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SHORT NOTES

A note on fault reactivation

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Abstract—Reactivation of existing faults whose normal lies in the $\sigma_1'\sigma_3'$ plane of a stress field with effective principal compressive stresses $\sigma_1' > \sigma_2' > \sigma_3'$ is considered for the simplest frictional failure criterion, $\tau = \mu\sigma_n' = \mu(\sigma_n - P)$, where τ and σ_n are respectively the shear and normal stresses to the existing fault, P is the fluid pressure and μ is the static friction. For a plane oriented at θ to σ_1', the stress ratio for reactivation is $(\sigma_1'/\sigma_3') = (1 + \mu \cot \theta)/(1 - \mu \tan \theta)$. This ratio has a minimum positive value at the optimum angle for reactivation given by $\theta^* = \frac{1}{2} \tan^{-1} (1/\mu)$ but reaches infinity when $\theta = 2\theta^*$, beyond which $\sigma_3' < 0$ is a necessary condition for reactivation. An important consequence is that for typical rock friction coefficients, it is unlikely that normal faults will be reactivated as high-angle reverse faults or thrusts as low-angle normal faults, unless the effective least principal stress is tensile.

IT IS now widely recognized that much intracontinental deformation within the frictional seismogenic regime, which commonly extends to depths of 10–15 km (Sibson 1983), is accommodated by the reactivation of existing discontinuities rather than by the creation of new faults (McKenzie 1972, Sykes 1978). This is especially true of collision belts. Given our general lack of quantitative knowledge concerning the triaxial stress state at depth, full three-dimensional analysis of the conditions for frictional reactivation (Bott 1959, McKenzie 1969, Jaeger & Cook 1979) is rarely practicable, though it has been done successfully on occasion (Raleigh *et al.* 1972). However, in view of recent suggestions that many high-angle reverse faults and low-angle normal faults have developed by reactivation of normal and thrust faults respectively (e.g. Jackson 1980, Winslow 1981, Brun & Choukroune 1983, Smith & Bruhn 1984), it is instructive to consider certain limitations imposed by the simplest two-dimensional analysis for frictional reactivation of a cohesionless fault.

CONDITIONS FOR REACTIVATION

Consider a triaxial stress state with principal compressive stresses $\sigma_1 > \sigma_2 > \sigma_3$ containing a cohesionless plane lying at an angle, θ, to σ_1, with its normal contained in the $\sigma_1\sigma_3$ plane (Fig. 1). If a fluid pressure, P, is present, the effective principal stresses (Hubbert & Rubey 1959) are

$$\sigma_1' = (\sigma_1 - P) > \sigma_2' = (\sigma_2 - P) > \sigma_3' = (\sigma_3 - P). \quad (1)$$

Byerlee (1978) has shown that nearly all rocks share the same frictional properties with a failure criterion which may be adequately approximated by Amonton's Law

$$\tau = \mu\sigma_n' = \mu(\sigma_n - P), \quad (2)$$

where τ and σ_n are, respectively, the shear and normal stresses to the plane, and the coefficient of friction, μ is *c.* 0.75 (Sibson 1983).

In terms of the effective principal stresses, equation (2) may be rewritten

$$(\sigma_1' - \sigma_3') \sin 2\theta = \mu[(\sigma_1' + \sigma_3') - (\sigma_1' - \sigma_3') \cos 2\theta] \quad (3)$$

which reduces to

$$R = (\sigma_1'/\sigma_3') = (1 + \mu \cot \theta)/(1 - \mu \tan \theta). \quad (4)$$

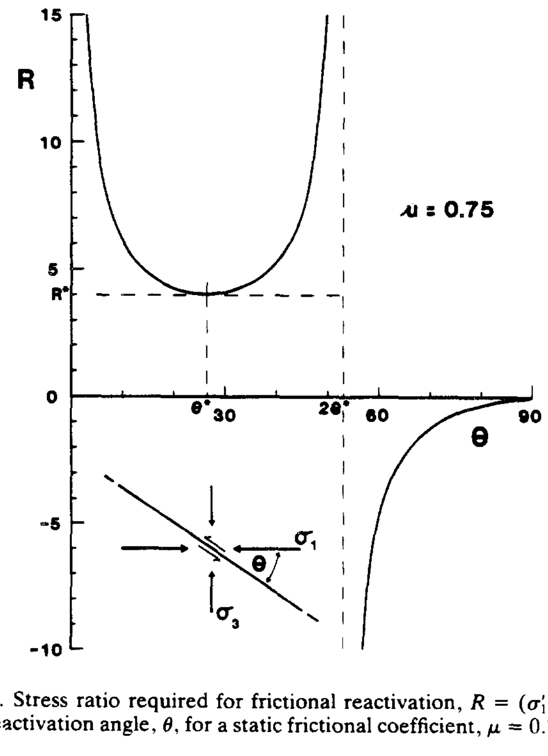

Fig. 1. Stress ratio required for frictional reactivation, $R = (\sigma_1'/\sigma_3')$, vs reactivation angle, θ, for a static frictional coefficient, $\mu = 0.75$.

