INFLUENCE OF GRAVITY ON THE GEOMETRY OF MARTIAN NORMAL FAULTS.

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Introduction: Extensional fault scarps on Mars bear a striking resemblance to fault scarps on Earth, including geometric features such as horsts, grabens, relay ramps and breached relay ramps, *en echelon* arrangement of faults and grabens, and scaling characteristics [1], [2], [3]. Other surface features associated with extensional faulting on Mars are lines ("chains") of circular topographic depressions, referred to as pit craters. These pit chains are easily observed in remotely sensed data from Mars. Although rare, pit chains also occur on Earth associated with extensional deformation. Based on the similarity in map view, one might surmise that the subsurface geometry of faults on Mars would similarly mimic structural style on Earth. However, a fundamental difference exists between Earth and Mars, which may have a profound effect on fault architecture—the difference in the gravitational acceleration on the two planets. We consider likely fault dips and fault profiles on Mars by accounting for Mars' gravity, likely rock types, fluid pressure conditions, and analogs from Earth. The results demonstrate that fault profiles on Mars are likely to be similar in shape to analogs on Earth, but that depth-dependent fault dip transitions are likely to occur deeper than on Earth and occur more gradually with depth. These results provide the basis for more robust structural interpretations of remote sensing data from Mars, and technically more sound models of faulting and related processes on Mars. Dilational faulting, found in the upper ~2 km on Earth, may extend to depths of 5 km or more on Mars. This dilational faulting may influence subsurface fluid flow, as well as dissolution and mineralization along faults. Similarly, the seismogenic zone on Mars is likely to be considerably deeper than on Earth.

Failure modes, failure angles, and fault dip: Initial fault orientations are controlled by mechanical properties of the faulted rocks, and magnitudes and orientations of the effective principal stresses at the time of failure [4]. Failure angle is defined as the angle between the failure plane and the maximum principal compressive stress (σ_1) at the time of failure. At low differential stress ($\sigma_1 - \sigma_3$), failure is commonly in the tensile mode, producing fractures with failure angles of 0° (fault dip = 90°) that experience wall-normal extensional displacement. Failure at high differential stress is typically in the shear mode, producing fractures that are oblique to the maximum principal stress, with wall-parallel shear displacement. Transitional behavior between tensile and shear modes is termed hybrid; faults with low failure angles (>0°) form and have wall-oblique displacement. Failure mode depends on the differential stress and the effective minimum principal compressive stress (σ_3'; $\sigma_3' = \sigma_3 - P_f$, where P_f = pore fluid pressure) at the time of failure, and the strength characteristics of the rock. Because of this influence of failure mode on fault dip, normal faults on Earth have steep dips near the surface, and progressively more gentle dips at depth. Very steep dips of 70°–90° are common in the uppermost brittle crust (0–2 km) in a variety of rocks including volcanic tuffs, limestones, and clastic sedimentary rocks [5]. Dips of 60° are common at intermediate depths (2–5 km), and moderate dips of 35°–55° are common at seismogenic depths in the lower part of the brittle crust (>5 km) (e.g., [6]). Low angle dips of 0°–35° are associated with detachments at the brittle-ductile transition in the crust and in extremely weak sedimentary layers.

Lithostatic stress and normal faulting: In normal faulting regimes σ_1 is vertical and equivalent to lithostatic stress (σ_v), which is a function of the thickness (h) of the overburden, the average density of the overburden (ρ), and the acceleration due to gravity (g) ($\sigma_v = \rho g h$). As a result of the vertical stress gradient, differential stress required for failure also increases with depth. Assuming a range of density values of 2.7 to 3.1 g/cm^3 for basalt [7] as examples, the lithostatic stress gradient can be calculated for Earth (g = 9.81 m/s^2), and Mars (g = 3.72 m/s^2) (Fig. 1). We constructed Hoek-Brown failure envelopes [8] based on failure test data from 37 basalts [9]. Basalt was chosen as a likely rock type of Mars because extensive volcanic plains cover half of its surface [10]. Ignoring the influence of fluid pressure, and assuming an average crustal density of 2.7 g/cm^3, depths on Mars and Earth can be assigned to points on the failure envelopes. Tensile and hybrid failure for an "average basalt" and corresponding fault dips of 70°–90°, would be limited to <2 km on Earth, but are likely to depths of ~5 km on Mars.

Discussion: As a result of lithostatic stress variation with depth, active normal faults on Earth commonly have listric shapes with very steep dips (70°–90°) near the surface, and profiles that flatten to moderate or even low angles at depth. In some cases, steep fault segments in the uppermost crust are dilational, experiencing volume increase. Because gravitational acceleration on Earth (9.81 m/s^2) is higher than on Mars (3.72 m/s^2), stress within Earth is greater than Mars for any given depth. If faults form in similar situations on the two planets, and if rock types are similar, fault-dip transitions would occur at greater depths (approx. 2.64 times) on Mars than on Earth. Consequently, steep fault segments in the crust are likely to extend to about 5 km depth on Mars compared with about 2 km depth on Earth. Dilation of these steep segments associated with fault slip at depth on Mars could result in large volume increase in the uppermost crust. Highly dilational faults would help explain the common occurrence of pit chains near faults (Fig. 2) and would strongly influence fluid movement and mineralization in the Martian crust. The seismogenic depth associated with extensional deformation on Mars is expected to be shifted deeper due to lower gravity but would also depend on geothermal gradient at the time of active faulting.

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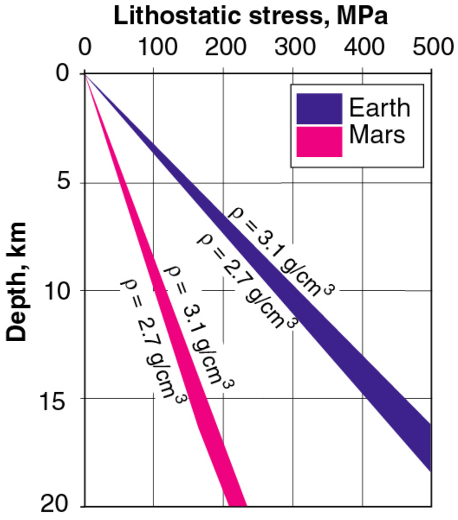

Fig. 1. Lithostatic stress gradients on Earth versus Mars assuming same rock type (basalts) and no hydrostatic gradient.

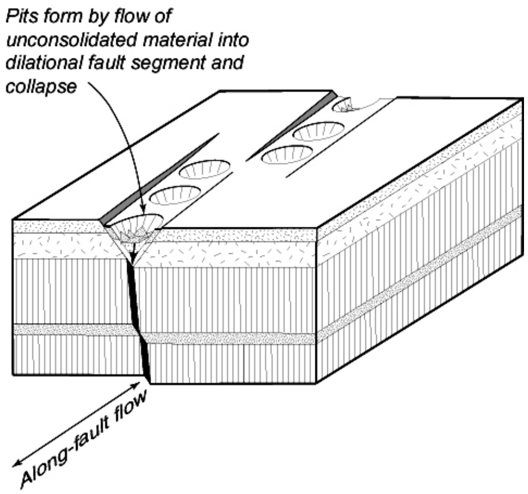

Fig. 2. Schematic illustration of faulting on Mars that displays steep dilated faults and their potential relationship to fluid flow and pit chain development.