is associated with fault propagation through its connection to material yield strength. This method of relating fault tip gradient to yield strength is applied to four Martian normal faults in the Tempe Terra region of northeast Tharsis, with tip gradients ranging between 0.126° and 0.212°, corresponding to yield strengths between 9 and 17 MPa. These values are dependent on the lithology and water content in the crust, so our methods can be used to examine how rock type and water content vary spatially across Mars.

Introduction and Background: The Dugdale model, which was developed for examining inelastic deformation at crack tips [1], avoids the stress singularity that is problematic in previous Linear Elastic Fracture Mechanics models by explicitly considering a high cohesion zone at the crack tip [e.g. 2,3]. One of the key characteristics of the Dugdale model, that is also found in many faults, is that the profile of displacement along the crack length tapers gradually toward the crack tip [4]. Cowie and Scholz [4] applied the Dugdale model to faults and showed that it provides a sound mechanical basis for the D/L ratios observed in the field. A representative D/L ratio for terrestrial faults is $1\text{-}5\times10^{-2}$ [4,5], while for Mars the D/L ratio is $\sim1\times10^{-3}$ [6].

In this study, we show that the Dugdale model can be used to define a new criterion for fault propagation using a quantity observable in topography data (fault tip gradient). Fault propagation is related to yield strength and, in turn, to fault tip gradient. We apply this method of yield strength determination to Mars and discuss implications for using changes in tip gradient across Mars to determine how rock type and water content vary in the crust and how they enhance or impede fault propagation.

Fault Propagation: The Dugdale equations describing the fault end-zone length and the fault tip shearing displacement [1] can be used to solve for the fault tip displacement gradient, δ_t/d, and the yield strength, σ_y. The tip gradient, in degrees, is

$$\theta = \frac{180}{\pi}\tan^{-1}\left\{\frac{\delta_t}{a\left[\sec\left(\pi\sigma_d/2\sigma_y\right)-1\right]}\right\} \tag{1}$$

where δ_t is the fault tip shearing displacement, σ_d is the driving stress, σ_y is the yield strength, and a is related to the fault half-length (c) and the end zone length (d) by $c = a - d$. The yield strength, in MPa, is

$$\sigma_y = \frac{\pi E}{8}\frac{\delta_t}{a\ln\left[\sec\left(\pi\sigma_d/2\sigma_y\right)\right]} \tag{2}$$

where E is Young's modulus, in MPa.

The stress concentration at the tip of a fault must exceed the yield strength of the surrounding material in order to propagate [4], implying that if the fault tip gradient is equal to or above a critical value, the yield strength will be met, so the fault will propagate.

Methods: To verify that the relation between tip gradient and yield strength using the Dugdale model can be applied to fault propagation, we calculate yield strengths by using fault tip gradient and other parameter values from two studies of terrestrial faults and compare these values to published yield strength values.

Cowie and Scholz [4] analyzed data from the Coal Measure normal faults in Britain to obtain values of modulus, the driving stress to yield strength ratio (σ_d/σ_y), and yield strength. Using the values for modulus and σ_d/σ_y and equations (1) and (2), we plot the relation between fault tip gradient and yield strength. We use their average values for several fault parameters to determine the fault tip gradient.

Soliva and Benedicto [7] studied a population of normal faults and obtained values for modulus and σ_d/σ_y. We use these values with measured tip gradient values to determine yield strength.

Results: Using parameters from Cowie and Scholz [4], we calculated a yield strength of ~140 MPa (**Fig. 1**), while they determined yield strength values between 170 and 190 MPa [4]. Although lower than the yield strengths of Cowie and Scholz [4], our value is well within a factor of two, indicating that the use of the Dugdale model to determine yield strength is valid.

