Earth and Planetary Science Letters 411 (2015) 188–198

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The applicability of frictional reactivation theory to active faults in Japan based on slip tendency analysis

Yohei Yukutake [a,*], Tetsuya Takeda [b], Akio Yoshida [c]

[a] Hot Springs Research Institute of Kanagawa Prefecture, Japan
[b] National Research Institute for Earth Science and Disaster Prevention, Japan
[c] Shizuoka University, Japan

ARTICLE INFO

Article history:
Received 30 June 2014
Received in revised form 1 December 2014
Accepted 4 December 2014
Available online 23 December 2014
Editor: P. Shearer

Keywords:
active fault
stress field
slip tendency
fault reactivation theory
focal mechanism
Japan

ABSTRACT

To investigate the applicability of frictional reactivation theory to active faults, we evaluated the slip tendency of active faults in Japan. Slip tendency is defined as the ratio of shear stress to the frictional resistance acting on a fault plane. To estimate the stress field near active faults, we determined focal mechanisms for numerous shallow earthquakes in the intraplate region of Japan, using data from dense seismic observation networks. The stress fields were estimated by applying the stress inversion method to the focal mechanisms. We found that most active faults are well oriented with respect to the stress field, having slip tendencies of ≥0.6, which indicates that fault reactivation theory is applicable to active faults, and that the present day tectonic stress field has contributed substantially to the development of active faults. Conversely, several steeply dipping active faults in northeast Japan, as well as the source faults of the 1995 Hyogoken–Nanbu earthquake, are mis-oriented, with slip tendencies of <0.6, which may indicate that highly pressurized fluids have contributed to earthquake triggering on these mis-oriented faults. We also discuss the applicability of slip tendency analysis to earthquake hazard assessment; i.e. estimating the probability of a future rupture on active faults. Our results indicate that slip tendency does not correlate with elapsed time since the most recent earthquake event. This observation shows that slip tendency may not be an efficient parameter with which to assess the risk of an earthquake occurring in the near future on a specific fault.

1. Introduction

The occurrence of intraplate earthquakes may be explained in the context of frictional fault reactivation theory. Anderson (1905) established a basic theory concerning the formation of frictional faults, in which three fault types (normal, strike-slip, or reverse faults) occur depending on the directions of the principal stress axes relative to the Earth's surface. Sibson (1985) founded a two-dimensional frictional fault theory, in which the fault strike is assumed to contain the intermediate principal stress axis. Subsequently, Sibson and Xie (1998) and Collettini and Sibson (2001) applied the two-dimensional frictional fault theory to the reactivation of reverse faults, and to both normal and reverse faults for moderate to large earthquakes, respectively. Sibson and Xie (1998) also suggested that reactivated faults are characterized by rock friction coefficients similar to those observed in laboratory experiments (Byerlee, 1978).

In a three-dimensional frictional fault theory which allows oblique slip on faults and the deviation of the principal stress axes from the vertical and horizontal directions, Morris et al. (1996) developed "slip tendency" analysis based on the notion that slip on a fault is controlled by the ratio of shear stress to normal stress acting on the fault surface. By using slip tendency analysis, fault reactivation theory has been shown to be applicable to geological fault data (Lisle and Srivastava, 2004) and aftershock sequences (Collettini and Trippetta, 2007). However, the applicability of fault reactivation theory to active faults has not been established, and the relationship between the orientation of active faults and the ambient regional stress field is poorly understood. To clarify this relationship is important to our understanding of the development of active faults and the mechanisms that lead to the occurrence of large intraplate earthquakes.