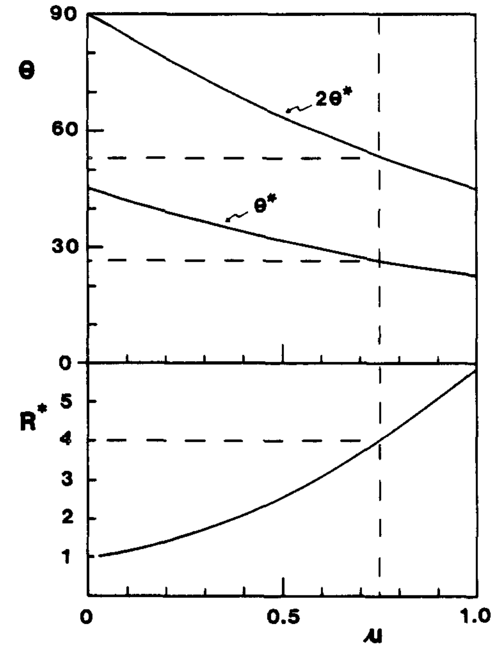

Fig. 2. Variation of optimum reactivation angle, θ^*, $2\theta^*$ and minimum positive stress ratio for reactivation, R^*, with frictional coefficient, μ.

The stress ratio for reactivation, R, is plotted against θ for the particular case of $\mu = 0.75$ in Fig. 1. R has a minimum positive value,

$$R^* = (\sqrt{1 + \mu^2} + \mu)^2 \tag{5}$$

at the optimum angle for frictional reactivation given by $\theta^* = \frac{1}{2}\tan^{-1}(1/\mu)$ (Sibson 1974), but increases to infinity for $\theta = 0$ and $\theta = 2\theta^*$. For $\mu = 0.75$, $\theta^* = 26.5°$ with $R^* = 4$, and $2\theta^* = 53°$. For $\theta > 2\theta^*$, $R < 0$ which requires $\sigma_3' < 0$, that is, the effective least principal stress must be tensile. Values of R^*, θ^* and $2\theta^*$ corresponding to other values of μ are plotted in Fig. 2.

A further limitation on allowable stress states for frictional reactivation is that they must not induce failure of the surrounding rock either in shear or in tension. In Fig. 3, a composite failure envelope for intact rock is plotted together with the envelope for frictional failure in a series of Mohr diagrams illustrating the range of allowable stress states for reactivation. Following Brace (1960), the failure envelope for intact rock is taken to be approximately of parabolic Griffith form in the tensile field with a cohesive strength, C, equal to twice the tensile strength, T_0. In the compressional field the envelope is assumed to be of the linear Coulomb form,

