The Scaling of Geological Faults

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ABSTRACT

Geological faults are shear fractures in rock that may range in length from a cm to 1000km, allowing for a the study of scaling over an unusually broad range. Their shear displacements are found to scale linearly with fault length, with a proportionality constant of the order of 10^{-2}. Their displacement profiles are self-similar, with linear displacement tapers near the tips. These tip tapers are scale-independent. Faults propagate by forming a brittle process zones in the region surrounding their tips. These consist of intergranular tensile microcracks oriented parallel to the maximum compressive stress in the crack-tip stress field. Their maximum crack density is at the edge of the fault and is scale independent. Crack density falls away exponentially with distance from the fault and the width of the process zone increases linearly with fault length. All of these observations are consistent with an elastic-plastic (CTOA) crack model in which yielding occurs in a volume surrounding the crack tip. This implies that fracture energy increases linearly with fault length such that a classical Griffith type instability will not occur. Similar scaling laws apply to earthquakes and joints (macroscopic opening mode fractures in rock).

1 INTRODUCTION

Geological faults are shear fractures in rock with friction on their interfaces. Work over the past decade has revealed their scaling laws as well as the mechanism by which they propagate. Most of these results, as well as related topics such as fault interactions and populations, has been reviewed in Scholz [1], but because most materials scientists are unlikely to consult that work, we briefly recapitulate the more important results here.

The upper few tens of km of the Earth is brittle and under overall compressive stresses so that deformation is primarily through the formation of faults, which accommodate displacements by frictional sliding in their interiors. The rocks through which they propagate are primarily crystalline aggregates of silicates formed under high temperature and pressure, with sintered grain boundaries. Because three or more silicate phases are usually present, and because each is anisotropic in its material properties, strong stress concentrations are developed at the grain scale that results in the grain boundaries being partially cracked, producing a small but connected crack porosity. This also results in there being a high degree of stress heterogeneity at the grain scale. The engineering materials they most closely resemble are the high toughness ceramics (e.g. Evans [2].

2 DISPLACEMENT SCALING

Faults initiate at a point and as shear displacement D accumulates in their interiors they grow in length L. Figure 1(left) shows the displacement profiles normalized to fault length for a number of faults in the same rock type with lengths ranging from 690-2200m,. A good data collapse is observed, indicating linear scaling between D and L. Notice also that the displacement taper near the fault tips is approximately linear and is scale invariant. A global collection of data is shown in Figure 1 (right), which shows D scaling linearly with L over seven orders of magnitude. The maximum displacement is shown in that figure: if average displacement were shown, the scaling would be the same with a slightly lower proportionality constant. The proportionality constant is

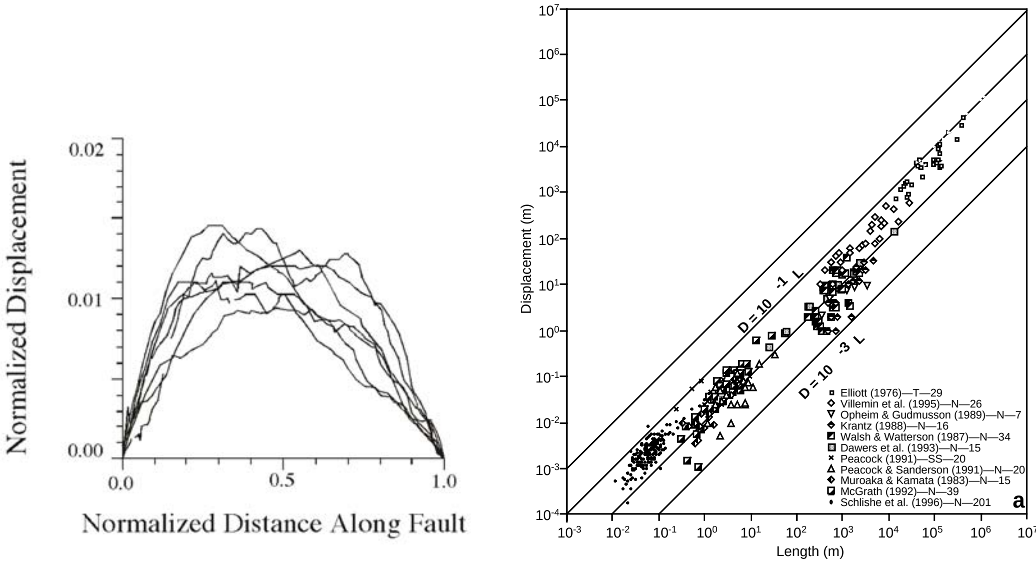

Figure 1 Left, displacement profiles, normalized by fault length, for faults in welded tuff in the Volcanic Tablelands, eastern California (after Dawers [3]). Right, Displacement vs. length for a global fault dataset (after Schlische et al. [4]).

