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Change of Pore Fluid Pressure Versus Frictional Coefficient During Fault Slip

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1. Introduction

Frictional resistance on a slip interface controls slip behavior as a boundary condition within an elastic space. According to the Amonton-Coulomb principle, frictional resistance is proportional to normal stress.

In particular, in fluid-filtrated conditions, pore fluid pressure around the slip interface reduces frictional resistance as follows. Let us consider a condition that pore fluid fills around slip surfaces, confined by macroscopic normal stress σ . The conceptual model is illustrated in Figure 1. In macroscopic contact area A , solid parts support partial normal stress σ_s only by real contact area A_r and pore fluid with pressure p supports the residual normal stress. Then we obtain the equation

$$\begin{aligned}\sigma A &= p(A - A_r) + \sigma_s A_r \\ \Rightarrow \frac{\sigma_s A_r}{A} &= \sigma - p \left(1 - \frac{A_r}{A}\right)\end{aligned}\quad (1)$$

Since just the solid part can support shear stress, the macroscopic area can resist shear only for $\sigma - p(1 - A_r/A)$. When $A_r/A \ll 1$ (this is a common feature in many materials (Dieterich & Kilgore (1994))), $\sigma - p(1 - A_r/A)$ results in $\sigma - p$. Thus usually the effective normal stress $\bar{\sigma}$ for fluid-saturated frictional surfaces is defined as $\sigma - p$. This idea was

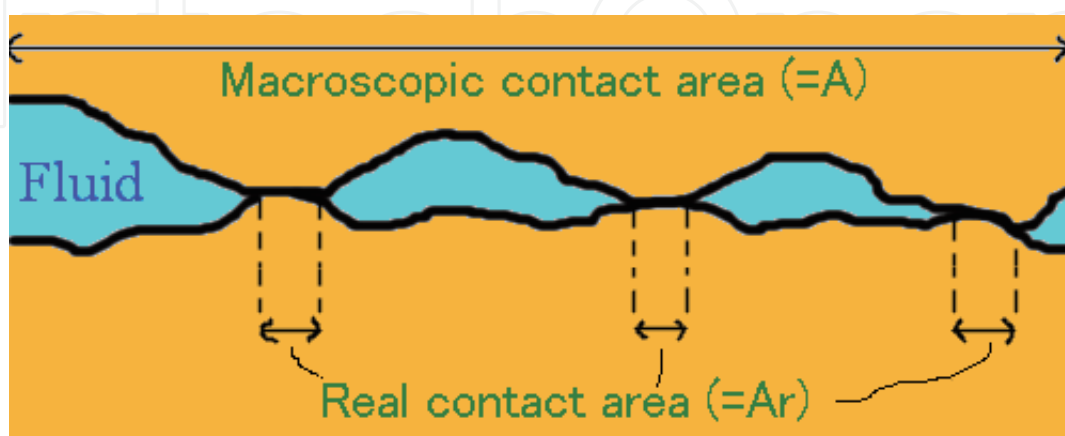


Fig. 1. Schematic illustration around a slip surface filled with pore fluid. Macroscopic and apparent contact area is A , but real contact area by solid parts is only A_r .

introduced in Soil mechanics (Terzaghi (1943)) and accepted for rocks by certain experiments (Brace & Martin (1968); Handin et al. (1963)).

Therefore, if a slip interface is fluid-infiltrated, evolution of pore fluid pressure has the same importance as frictional coefficient for governing the slip behavior. Hitherto, no one could state that pore pressure is always constant on a fluid-infiltrated slip interface. As examples of physical processes to change pore pressure, thermal pressurization due to shear heating (e.g., Lachenbruch (1980); Sibson (1973); Ujiie et al. (2010)) and pore-related pressurization due to porosity change (e.g., Brace & Martin (1968); Marone et al. (1990); Rudnicki (1986)) have been well studied.