$$\tau = C + \mu_i \sigma_n'. \tag{6}$$

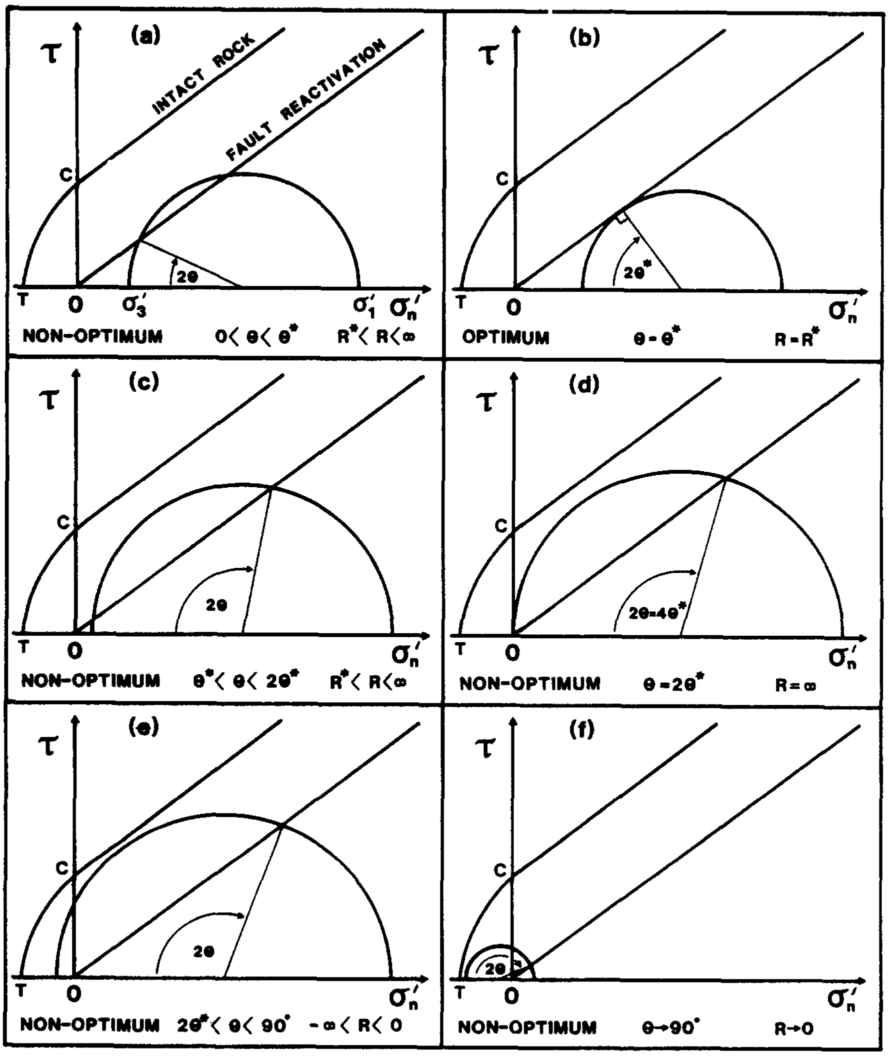

Fig. 3. Allowable stress states for frictional reactivation of an existing fault (see text for discussion).

Hoek (1965) found that the coefficient of internal friction, μ_i generally lies between 0.5 and 1.0 for rocks, so that for convenience the failure envelopes for intact rock and fault reactivation in the compressional field are plotted parallel with $\mu_i = \mu = 0.75$.

The optimum condition for reactivation with $R = R^*$ and $\theta = \theta^*$ is shown in Fig. 3(b) with the stress circle touching the frictional failure envelope. Note that σ_3' here may have any value greater than zero for reactivation to be possible. Stress conditions for reactivation with $0 < \theta < \theta^*$ and $\theta^* < \theta < 2\theta^*$ are shown in Figs. 3(a) and (c), respectively. Clearly, the diameter of the stress circle is constrained by the presence of the intact rock envelope to be not too great, so that $\sigma_3' \rightarrow 0$ as θ trends towards 0 or $2\theta^*$. At $\theta = 2\theta^*$, $R = \infty$, requiring $\sigma_3' = 0$ (Fig. 3d). Reactivation at $\theta > 2\theta^*$ requires $\sigma_3' < 0$ with a progressively diminishing differential stress as $\theta \rightarrow 90°$ in order to prevent failure of the intact rock (Figs. 3e & f).

DISCUSSION

In the framework of simple 'Andersonian' faulting (Anderson 1951), principal stress trajectories are either vertical or horizontal and the three main classes of fault, thrust, wrench and normal, develop in homogeneous crust in accordance with the Coulomb criterion (eqn. 6), depending on which of the three principal stresses is vertical. For typical values of internal friction, faults develop at *c.* 30° to σ_1. Thus, ideal normal faults should dip at *c.* 60° and thrusts at *c.* 30°. If σ_1 and σ_3 are interchanged, as may occur if a former rifted continental margin becomes involved in continental collision, or when a former thrust belt is caught up in a zone of distension, normal faults may potentially be reactivated as high-angle reverse faults, and thrusts as low-angle normal faults. However, in both cases the θ angle for reactivation is *c.* 60° if the stress trajectories remain horizontal and vertical. Such a high reactivation angle requires either a friction coefficient, $\mu < 0.55$ (Fig. 2), significantly lower than the usual value of 0.75, or σ_3' must be tensile. In fact, Bruhn *et al.* (1982) have demonstrated reactivation of gently dipping joints as low-angle normal faults with θ values of 70–80°, implying either $\mu < 0.35$ or $\sigma_3' < 0$. Vein systems associated with a normal fault reactivated in high-angle reverse mode in North Wales unequivocally demonstrate $\sigma_3' < 0$ during reactivation (Sibson 1981).

Even if the conditions described above are not met fully, it is apparent from Fig. 3(c) that for frictional reactivation to occur at large θ values in preference to the formation of a new, favourably oriented fault, σ_3' must tend towards zero, implying abnormal fluid pressure conditions and comparatively low differential stress levels at the time of reactivation. Clearly, however, listric normal faults would be more easily reactivated in reverse mode than the ideal 'Andersonian' variant. In contrast, flattening of thrusts with depth tends to exacerbate the problem if they are to undergo frictional reactivation in normal slip mode. The problem is acute also in the case of the brittle, flat-lying detachment faults associated with regional extension in the western United States which, in some cases at least, appear to have been active with dips of only a few degrees (Davis *et al.* 1980). For reactivation of such faults to occur, either fluid pressures must be high with $\sigma_3' < 0$, at least intermittently, or the frictional coefficient must be abnormally low, or stress trajectories must deviate markedly from the horizontal and vertical. When fault reactivation at high θ values is suspected, evidence in the form of fault-related hydraulic extension fractures (e.g. Sibson 1981) should be sought in support of the hypothesis for an effectively tensile least principal compressive stress accompanying reactivation.

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