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Growth of plastic shear zone and its duration inferred from theoretical consideration and observation of an ancient shear zone in the granitic crust

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A new model for growth of plastic shear zone is proposed based on the basis of a theory of fluid dynamics coupled with a rheological constitutive function, and is applied to a natural shear zone. Mylonite, ultramylonite and other ductile fault rocks are well known to deform in a plastic flow regime. The rheological behavior of these kinds of rocks has been well documented as a non-linear viscous body, which is empirically described as $\dot{\gamma} = A\tau^n \exp(-Q/RT)$, where $\dot{\gamma}$: strain rate, τ: shear stress, Q: activation energy, R: universal gas constant, T: absolute temperature, and A and n are constants. Strain rate- and temperature-dependent viscosity is obtained by differentiating the equation, and simplified by substituting $n = 1$. Then, substitution of the equation into a diffusion equation, $\delta = 4\sqrt{\nu t}$, derives an equation $\delta = 4[t/\rho \cdot A \exp(-Q/RT)]^{1/2}$, where δ: thickness of active layer of viscous deformation, ν: kinematic viscosity, and ρ: density. The duration of creep deformation along the ancient plastic shear zone (thickness: 0.076 m) is estimated to be around 760 s, in a temperature range from 300 to 500°C. This estimation is rather good agreement with intermittent creep during inter-seismic period, than steady state creep or co-seismic slip.

1. Introduction

Deformation in the deeper part of the continental crust frequently involves the formation of localized zones of plastic strain, and these shear zones commonly associate with past records of unstable slip (Hobbs *et al.*, 1986; Harris and Cobbold, 1984; Beach, 1985; Mitra, 1978; Poirier, 1980; Shigematsu and Tanaka, 2000). However, the results from High-T/P experimental studies suggest that the plastic deformation prefers stable slip, which is rather insensitive to the strain (Carter *et al.*, 1981; Shelton, 1981; Christie *et al.*, 1979; Heard, 1972). The conditions favoring or otherwise the formation of such deformation zones in rocks are therefore of great interest of structural geologists and geophysicists.

The stable motion of shear zone in the plastic regime can also be approved by simple theory of fluid dynamics. Thus, as a first step to consider the problem, we will present a new model for growth of plastic shear zone, assuming the constant viscosity of the rocks under the conditions of simple shear. We also applied this model to natural ductile shear zone (Hatagawa shear zone) to estimate the order of duration time of creep deformation.

2. Field Occurrence of Plastic Shear Zone

In this section, we describe an example of field occurrence of natural plastic shear zone. The swarm of minor shear zones constitute a particular zone of about 500 m in width at the western region of Hatagawa main shear zone, extending further north and south with a direction of NNE-SSW, subparallel to the Hatagawa main shear zone (Fujimoto *et al.*, 2002). The outcrop of minor plastic shear zone, as shown in the Fig. 1, is well exposed along Takasegawa (outline geology and location of the outcrop are shown in figure 1 in Fujimoto *et al.*, 2002). The plastic shear zone is recognized by existence of asymmetric curviplanar fabric referred to as 'S' surfaces (Fig. 1, Simpson and Schmid, 1983), which indicates a dextral shear sense. The thickness of the shear zone, donated as 'δ', is 0.076 m. Shear deformation is more concentrated closer to the boundary surface (A in Fig. 1) along which the thin, very fine-grained layer (B in Fig. 1, ultramylonite layer) is observed. The plastic shear zone is juxtaposed by nondeformed granitic rocks (lower half of Fig. 1), bounded by the surface A.

3. Boundary Layer Equation and Creep Rheology of Rocks

A plastic shear zone described in previous section can be modeled as shown in Fig. 2(a), in which viscous half space overlies on the horizontal rigid floor of infinite length and the floor moves to the x direction at $t = 0$ with a constant veloc-