Regarding these effects, Suzuki & Yamashita (2007) analytically derived a non-dimensional controlling parameter for slip behavior, assuming constant frictional coefficient, no diffusion of pore pressure and heat, and simple rate-dependent pore dilatation. Noda & Shimamoto (2005) presented a characteristic distance of fault slip-weakening behavior is controlled by a width of deformation zone and fluid diffusion, and Rice (2006) derived some analytical expressions for the slip-weakening behavior, owing to thermal pressurization, assuming constant slip rate and frictional coefficient. They focus on the effects of the pore pressure change on frictional resistance. On the other hand, they ignore the evolution of frictional coefficient. While the effects of the pore pressure change exceed that of frictional coefficient, their results can be regarded as constitutive laws of fault friction. But while not, they can not. It depends on circumstances.

In fact, some numerical studies including both the change of pore pressure and frictional coefficient have shown that the fluid pressurization can notably affect dynamic rupture propagation (e.g., Andrews (2002); Bizzarri & Cocco (2006)), quasi-static nucleation (e.g., Segall & Rice (2006); Shibazaki (2005)) and whole earthquake cycle (e.g., Mitsui & Hirahara (2009a;b)). These numerical studies clarified the fundamental effects of the pore pressure evolution, i.e., thermal pressurization enlarges seismic slip its recurrence intervals, and pore-related pressurization restrains seismic slip and its occurrences.

However, applying their results to actual faults is not easy, since they depend on many constitutive parameters. In order to provide a clue for obtaining a clear view, here, we will focus on an analytic representation for comparing pore pressure change with frictional coefficient change. We will obtain the condition in which the effects of the pore pressure change can exceed. Then, we will substitute the typical values of rock materials and several types of the evolution law of frictional coefficient, to get several easy relations.

2. Derivation of analytic representation

First of all, we clarify the model setup in this study. We assume a fault embedded in a poroelastic body. The frictional resistance of the fault obeys the Amonton-Coulomb principle and the Terzaghi law of effective normal stress. Frictional resistance τ_f is equal to frictional coefficient μ multiplied by effective normal stress $\bar{\sigma}$, which is macroscopic normal stress σ minus pore fluid pressure p . One more fundamental assumption is that μ does not depend on fluid pressure p and normal stress σ .

Differentiating the relation $\tau_f = \mu(\sigma - p)$ with time t , we obtain

$$\frac{d\tau_f}{dt} = -\mu \frac{dp}{dt} + \bar{\sigma} \frac{d\mu}{dt} \quad (2)$$

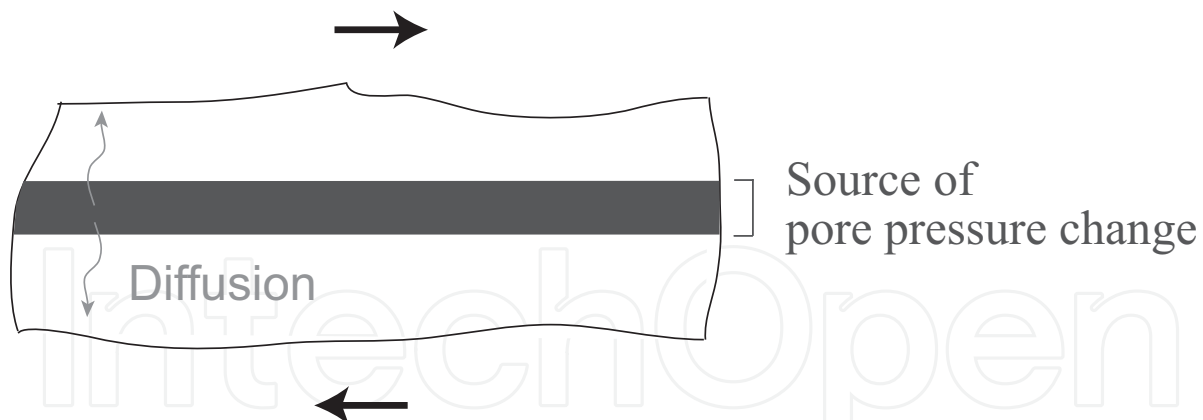


Fig. 2. Schematic illustration for the fault model with pore pressure change in this study.