Slip tendency analysis has also been applied to fault-rupture risk assessment in earthquake-prone areas (Morris et al., 1996) and to induced seismicity in a geothermal reservoir (Moeck et al., 2009). The probability of a future rupture on an active fault has

* Corresponding author at: 586 Iriuda, Odawara, Kanagawa Prefecture, 250-0031 Japan. Tel.: +81 465 3588; fax: +81 465 3589.
E-mail address: yukutake@onken.odawara.kanagawa.jp (Y. Yukutake).

http://dx.doi.org/10.1016/j.epsl.2014.12.005

so far been statistically evaluated based on topographical and geological information such as the mean recurrence interval and the elapsed time since the most recent event. However, this approach is likely to introduce a significant error due to large uncertainties in the estimation of the mean recurrence interval and the elapsed time. Therefore, it is important to investigate whether slip tendency analysis provides us with useful information regarding risk assessment; i.e. the probability of future rupture on active faults.

The Japanese islands provide an ideal setting in which to examine the problems mentioned above. Comprehensive data have been obtained from active faults (e.g., Nakata and Imaizumi, 2002; Research Group for Active Faults in Japan, 1991). In addition, the establishment of an extensive and dense seismic observation network throughout the Japanese Islands (e.g., Obara et al., 2005) enables us to obtain a detailed picture of the stress field in the intraplate region. In this paper, we estimate the stress field around active faults using precisely determined focal mechanisms from numerous earthquakes, and we calculate the slip tendencies of active faults. Based on the results of the slip tendency analysis, we discuss whether frictional reactivation theory is applicable to active faults, including a case in which the directions of the principal stress axes at depth deviate significantly from the vertical and horizontal directions. We also study whether the frictional values obtained by Byerlee (1978) are applicable to faults with large displacements. The applicability of slip tendency analysis to evaluations of the relative risk of earthquake occurrence on active faults is also investigated by comparing slip tendency values with quantifiable properties of active faults, such as the elapsed time since the most recent event.

2. Method for the estimation of slip tendency

In this study, we define the slip tendency as

$$Ts = \frac{|\sigma_s|}{\mu|\sigma_n|}, \tag{1}$$

where σ_s and σ_n are shear and normal stresses, respectively, and μ is the frictional coefficient on the fault plane. The denominator in Eq. (1) quantifies the frictional resistance of the fault. The definition of slip tendency in our study is different from that of Morris et al. (1996), who defined slip tendency as the ratio of shear stress to normal stress. Since the denominator in Eq. (1) represents the frictional resistance, a slip tendency of 1.0 indicates that the orientation of the fault plane is optimal, relative to the stress field, under the assumed frictional coefficient. A high value of slip tendency means that the magnitude of shear stress is approaching the frictional resistance. A fault plane with a high slip tendency is oriented in an unstable direction with respect to the stress field (i.e., a well-oriented direction for slip).

σ_s and σ_n can be expressed by the following equations, when the stress tensor and the normal vector on the fault plane are represented as $\boldsymbol{\sigma}$ and $\mathbf{n}$, respectively:

$$\sigma_n = \mathbf{n}\big[\mathbf{n}\cdot(\boldsymbol{\sigma}\cdot\mathbf{n})\big], \tag{2}$$

$$\sigma_s = \boldsymbol{\sigma}\cdot\mathbf{n} - \mathbf{n}\big[\mathbf{n}\cdot(\boldsymbol{\sigma}\cdot\mathbf{n})\big]. \tag{3}$$

The absolute stress tensor $\boldsymbol{\sigma}$ can be transformed as follows:

$$\boldsymbol{\sigma} = d\boldsymbol{Q}\cdot\begin{bmatrix}1 & 0 & 0\\ 0 & R & 0\\ 0 & 0 & 0\end{bmatrix}\cdot\boldsymbol{Q}^T + (\sigma_3 - P)\cdot I, \tag{4}$$

where $\boldsymbol{Q}$ is the rotation matrix with which to express direction in terms of the three principal stress axes, d is the magnitude of differential stress ($\sigma_1 - \sigma_3$), and P is pore pressure. R in Eq. (4) is the stress ratio, defined by $R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, where σ_1, σ_2, and