A measure of stress drop, (σ_y - σ_f) where σ_y is the yield strength of the intact rock and σ_f is the residual friction. The stress drop varies with rock type but is scale invariant and of the order of several hundred MPa. Most faults grow intermittently by earthquakes, a stick-slip frictional phenomena. Earthquake displacement profiles and D/L scaling are identical with faults, but with much smaller stress drops, of the order of 1 MPa. In this case the stress drop represents the drop from static to dynamic friction.

These observations differ markedly with the predictions of linear elastic fracture mechanics. If a fault was an elastic crack, it would have an elliptical displacement distribution, rather than the one observed. Furthermore, if fracture energy G was a constant, we would expect $D \propto \sqrt{L}$. The observed linear scaling of D with L implies that G also scales linearly with L. The crack model that agrees with the fault data is the CTOA (constant tip opening angle) model (Kanninen and Popelar [5]). This is a numerical model in which inelastic yielding is allowed to occur in a volume around the crack tip wherever the stress exceeds the yield strength σ_y. As its name applies, it predicts a scale invariant linear displacement taper near the tip. It also predicts a linear scaling between D and L. Both these agree with the two observations seen in Fig. 1.

3 PROCESS ZONE SCALING

The CTOA model also predicts that inelastic deformation occurs in a volume surrounding the crack tip and that G increases linearly with L. To test these predictions, a series of holes were cored across several strike slip (Mode II) faults in quartzite (a pure sintered quartz rock). Intergranular microcracks were counted from thin sections and their orientations measured (Vermilye and Scholz [6]). A brittle process zone was observed consisting of Mode I

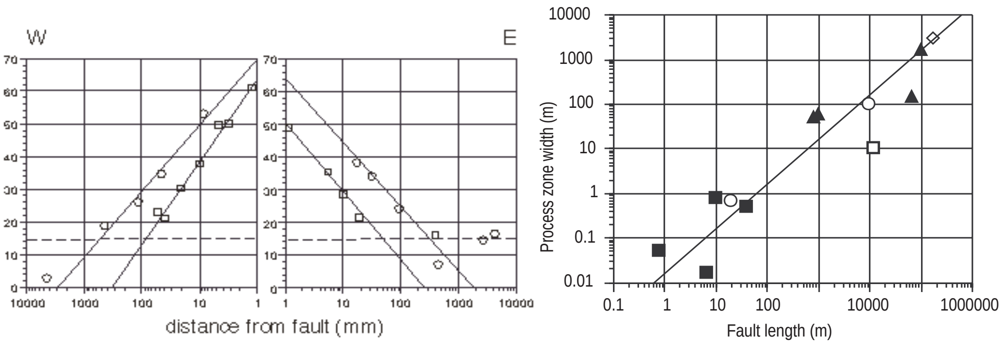

Figure 2. Left, microcrack density as a function of distance from two mode II cracks in quartzite. The dashed line is the background microcrack density. Open circles are for a 40 m long fault, open squares for one 2 m long. Right, process zone widths for faults of different lengths. The slope of the line is 1. Both figures are after Vermilye and Scholz [6].

microcracks in which the their density fell off exponentially with distance from the faults (Fig. 2, left). The orientations of the poles of the microcracks in the process zone had strong maxima perpendicular to the maximum principal compressive stress predicted from the Mode II elastic crack tip stress field, whereas those outside the process zone had pole maxima perpendicular to the regional maximum principal compressive stress, which was about 25° from the fault trace, as expected for Coulomb failure with a friction coefficient of about 0.5. The open circles are for a 40m long fault and the open squares for a 2m long fault. The dashed line indicates the background microcrack density. The maximum microcrack density is independent of fault length but the width of the process zone is proportional to it. This is shown for a wider range of fault lengths in Fig. 2 (right), where the line has a slope of 1. This linear scaling of process zone width with fault length indicates that G scales linearly with L because the surface energy associated with fault growth is the sum of the surface energy of all the microcracks in the process zone.

4 JOINTS AND EARTHQUAKES

Although less work has been done on them, It appears that joints (macroscopic mode I cracks in rock) also best agree with the CTOA model. They have linear scaling between opening and length and tend to have linear opening profiles near the crack tip (Vermilye and Scholz [7]). They have also been observed in the laboratory to have brittle process zones (Swanson [8]). Earthquakes also have linear scaling between D and L and linear tip tapers (Scholz [1]).

5 DISCUSSION

Neither the elastic crack model or LEFM is appropriate for modeling the growth of macroscopic cracks in rock. Because G scales with L rather than being constant, the classic Griffith instability does not occur. The only instability in faults is the frictional one which causes earthquakes. Faults grow intermittently at the time of earthquakes (Cowie and Scholz [9]), but otherwise are quasi-static. We think that the development of brittle process zones at fault and joint tips results from the granular nature of the rock and the resulting stress heterogeneity at the grain scale. It appears that fractures high-toughness ceramics behave the same as rock. They develop brittle process zones and have R-curve behavior (Evans [2]). Although in the laboratory fracture toughness K is measure over only a factor of 2 to 4 and so cannot be proved, from our observations of G scaling with L for rock, we would interpret the R-curve behavior of these ceramics as meaning that K scales with $\sqrt{L}$.

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