The right-hand first term means the temporal alteration of friction by pore pressure change and the right-hand second term represents that by frictional coefficient. In order to compare the degree of both terms, we consider inequality with respect to the condition for exceeding of the pore pressure change. From Equation (2), the condition is written as

$$\left| \frac{d\mu}{dt} \right| \ll \frac{\mu}{\bar{\sigma}} \left| \frac{dp}{dt} \right| \quad (3)$$

Inequality (3) is a rather general representation, however, as a practical matter, we need more useful relations. In order to expand the term of the pore pressure change, we introduce a simplified poroelastic model following Segall & Rice (2006).

We assume that the pore fluid pressure first alters within the fault due to physicochemical processes, and diffuses outside via conduction processes in the poroelastic body, as illustrated in Figure 2. Based on the equation of mass conservation and the Darcy law, changing rate of a fluid mass m per unit volume in a certain bulk is given by:

$$\frac{dm}{dt} = \frac{\rho_f \kappa}{\nu} \nabla^2 p \quad (4)$$

where ρ_f is the fluid density, κ is the permeability of the poroelastic bulk and ν is the fluid viscosity.

Since a fluid mass per unit volume m is equivalent to $\rho_f \phi$, where ϕ is the porosity, we write down the following equation:

$$\frac{dm}{dt} = \rho_f \frac{d\phi}{dt} + \phi \frac{d\rho_f}{dt} \quad (5)$$

Moreover, we divide the temporal change of the porosity ϕ into elastic change and plastic change. The elastic change is given by

$$\frac{d\phi}{dt} = \phi \beta \frac{dp}{dt} + \phi \alpha \frac{dT}{dt} \quad (6)$$

introducing the pressure compressibility of the solid $\beta = (\partial\phi/\partial p)/\phi$ and the thermal expansivity of the solid $\alpha = (\partial\phi/\partial T)/\phi$, where T is the bulk temperature. Thus the form of Equation (6) is changed into

$$\frac{dm}{dt} = \rho_f \left. \frac{d\phi}{dt} \right|_{pl} + \rho_f \phi \beta \frac{dp}{dt} + \rho_f \phi \alpha \frac{dT}{dt} + \phi \frac{d\rho_f}{dt} \quad (7)$$

where the suffix $|_{pl}$ means “plastic”. Likewise we divide the temporal change of the fluid density ρ_f into that by fluid pressure and temperature. The representation is as follows:

$$\frac{d\rho_f}{dt} = \rho_f \beta_f \frac{dp}{dt} - \rho_f \alpha_f \frac{dT}{dt} \quad (8)$$

where we introduce the pressure compressibility of the fluid $\beta_f = (\partial\rho_f/\partial p)/\rho_f$ and the thermal expansivity of the fluid $\alpha_f = -(\partial\rho_f/\partial T)/\rho_f$. Using the constitutive relations, Equation (7) is rewritten as

$$\frac{dm}{dt} = \rho_f \left[\frac{d\phi}{dt} \Big|_{pl} + \phi[\beta + \beta_f] \frac{dp}{dt} + \phi[\alpha - \alpha_f] \frac{dT}{dt} \right] \quad (9)$$

Finally, from Equations (4) and (9), we obtain the following equation for representing fluid pressurization:

$$\frac{dp}{dt} = \Lambda \frac{dT}{dt} - \frac{1}{S_t} \frac{d\phi}{dt} \Big|_{pl} + \omega \nabla^2 p \quad (10)$$

where Λ is $[\alpha_f - \alpha]/[\beta + \beta_f]$, the storage capacity S_t is $\phi[\beta + \beta_f]$ and the pressure diffusivity ω is $\kappa/[\nu\phi(\beta + \beta_f)]$.