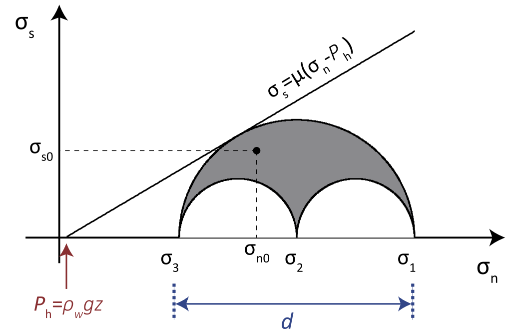

Fig. 1. Three-dimensional Mohr diagram with horizontal and vertical axes corresponding to the normal and shear stresses acting on a fault plane, respectively. A point in the gray zone surrounded by three Mohr circles indicates the stress state acting on the plane (σ_{n0}: normal stress, σ_{s0}: shear stress). The diameter of the Mohr circle represents the differential stress (d). σ_1, σ_2, and σ_3 are the magnitudes of the maximum, intermediate, and minimum principal stresses, respectively. P_h, ρ_w, g, z, and μ are hydrostatic pore fluid pressure, density of water, gravity, depth, and the friction coefficient, respectively. The straight line indicates the Mohr Coulomb failure line under the condition of P_h and $\mu = 0.6$.

σ_3 are the magnitudes of the maximum, intermediate, and minimum principal stresses, respectively. I denotes the unit matrix. If $\boldsymbol{\sigma}''$ is defined as follows:

$$\boldsymbol{\sigma}'' = \boldsymbol{Q}\begin{bmatrix}1 & 0 & 0\\ 0 & R & 0\\ 0 & 0 & 0\end{bmatrix}\cdot\boldsymbol{Q}^T, \tag{5}$$

then Eq. (1) can be expressed as

$$Ts = \frac{|\sigma_s|}{\mu|\sigma_n|} = \frac{|\boldsymbol{\sigma}''\cdot\mathbf{n} - \mathbf{n}[\mathbf{n}\cdot(\boldsymbol{\sigma}''\cdot\mathbf{n})]|}{\mu|\mathbf{n}[\mathbf{n}\cdot(\boldsymbol{\sigma}''\cdot\mathbf{n})] + (\frac{\sigma_3 - P}{d})\cdot\mathbf{n}|}. \tag{6}$$

$\boldsymbol{\sigma}''$ is a non-dimensional stress tensor that can be estimated using stress inversion analysis (e.g., Gephart and Forsyth, 1984; Hardebeck and Michael, 2006; Horiuchi et al., 1995; Michael, 1987) using earthquake focal mechanism data. Note that the parameters d, μ, P, and σ_3 remain unknown, even after performing the stress inversion analysis.

These unknown parameters are estimated on the basis of the following assumptions.

(1) Seismic slip on the optimally oriented fault planes, relative to the dominant regional stress field, occurs under hydrostatic fluid pressure (P_h).
(2) The strength of an optimally oriented fault plane is governed by the Coulomb failure criterion with a standard frictional coefficient of $\mu = 0.6$; i.e., the lower limit of the static coefficient for rock friction, which lies in the range of $0.6 \le \mu \le 0.85$ (Byerlee, 1978).
(3) The magnitude of the vertical stress (i.e., the normal stress that acts on a horizontal plane) is equal to the overburden stress ($\sigma_v \approx \rho g z$).

Under the above assumptions, d can be defined as shown in Eq. (7) using the relationship between the Mohr failure line and the position of the Mohr circle (Fig. 1):

$$d = \frac{2\mu(\sigma_v - P_h)}{\sqrt{\mu^2+1} + \mu(2\cos^2\theta_1 + 2R\cos^2\theta_2 - 1)} \tag{7}$$

where θ_1 and θ_2 are the angles at which the axes σ_1 and σ_2 are inclined from the vertical, respectively. The same assumptions in estimating d were made by Terakawa et al. (2010) and Terakawa et al. (2013). If the parameters d, P, and σ_3 are proportional to the depth of the seismogenic zone (e.g., Townend and Zoback, 2000; Yamashita et al., 2004), the value of the slip tendency expressed as