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The work budget of rough faults

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ABSTRACT

Faults in nature have measurable roughness at many scales and are not planar as generally idealized. We utilize the boundary element method to model the geomechanical response of synthetic rough faults in an isotropic, linear elastic continuum to external tectonic loading in terms of the work budget. Faults are generated with known fractal roughness parameters, including the root mean square slope (β), a measure of roughness amplitude, and the Hurst exponent (H), a measure of geometric self-similarity. Energy within the fault models is partitioned into external work (W_{ext}), internal elastic strain energy (W_{int}), gravitational work (W_{grav}), frictional work (W_{fric}), and seismic energy (W_{seis}). Results confirm that W_{ext}, or work done on the external model boundaries, is smallest for a perfectly planar fault, and steadily increases with increasing β. This pattern is also observed in W_{int}, the energy expended in deforming the host rock. The opposite is true for gravitational work, or work done against gravity in uplifting host rock, as well as with frictional work, or energy dissipated with frictional slip on the fault, and W_{seis}, or seismic energy released during slip events. Effects of variation in H are not as large as for β, but W_{grav}, W_{fric}, and W_{seis} increase with increasing H, with W_{int} and W_{ext} decreasing across the same range. Remarkably, however, for a narrow range of roughness amplitudes which are commonly observed along natural faults, the total work of the system remains approximately constant, while slightly larger than the total work of a planar fault. Faults evolve toward the most mechanically efficient configuration; therefore we argue that this range of roughness amplitudes may represent an energy barrier, preventing faults from removing asperities and evolving to smooth, planar discontinuities. A similar conclusion is drawn from simulations at relatively shallow depths, with results showing that shallower faults have larger energy barriers, and can be mechanically efficient at higher roughness amplitudes.

1. Introduction

Faults in nature, while generally idealized as planar shear discontinuities, are indeed rough and non-planar. Much research has been done to characterize the mechanical effects of roughness on faults both in nature and in the laboratory, with application to many fields of geology and geophysics. Fault roughness, in the form of jogs and step-overs, has been shown to affect patterns of mineralization around faults (Micklethwaite and Cox, 2004; Sheldon and Micklethwaite, 2007), as well as control the flow of fluids along faults (Veatch et al., 1965). Fault roughness has also been shown to have an appreciable effect on patterns of seismicity on faults of many scales (Candela et al., 2011a; Powers and Jordan, 2010). In addition to causing stress heterogeneity around faults (Chester and Chester, 2000; Nielsen and Knopoff, 1998; Saucier et al., 1992), fault roughness has been demonstrated to impede slip on faults (Dieterich and Smith, 2009; Fang and Dunham, 2013; Nielsen and Knopoff, 1998). Together, such heterogeneity in slip, slip rate, and normal stress may lead to heterogeneous frictional weakening processes during slip events, including fault opening (Griffith et al., 2010). Geometric irregularities have even been shown to stop earthquake rupture and affect patterns of fracture nucleation due to its tendency to act as a kinetic barrier (Sibson, 1985).

Fault roughness is thought to develop by the irregular linkage of smaller fault segments (Ben-Zion and Sammis, 2003; Candela and Renard, 2012; Walsh et al., 2003), and evolves by linkage and abrasive wear during individual slip events integrated over time (Marshall and Morris, 2012; Sagy et al., 2007). More mature and smoother faults are thought to be mechanically more efficient (Cooke and Murphy, 2004). Therefore, a general pattern of decreased roughness and increased mechanical efficiency is expected as faults evolve with increasing slip. However, faults in nature never reach planarity (e.g., Power and Tullis, 1991; Renard et al., 2013), even though planarity is the logical conclusion for maximized mechanical efficiency.

In this work, we investigate the possible mechanisms by which faults maintain measurable levels of roughness by quantifying the total work budget, including partitioning between various types of mechanical work, for synthetic faults of known roughness.

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2. Fractal descriptions of 2D fault roughness

Roughness, defined as the deviation from geometric planarity, is observable over many orders of magnitude on faults with length scales from microns to several kilometers (Power et al., 1987; Power et al., 1988). Self-affinity, or non-uniform scaling in shape and spatial trajectory along a geometric profile (Addison, 1997), has also been observed on natural faults and fractures over more than twelve orders of magnitude (Power et al., 1987; Power et al., 1988; Power and Tullis, 1991; Candela et al., 2011b; Renard et al., 2013). The geometry of fractal faults can be parameterized using the Hurst exponent, H, and an amplitude factor, β (e.g., Dieterich and Smith, 2009). These represent the degree of self-affinity of the fault profile and the root mean square (rms) slope of fault elements, respectively. An H of 0 represents pure random fractional Brownian motion, or complete randomness of spatial trajectory along a profile, and $H = 1$ represents pure self-similarity, or uniform scaling of geometric shape and spatial trajectory. In other words, profiles characterized by $0 < H < 0.5$ are deemed *antipersistent*, or more random in their surface trajectories, and profiles characterized by $0.5 < H < 1$ are deemed *persistent*, or more likely to maintain consistent surface trajectories (Addison, 1997). Feder (1988) suggests that it is rare for measurements of natural phenomena to have values of H less than 0.5 or greater than 0.8. Small values of β represent smaller changes in the slope of the fractal surface, with larger values increasing the rms value of the slope between the nodes of the profile. This change in β can be interpreted physically as a scale factor for roughness amplitude, with increased values representing increased visible surface roughness, and with H having an overall limiting effect on the total deviation of a fault profile. The relationship between these two parameters can be seen in the formula for the mean amplitude of deviations from a planar fault, or:

$$h = \beta x^H, \tag{1}$$

where h is the mean amplitude and x is the length interval that represents the fault. A geometric example of the interplay between H and β can be seen in Fig. 1.

