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Depth dependent strength of the fault gouge at the Atotsugawa fault, central Japan: A possible mechanism for its creeping motion

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Abstract

From the friction experiments of the Atotsugawa fault gouge using a tri-axial apparatus under several pressure–temperature conditions at depths down to 9 km, we found an increase in the coefficient of friction from 0.50 to 0.58 as depth increases from 1 km to 9 km. Based on this result, we proposed a fault slip model which explains the creeping motion of the Atotsugawa fault. In this model, stress on the fault attains to the low frictional strength in the shallow part earlier than that in the deep so that this difference results in a creeping slip in the shallow depth during inter-seismic period. The model could successfully describe the presence of a creeping section along the Atotsugawa fault at shallow depth with its creeping rate similar to the field observation on the fault.

Keywords: Atotsugawa fault; Fault gouge; Friction experiment; Creep; Earthquake cycle

1. Introduction

To investigate the earthquake cycle along an active fault, information is necessary on both shear stress applied to the fault and frictional strength of the fault during the cycle. If we knew the balance between them, we could judge a possibility whether the fault slips or not. This approach is one of the simplest and the most efficient methods to predict when next earthquake occurs. For the shallow part of the fault, the stress on the fault is evaluated by the in situ borehole measurements such as hydraulic fracturing and overcoring tests. It becomes difficult to measure the stress as the depth increases to seismogenic zone. The frictional strength of the fault can be estimated from laboratory experiments conducted under the depth conditions. For creeping faults, along which aseismic slip occurs, we need only the laboratory-derived frictional strength of the faults because both stress applied to the fault and strength of the fault are considered to be in equilibrium there.

Creeping faults are rarely observed among many faults existing in the brittle crust. The San Andreas fault, California, is the most famous for its strike-slip creeping rate of several ten millimeters per year (e.g., Titus et al., 2005). In Japan, the Atotsugawa fault (AGF) is famous in its creeping motion, located along a highly deformed region (strain rate of $\sim 10^{-6}$) in central Japan (Sagiya et al., 2000) with its length of about 60 km, striking to N60°E and dipping to 90° (Fig. 1). Recent detailed

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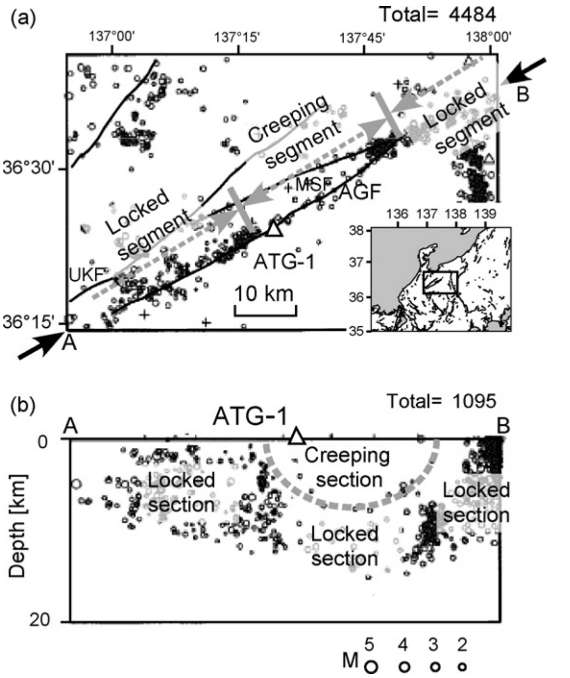

Fig. 1. (a) Epicenter distribution of microearthquakes occurring around the Atotsugawa fault from 1996 to 1999 and (b) its cross-section along A–B line (modified from Ito and Wada [5]). Open circles are hypocenters and plus signs are seismic stations. Open triangle (ATG-1) is a borehole location drilled by NIED in 2004 (36°24′38″N, 137°18′56″E) [AGF, Atotsugawa fault; UKF, Ushikubi fault; MSF, Mozumi–Sukenobe fault].

observation of the laser distance measurement survey along the Atotsugawa fault reveals the existence of a fault creep at an average slip rate of 1.5 mm/year in the northeastern part as the first example in Japan (Geogr. Surv. Inst., 1997). Trenching surveys at the central region of AGF indicated an average recurrence interval of 2413 years (Awata and Tsukuda, 1993). The previous earthquake that occurred along the fault is the 1858 Hietsu earthquake with a magnitude of 7. As shown in Fig. 1b, in the creeping section, a low seismicity region down to a depth of 7 km was found above the seismically active region down to 15 km (Ito and Wada, 2002). The low and high seismicity regions are considered to be creeping and locked area, respectively. It should be noted that in San Andreas fault, seismicity is high in the locked section and creeping section has low seismicity (e.g. Waldhauser et al., 2004). This difference might come from the different tectonic setting: San Andreas fault is located at the plate boundary and the Atotsugawa fault is inside the plate.

In the present paper, we first propose a fault slip model based on the assumption that the stress on a fault and the frictional strength of the fault are balanced in the creeping area. Then, we conduct several tri-axial friction experiments of the Atotsugawa fault gouge collected from the core samples at shallow depth under high-pressure and high-temperature conditions with pore fluid of water. We estimate a variation in friction coefficient, μ, of the Atotsugawa fault at depth down to 10 km depth assuming that the experiments on the near-surface fault gouge sample of the fault are more effective than that on artificial gouge samples for examination of its frictional strength. Finally, we apply the experimental results to the fault slip model to explain the characteristic features of creeping fault motion of the Atotsugawa fault at depth.

2. Fault slip model

We propose a fault slip model including earthquake cycles of shallow inland earthquakes as shown in Fig. 2. In the model, creeping slip occurs to balance the shear stress applied on a fault and the frictional strength on the fault. The amount of slip required for the creep is calculated using a theoretical relationship between stress and slip on a fault in elastic half space (Okada, 1992).

As noted by some in situ stress measurements (e.g., Zoback and Healy, 1992; Brudy et al., 1997), the magnitudes of three principal stresses ($\sigma_1 > \sigma_2 > \sigma_3$ and compression is taken positive) in tectonic stress field would increase linearly with depth. For the strike slip faulting case of the Atotsugawa fault, the σ_2-direction is vertical and the σ_1- and σ_3-directions are on the horizontal plane. The principal stresses of σ_1 and σ_3 can be decomposed into fault parallel and fault perpendicular components. The sum of fault parallel components is shear traction (τ), and that of the perpendicular components is normal traction (σ_n). The ratio of τ to σ_n becomes constant at depth on any oriented fault plane due to the general observation of the linear increase in each principal stress. This comes from the assumptions that the orientations of the principal stresses are constant with depth and the stresses increase linearly with depth. We also assume that μ on the fault recovers immediately after the earthquake and is almost constant during the earthquake cycle. The stress ratio (τ/σ_n) drops to or less than the minimum frictional strength when the slip occurs on the fault. Then, the ratio increases with a constant rate during inter-seismic period due to tectonic loading. When τ/σ_n reaches μ, the fault slips again.

It should be noted that whether the fault slips stably or unstably has been discussed based on the $a-b$ parameter in the rate and state variable friction laws (e.g., Dieterich, 1979; Ruina, 1983). Previous studies using rotary shear apparatus revealed that $a-b$ evolves from positive to negative with displacement of several hundred millimeters (Beeler et al., 1996). But that apparatus