In addition, when dehydration reactions occur during fault slip (Brantut et al. (2010); Hirono et al. (2008); Hirose & Bystricky (2007)), we must consider an additional term “ $+c_{de}$ ” in the left-hand term of Equation (4), where c_{de} is the dehydration rate of fluid per unit volume of a bulk. It leads to the same additional term in the right-hand term of Equation (10):

$$\frac{dp}{dt} = \Lambda \frac{dT}{dt} - \frac{1}{S_t} \frac{d\phi}{dt} \Big|_{pl} + \frac{c_{de}}{S_t} + \omega \nabla^2 p \quad (11)$$

The right-hand first term of Equation (11) corresponds to the pore pressure change due to shear heating under undrained conditions, and the second term corresponds to that owing to plastic porosity change. The third term represents the fluid pressure diffusion. Figure 3

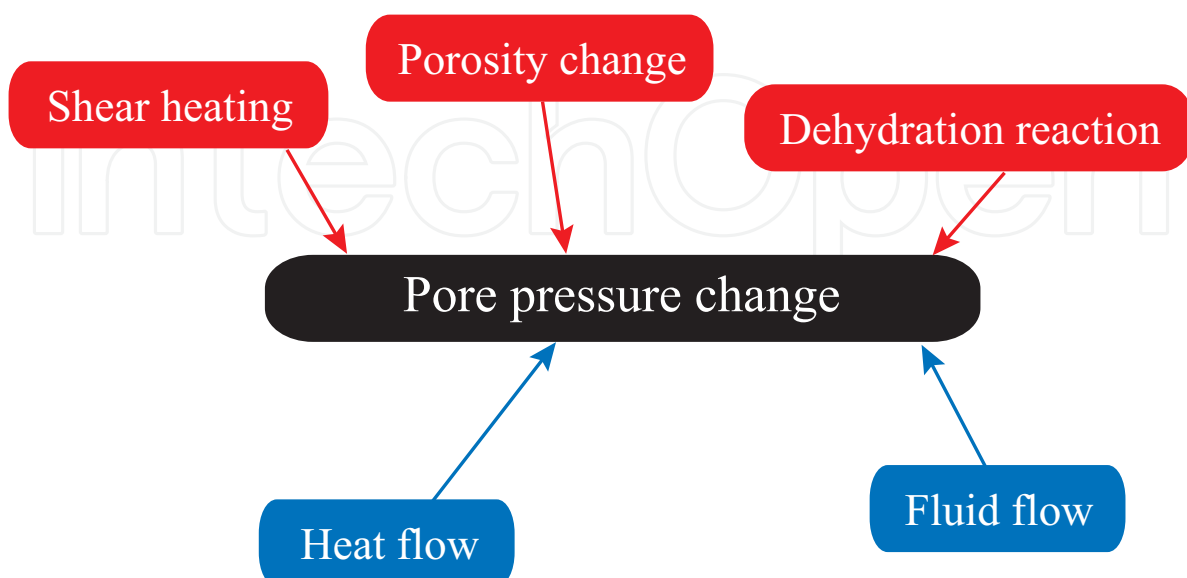


Fig. 3. A schematic presenting what factors cause the pore pressure change.

shows an illustration for the alteration processes of pore pressure. Using this equation, we can rewrite Inequality (3) as

$$\left| \frac{d\mu}{dt} \right| \ll \left| \frac{\mu}{\bar{\sigma}} \left[\Lambda \frac{dT}{dt} - \frac{1}{S_t} \frac{d\phi}{dt} \right]_{pl} + \frac{c_{de}}{S_t} + \omega \nabla^2 p \right| \quad (12)$$

2.1 Constitutive equation for thermal pressurization

The right-hand first term of Equation (11) includes both effects of shear heating and heat diffusion. Based on the energy conservation law and the Fourier law, change of the temperature T is given by

$$\rho c \frac{dT}{dt} = \tau_f Y + \lambda \nabla^2 T \quad (13)$$

where ρ , c and λ is respectively represents the density, the specific heat capacity and the thermal conductivity of the bulk composite, Y is the shear strain rate.

How should we represent the shear strain rate Y ? This issue is in itself of consequence. One simple assumption is that Y is roughly given by v/w , where v is the dislocation rate from a macroscopic viewpoint and w is the slip zone width (Cardwell et al. (1978); Fialko (2004)). The shear strain is assumed to be homogeneous in the slip zone. The other assumption is the Gaussian strain distribution (Andrews (2002)). Although actual processes of strain localization is much more complicated (e.g., Mandl et al. (1977); Marone et al. (2009)), here we assume $Y = v/w$ and w is constant as illustrated in Figure 4, for simplicity. p and T are the representative values at the center of the slip zone.