The value of yield strength that we determine from parameters set in Soliva and Benedicto [7] is ~31 MPa (**Fig. 1**), whereas the value in Hatheway and Kiersch [8] for the unconfined compressive strength (UCS) of a material with similar modulus and Poisson's ratio values is ~12 MPa. Since the faulting depth was below the surface, the yield strength value should be higher

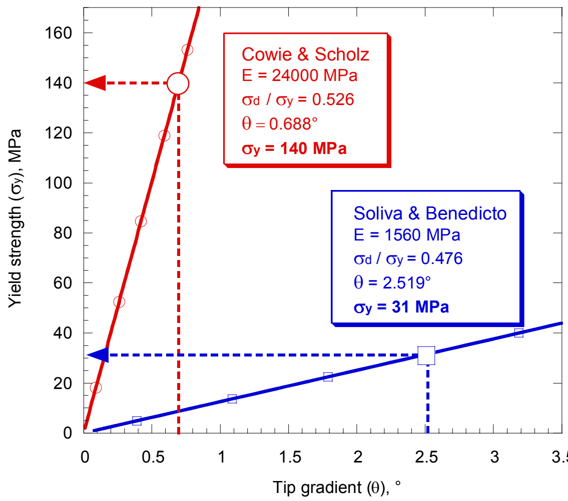

Figure 1. Yield strength vs. tip gradient for terrestrial examples [4,7], with graph input parameters, individual tip gradients, and resulting yield strengths shown.

than the UCS value. When taking this into account, the value of yield strength obtained here and the published value appear to be a reasonable match.

Application to Mars: The two case studies above show that using the Dugdale model to determine yield strength is a valid approach. To apply this method to Mars, we examine four graben-bounding faults (from two grabens) in the Tempe Terra region. Using MOLA based DEM's gridded at 200 pixels/° [9] we measure relief along the fault strike and convert these measurements to displacement, assuming a fault plane dip of 60°. From these displacement profiles, four fault tip gradients, one from each fault, are extracted. Since Young's modulus values on Mars cannot be directly measured, we use a reasonable approximation of deformation modulus (*E**), a measure of the deformability of a fractured rock mass that corresponds to Young's modulus in equations (1) and (2) [10]. To calculate *E**, a Rock Mass Rating value of 50, typical for surface fracture densities, was chosen, with a resulting modulus value of 10 GPa [10,11]. A representative range of values for σ_d/σ_y is between 0.2 and 0.5, with most faults having σ_d/σ_y values between 0.33 and 0.5 [12]. We apply the range between 0.2 and 0.5 to show how this parameter affects yield strength.

The four tip gradient measurements and the above parameter values are used to calculate possible yield strengths for the material surrounding the fault tips for the two Tempe Terra grabens (**Fig. 2**). The values range between 9 and 15 MPa for a σ_d/σ_y value of 0.2 and between 10 and 17 for a σ_d/σ_y ratio of 0.5.

Conclusions and Implications: The Dugdale model can be used to define a material yield strength and a critical fault tip gradient for propagation. As shown, this method can be applied to the determination of yield strengths on Mars, with the yield strength ranging between 9 and 17 MPa for the material surrounding the four examined faults. The yield strengths for Mars are smaller than the terrestrial values we calculate of 31 MPa and 140 MPa, consistent with gravity scaling [13]. This relationship is also consistent with smaller values of D/L for Martian faults relative to terrestrial faults [6,13].

Yield strength is dependent on lithology and pore-water content [14]. Since tip gradient is directly related to yield strength, changes in displacement gradient across Mars can be used to examine how rock type and water content vary in the Martian crust. For example, the transition from Tharsis to the Northern plains on Mars would cause a reduction in tip gradients and yield strengths if the materials of the plains are either softer or wetter (or both) than those on the Tharsis rise.

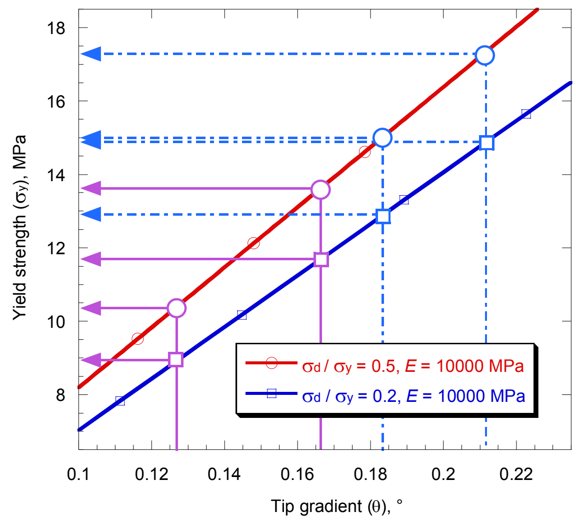

Figure 2. Yield strength vs. tip gradient for Martian examples, with input parameters shown. The tip gradients and resulting yield strengths for the two grabens examined are differentiated by line style and color.

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