Dieterich and Smith (2009) assert that $H = 0.5$–1.0 for natural fault surfaces, and that $\beta = 0.02$–0.10 for faults on the order of $L \geq 1$ km. Candela et al. (2009) suggest that values of β and H can be used to characterize the amount of mechanical wear of a fault surface at various scales, with these fractal parameters used to describe the level to which asperities have been worn down and removed from a fault surface. Faults that have incurred this mechanical wear and roughness reduction are said to be more "mature" than their rougher counterparts (e.g., Choy and Kirby, 2004), with values of β decreasing and H increasing as wear continues. Klinger (2010) argues that there is a scale-dependent inverse relationship between total fault displacement and fault-surface "smoothness", as faults generally become smoother with successive slip events.

Saucier et al. (1992) showed that slip on geometrically complex faults create stress field perturbations that dominate the stress field in the surrounding rock. Furthermore, Nielsen and Knopoff (1998) and Chester and Chester (2000) both argue that geometrical irregularity along rough faults creates stress field perturbations that may impede slip or allow for fault opening as well as cause off-fault tensile damage. This damage has been associated with geothermal fluid mineralization (e.g., Micklethwaite and Cox, 2004), and has been measured on multiple scales in relation to fracture density and damage zone area (e.g., Savage and Brodsky, 2011).

3. The work budget of a single-fault system

Work done in activating a faulted system can be partitioned into multiple types, describing work done on the fault surface, as well as throughout the rock surrounding the fault. Here we represent a rough, single fault system within a model domain that has bottom and left sides free of shear stress or normal displacement, allowing for lateral movement on each boundary (Fig. 2). The upper model boundary is free of shear and normal tractions, representing the Earth's surface. The right boundary is subject to a uniform leftward constant tectonic displacement (Δu_x), and the resultant contraction drives frictional slip and opening on the fault. Work done in the enforcement of these boundary conditions is calculated as internal strain energy (W_{int}) and gravitational work (W_{grav}) throughout the material continuum, external work on the boundary of the model (W_{ext}), frictional energy along the fault surface (W_{fric}), and seismic energy release (W_{seis}). Total work (W_{tot}) is the sum of all internal work terms:

$$W_{tot} = W_{int} + W_{grav} + W_{fric} + W_{seis}. \tag{2}$$

Assuming mechanical equilibrium, the total work within a system should equal the amount of external work imposed on the system (Griffith, 1921; Jaeger et al., 2007; Middleton and Wilcock, 1994). The work budget stated in Eq. (3) is represented in Fig. 2. Work terms

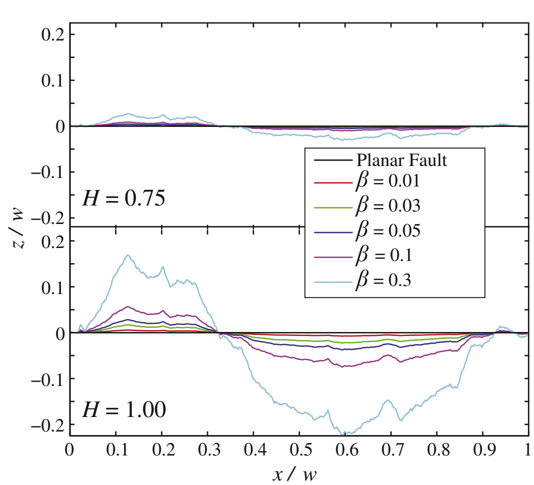

Fig. 1. A demonstration of the geometric effects of β and H. H has an overall limiting effect on planar deviations. The term w represents the true length of the fault, and is used as a normalizing factor.

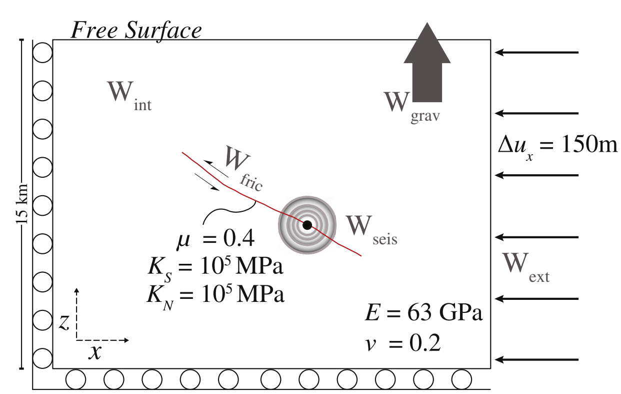

Fig. 2. A simple schematic of work due to a tectonic load Δu_x. The width and depth of the model are 20 and 15 km, respectively. The model is acted upon by a leftward tectonic contraction (Δu_x) on the right boundary. The elastic continuum representing the host rock are described by the Young's modulus (E) and Poisson's ratio (ν), and the fault is described by the constitutive behaviors of shear and normal elastic stiffness (K_S and K_N), as well as a static friction coefficient (μ). Each model used in this research has these dimensions and conditions. The resultant work budget of the model is divided into internal strain energy (W_{int}), gravitational work (W_{grav}), frictional work (W_{fric}), external work (W_{ext}), and seismic energy (W_{seis}). See the text for further discussion.