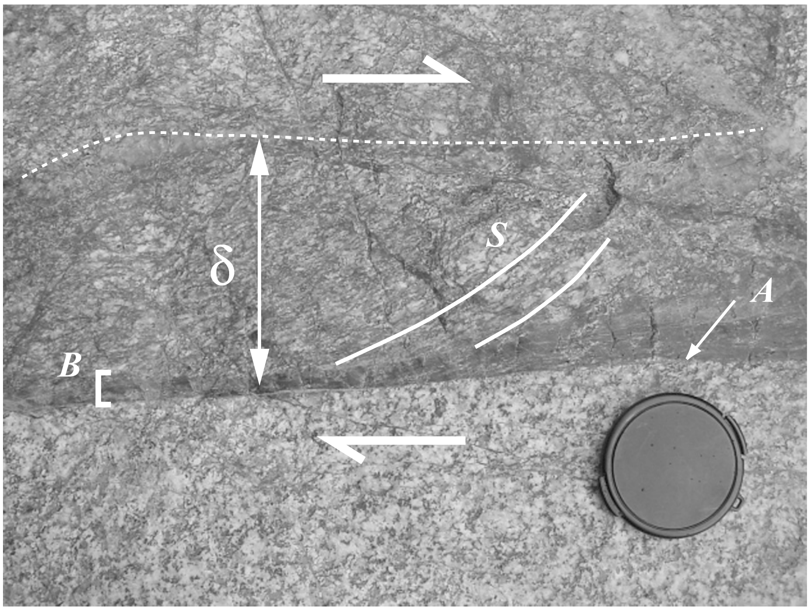

Fig. 1. Photograph showing a right-lateral shear zone with 0.076 m (δ) in thickness, at Takasegawa, northwestern part of Hatagawa main shear zone. See the text for implications of abbreviations A, B, and S.

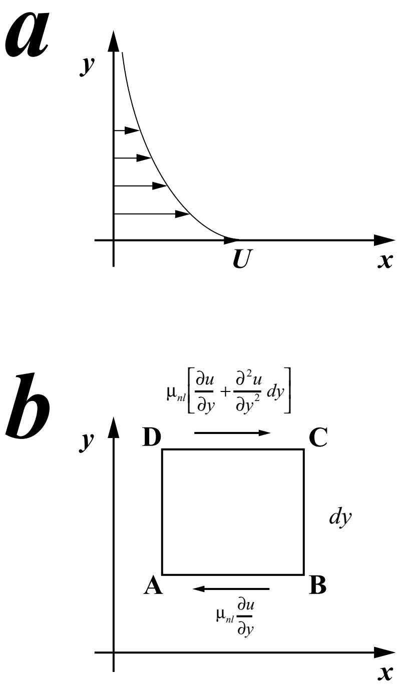

Fig. 2. (a) A model of viscous moment transfer induced by horizontal motion with a constant velocity U of a rigid floor. (b) Moment balance during shear flow for an infinitesimal rectangle ABCD. See the text for explanations.

ity U. The horizontal axis x coincides with the boundary between the floor and the viscous body. The edge effect can be neglected in the supposed region since the floor has infinite horizontal length. The viscous half space and rigid floor correspond to deformed and non-deformed domains in Fig. 1, respectively. In order to understand the mechanical behavior of this model, we first introduce boundary layer equations solved by Prandtl (1904). As initial conditions, we assume velocity and pressure gradients along the x-axis are 0.

$$\frac{\partial u}{\partial x} = 0, \qquad \frac{\partial p}{\partial x} = 0. \tag{1}$$

Substitution of Eq. (1) into continuum equation $\partial u/\partial x + \partial v/\partial y = 0$ provides:

$$\frac{\partial v}{\partial y} = 0 \tag{2}$$

where v is flow velocity along the y-axis. Since the infinitely long rigid floor has no velocity to y direction, $v = 0$ on $y = 0$, then Eq. (2) gives:

$$v(y) = 0 \tag{3}$$

in the entire region of flow deformation. The conservation of linear momentum based on Eqs. (1) to (3) (Fig. 2(b)) gives:

$$\rho\frac{\partial u}{\partial t} = \frac{\partial}{\partial y}\left(\mu_{nl}\frac{\partial u}{\partial y}\right) \tag{4}$$

where ρ is density and μ_{nl} is non-linear viscosity. For simplicity, we tentatively regard μ as a constant. Then, Eq. (4) becomes:

$$\rho\frac{\partial u}{\partial t} = \mu_l\frac{\partial^2 u}{\partial y^2} \tag{5}$$

where μ_l is linear viscosity. Substituting kinematic viscosity $\nu = \mu_l/\rho$ into Eq. (5), we obtain:

$$\frac{\partial u}{\partial t} = \nu\frac{\partial^2 u}{\partial y^2}. \tag{6}$$

This equation can be solved with the following initial and boundary conditions:

$$u = 0 \to t \le 0,\ y \ge 0$$
$$u = U \to t > 0,\ y = 0$$
$$u = 0 \to t > 0,\ y \gg 1.$$

