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A new three-dimensional method of fault reactivation analysis

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ABSTRACT

A 3-D method to evaluate the reactivation potential of fault planes is proposed. The method can be applied to cohesive or noncohesive faults whatever their orientation and without any conditions on the regional stress field. It allows computation of the effective stress ratio σ'_3/σ'_1 required to reactivate any fault plane and to determine whether the plane is favorably oriented, unfavorably oriented or severely misoriented with respect to the ambient stress field. The method also includes a graphical sorting tool that involves plotting poles of fault planes on stereoplots for which the boundaries separating the three domains corresponding to favorable orientations, unfavorable orientations and severe misorientations cases are shown. The delineation of these domains is based on the value of the σ'_3/σ'_1 ratio that depends on the orientation of the fault plane with respect to the principal stress axis orientations, the stress shape ratio ($\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$), the coefficient of static friction μ_s of the fault, and the fault cohesion C_0. The method is applied on 145 focal mechanisms of the 2011 March 11th Tohoku-Oki (Japan) earthquake sequence. This application delineates, along or in the vicinity of the Pacific-Okhotsk plate interface, three types of domains characterized by favorable orientations, unfavorable orientations or severe misorientations of mainshock/aftershock fault planes. Aftershock focal mechanisms that plot in the ‘severe misorientation’ domains are interpreted to have occurred because of pore fluid pressures exceeding the regional minimum principal stress at those locations. The distribution of these ‘severe misorientation’ domains partly overlaps the asperities or the low-velocity anomalies mapped on the plate interface off NE Japan. The proposed 3-D fault reactivation analysis appears complementary to geophysical investigations.

1. Introduction

The mechanical control of fault reactivation is a very important issue for understanding earthquake hazard (McKenzie, 1969; Scholz, 1998). For three decades, researchers have developed methods directly derived from the Mohr–Coulomb theory and focused on estimating the reactivation potential of pre-existing faults.

The first method, introduced by Sibson (1985), consists of a 2-D analysis that computes the effective stress ratio $R = \sigma'_1/\sigma'_3$ required to reactivate a fault plane. To be reactivated, the fault plane must reach the reactivation envelope governed by the Coulomb criterion ($\tau = \mu_s \sigma_n$) where τ is the shear stress on the pre-existing plane, μ_s the coefficient of static friction and σ_n the normal stress acting on the pre-existing plane (Fig. 1a). The 2-D fault reactivation analysis requires knowledge of the angle θ_r between the fault plane and the maximum principal stress σ_1. It is also limited to cases for which the intermediate principal stress axis σ_2 is in the fault plane. Lastly, it assumes that faults are cohesionless.

Depending on the value of the effective stress ratio, R, Sibson (1985) introduced three classes of fault orientations. (1) “Favorably oriented” faults have R values between the minimal R-value (R_{optimal}) and ($R_{\text{optimal}} \times 1.5$) (Fig. 1a, case (1) and (2)). (2) “Unfavorably oriented” faults have R values larger than 1.5 R_{optimal} (Fig. 1a, case (3)). (3) “Severely misoriented” faults have negative R values (Fig. 1a, case (4)). A negative R value indicates that the magnitude of the minimum principal effective stress is negative ($\sigma'_3 = \sigma_3 - p_f < 0$) and implies that fault reactivation is possible only if the pore fluid pressure p_f is larger than the magnitude of the minimum principal stress ($p_f > \sigma_3$). This 2-D fault reactivation analysis emphasizes the role played by coefficient of static friction along with pore fluid pressure on reactivation of unfavorably oriented or severely misoriented faults, which has been shown in a number of case studies (Collettini and Sibson, 2001; Sibson, 2009; Konstantinou et al., 2011).

To evaluate the reactivation potential of fault planes that do not contain the σ_2 axis, Morris et al. (1996) developed a fault-

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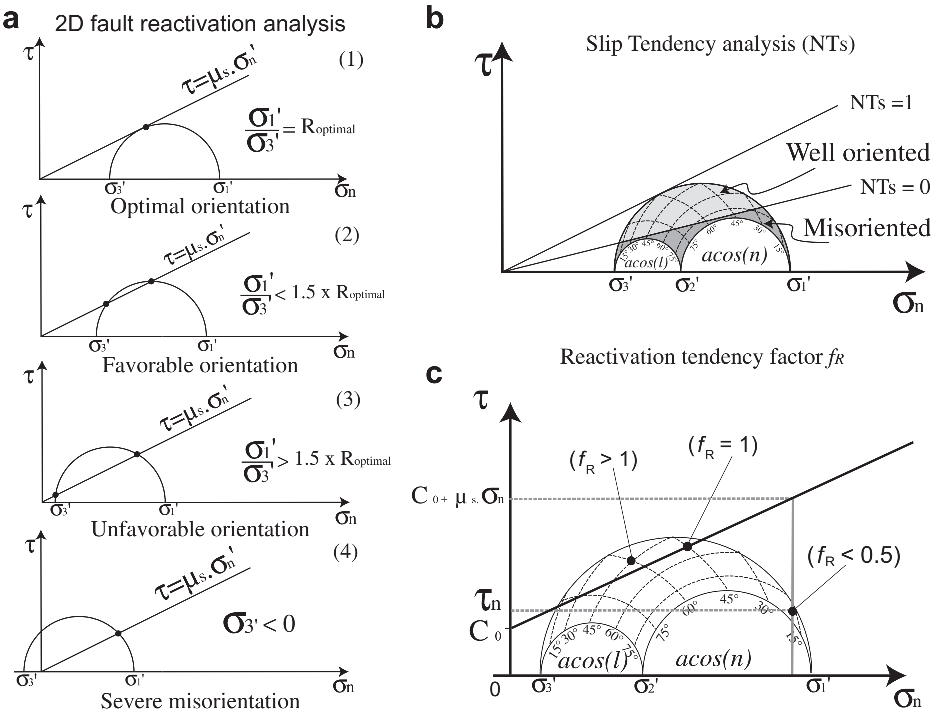

Fig. 1. Mohr diagrams corresponding to different fault-reactivation analyses. (a) Mohr diagrams of the 2-D fault reactivation analysis (Sibson, 1985). (b) Mohr diagram illustrating the Slip-Tendency method (NT$_s$) where the (σ'_1, σ'_3) Mohr circle is tangent to the reactivation envelope. In the inner circles, *acos* stands for the *inverse cosinus function*. (c) Mohr diagram illustrating the reactivation-tendency factor f_R. In the inner circles, *acos* stands for the *inverse cosinus function*. The reactivation envelope is governed by the Mohr–Coulomb failure criterion and the reactivation tendency factor f_R corresponds to the ratio $\tau_n/(C_0 + \mu_s\sigma_n)$.

reactivation characterization method named slip tendency. The slip tendency method estimates the reactivation potential for any fault plane whatever its orientation with respect to the orientation of the principal stress axes. It uses a 3-D Mohr–Coulomb diagram (Fig. 1b) and knowledge of the reactivation envelope to calculate the stress ratio $T_s = \tau/\sigma_n$ to reactivate any fault plane without knowing the magnitude of the principal stress components. In fact, the T_s value can be calculated by knowing only the orientation of the three principal stress axes and the stress shape ratio $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ (see Neves et al., 2009 for further details). To estimate the ability of a fault to be reactivated under a given stress state, Morris et al. (1996) normalized the slip tendency on any surface with the maximum possible slip tendency Ts$_{max}$. The normalizing ratio is called NT$_s$ and is equal to T_s/Ts$_{max}$. A NT$_s$ ratio between 1 and 0.5 indicates that the fault plane is well oriented with respect to the ambient stress field whereas a NT$_s$ ratio less than 0.5 indicates that the fault plane is misoriented. The NT$_s$ method has been applied on seismic sequences or on fault systems (Ventura and Vilardo, 1999; Lisle and Srivastava, 2004; Worum et al., 2004; Collettini and Trippetta, 2007; De Paola et al., 2007; Moeck et al., 2009; Neves et al., 2009; Massironi et al., 2011). Although the NT$_s$ method is applicable to fault planes with any orientation, it does not account for the fault cohesion and, unlike the 2-D method, it cannot identify those fault planes, which can be reactivated only with fluid overpressure ($p_f > \sigma_3$).

To account for the cohesive strength of pre-existing planes, Tong and Yin (2011) extended the work of Morris et al. (1996) by introducing a new parameter, the reactivation-tendency factor $f_R = \tau_n/(C_0 + \mu_s\,\sigma'_n)$, where τ is the shear stress acting on the pre-existing plane and $(C_0 + \mu_s\,\sigma'_n)$ is the critical shear stress required to reactivate a pre-existing cohesive fault plane (Fig. 1c). A reactivation-tendency factor f_R larger or equal to 1 indicates that the pre-existing plane is well oriented with respect to the ambient stress field and can be reactivated, whereas a f_R value below 0.5 indicates that the fault plane is misoriented.

In this study, we extend the analyses of Sibson (1985), Morris et al. (1996) and Tong and Yin (2011) by introducing a general fault reactivation method named 3-D fault reactivation analysis. This method allows evaluation of the reactivation potential for a fault plane without any prerequisite information about the orientations of the regional stress tensor axes with respect to the fault plane or to the Earth's surface. In particular, an Andersonian stress state (one principal stress axis vertical) need not be hypothesized. The method also incorporates cohesion and the coefficient of static friction into the analysis as well as the pore fluid pressure in the fault zone. Application of this method to the Tohoku-Oki (Japan) mainshock/aftershocks seismic sequence as an example provides information about the pore fluid pressures along or in the vicinity of the plate interface.

2. 3-D fault reactivation analysis

2.1. First step: derivation of basic equations

The reactivation of fault planes follows the Mohr–Coulomb failure criterion (Jaeger et al., 2007):

$$\tau = C_0 + \mu_s\left(\sigma_n - P_f\right) \qquad (1)$$

where C_0 is the cohesive strength of the fault plane and p_f is the pore fluid pressure.

If the fault plane is cohesionless, Equation (1) can be written as:

$$\tau = \mu_s\left(\sigma_n - P_f\right) \qquad (2)$$