Here, the non-dimensional coordinate and velocity are introduced to avoid complication. The dimensions of νt and y^2 are the square of the length. Then, the thickness of active deformation layer (δ) induced by horizontal motion of the rigid floor is proportional to $\sqrt{\nu t}$. This indicates that $y/\sqrt{\nu t}$ is an appropriate non-dimensional coordinate. For convenience we introduce:

$$\eta = \frac{y}{2\sqrt{\nu t}} \tag{7}$$

as a non-dimensional coordinate. As the velocity between 0 and δ is a function of η, the time can be eliminated from Eq. (7):

$$g(\eta) = \frac{u(y,t)}{U}. \tag{8}$$

Substituting Eqs. (7) and (8) into Eq. (6) and taking $\partial\eta/\partial y = 1/\sqrt{4\nu t}$ into account, we obtain:

$$\frac{d^2 g}{d\eta^2} + 2\eta\frac{dg}{d\eta} = 0 \tag{9}$$

which can be integrated as:

$$\frac{dg}{d\eta} = C\exp(-\eta^2) \tag{10}$$

where C is a constant. We rewrite the boundary conditions here as:

$$\eta = 0 \rightarrow g = 1$$
$$\eta \gg 1 \rightarrow g = 0.$$

Then Eq. (10) can be integrated as:

$$g(\eta) = \frac{u}{U} = 1 - \frac{2}{\sqrt{\pi}}\int_0^\eta e^{-\eta^2} d\eta \tag{11}$$

where the boundary conditions for $g = 0$ is satisfied by using an integral formula:

$$\int_0^\infty e^{-\eta^2} dy = \frac{\sqrt{\pi}}{2}.$$

The results shown in Fig. 3 indicates that velocity is approximately 0 at $\eta = 2$, where u/U is adopted as the horizontal axis and η as the vertical axis. Therefore, from Eq. (7), the thickness of active layer of viscous deformation, δ, can be estimated as:

$$\delta = 4\sqrt{\nu t}. \tag{12}$$

This equation has a similar form with that for heat transfer, and indicates that δ thickens with proportional to the square root of time. We can estimate the duration of creep deformation by applying this equation to natural shear zones if the strain rate is extremely small and so the heat generation by viscous shearing is insignificant.

However, the creep deformation of the crustal rocks in plastic regime shows the non-linear relationship between shear stress and strain rates, which is generally described as:

$$\dot{\gamma} = A\tau^n \exp(-Q/RT) \tag{13}$$

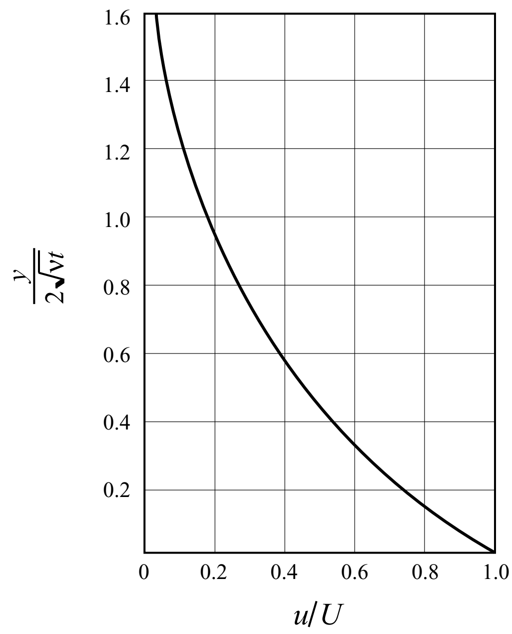

Fig. 3. Normalized velocity gradient across the shear zone. See the text for detailed explanations.

where $\dot{\gamma}$ is strain rate, τ is shear stress, Q is activation energy, R is universal gas constant, and T is absolute temperature. The effective viscosity can be defined as $\mu_{nl} = d\tau/d\dot{\gamma}$. Then the strain rate dependent viscosity can be estimated by differentiating τ in Eq. (13) with respect to $\dot{\gamma}$ as:

$$\mu_{nl} = \frac{d\tau}{d\dot{\gamma}} = \frac{1}{n}\left[\frac{\dot{\gamma}^{1-n}}{A\exp(-Q/RT)}\right]^{1/n}. \tag{14}$$

However, because we obtained Eq. (12) on the constant viscosity condition, Eq. (14) is available only for the case $n = 1$. Thus,

$$\mu_l = \frac{1}{A\exp(-Q/RT)}. \tag{15}$$

Substituting Eq. (15) into (12) and assuming constant velocity of deformation, we obtain:

$$\delta = 4\left[\frac{t}{\rho \cdot A\exp(-Q/RT)}\right]^{1/2}. \tag{16}$$

In the next section, we apply this relationship to estimate the duration of creep along natural ductile shear zones.

4. Estimation of the Duration of Creep along a Plastic Deformation Zone

Natural shear zones deformed in plastic regime occasionally show a symmetric future, that is, the shear concentration is the highest along the centralized layer and gradually decreasing towards the both marginal parts of the shear zone. Several workers have considered these kinds of shear zones as deformed in a framework of continuum geometry (Ramsay and Graham, 1970; Ramsay and Hubert, 1977). In this study, we would take into account the principles of fluid dynamics for constructing the deformation framework since

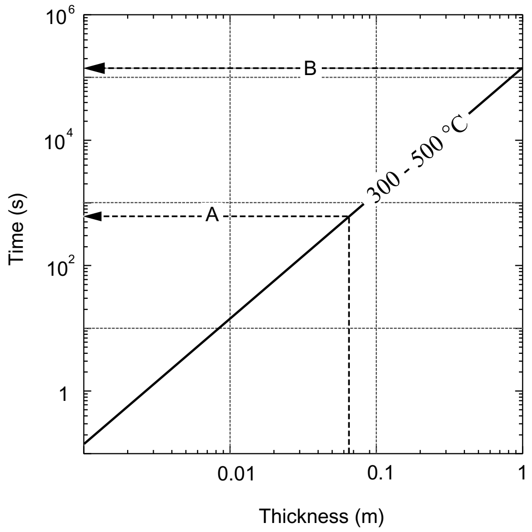

Fig. 4. Relation of the duration of creep with respect to the thickness of plastic shear zone, calculated from Eq. (16). Note that the effect of temperature is negligible.

plastic deformation observed at Hatagawa shear zone is commonly concentrated in one side of the shear zone and another side remains relatively undeformed, resulting in asymmetric feature of the shear zone (a typical occurrence is shown in Fig. 1). Although it remains unclear why plastic shear zones show symmetrical variety, asymmetric feature of the shear zone as shown in Fig. 1 is well approximated to the rigid floor-viscous half space model shown in Fig. 2(a). For these reasons, we propose an alternative model, in which the deformation initiates along any kind of small planar discontinuities, and thickens with time as examined by Eq. (16), although the equation can only be available for the case $n = 1$ at present. This deformation framework has three characteristics compared to previous models. (a) The shear fracture surface has an infinitesimal thickness at the initial stage of deformation. (b) The active layer of viscous deformation gradually thickens with time by moment diffusion, resulting in gradual lowering the strain rate. The strain is lowering from the center to margin of the shear zone. (c) The shear deformation is concentrated along the boundary layer of the shear zone, however, which is not a product of "shear localization" but a resultant product of "duration of shear" at the shear fracture surface and "moment diffusion," as suggested by Eq. (12).

We have tried to estimate duration time of creep during prolonged shear by applying Eq. (16) to a 0.076 m (δ) thick, minor shear zone along the Hatagawa shear zone, (Fig. 1). The other parameters are cited from Carter *et al.* (1981); that is, $A = 1.4 \times 10^{-9}$ MPa^{-1} s^{-1}, $Q = 106$ kJ/mole for dry Westerly granite. The temperature ranges are assumed to be 300 to 500°C for the deformation. Figure 4 shows the results of calculation. The duration of creep motion along the shear surface is about 760 s (A in Fig. 4), regardless of the temperature. A 1-meter thick shear zone could be formed by creep with the duration of about 36 hours (B in Fig. 4).

5. Discussion and Conclusion

We proposed a new model describing the growth of plastic shear zone during prolonged shear, and estimated the duration time of creep for a minor shear zone in the Hatagawa shear zone. The result suggests that the duration of shear is about 760 s. The estimation of creep duration is in rather good agreement with the intermittent creep during interseismic periods, than steady state creep, or co-seismic slip. It is also interesting to note that there is little effect of temperature on the duration time is observed at the calculated range (300–500°C).

It is difficult to evaluate our results at present, because few data/estimation by the other methods are available for comparison and our calculation clearly includes some assumptions and parameters cited from previous research may not be suitable to the natural shear zone. However, beyond these uncertainties, we suggest the dynamic framework presented in this research will give a powerful tool for parameter studies in future field-geological and experimental examinations, which are necessary for reliable estimation of creep in the middle/lower crust and its relation to deformation micromechanisms.

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