The temperature change can be rewritten as:

$$\frac{dT}{dt} = \frac{\tau_f v}{\rho c w} + \chi \nabla^2 T \quad (14)$$

where $\chi = \lambda/(\rho c)$ is the temperature diffusivity.

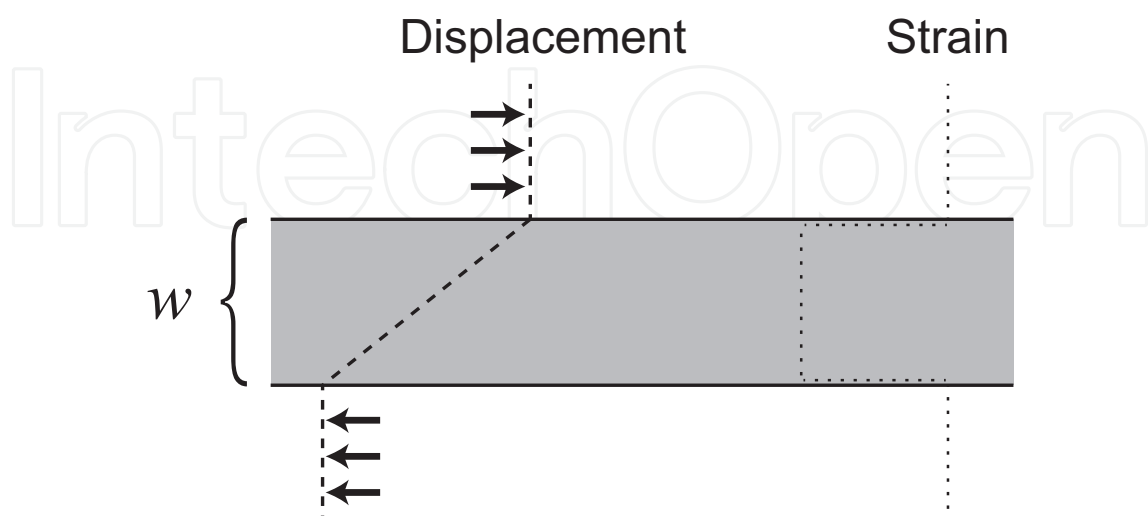


Fig. 4. A schematic for the simple assumption of the homogeneous shear strain within the slip zone.

Substituting Equation (14) into Inequality (12), we obtain an improved representation of the condition for exceeding of the pore pressure change:

$$\left| \frac{d\mu}{dt} \right| \ll \frac{\mu}{\bar{\sigma}} \left| \frac{A\tau_f v}{w} - \frac{1}{S_t} \frac{d\phi}{dt} \right|_{pl} + \frac{c_{de}}{S_t} + \omega \nabla^2 p + \Lambda \chi \nabla^2 T \quad (15)$$

where A equals $\Lambda/(\rho c)$. The new parameter A is a non-dimensional material parameter.

2.2 Constitutive equation for pore-related pressurization

The right-hand second term of Equation (10) means the porosity effect on the pore pressure change, so-called pore dilatation and compaction. Unlike thermal pressurization, the physical model of such the pore-related pressurization accompanying with shear has not been established well.

For example, Marone et al. (1990); Zhang & Tullis (1998) revealed by experiments that pore compaction (permeability decrease) evolve with shear from the initial experimental conditions. It is identical with observations of fault cores in actual faults, particularly in cases of high-porosity rocks such as sandstone (e.g., Aydin (1978); Balsamo & Storti (2010)).

However, pore compaction mechanism may not work effectively in lower-porosity rocks. For instance, Collettini et al. (2009) experimentally showed dilatational behavior with shear.

Such an effect of initial porosity is also presented experimentally by Tanikawa et al. (2010): Porosity (permeability) of initially higher-porosity rocks decreases by shear localization and that of lower-porosity rocks increases by cracking. Furthermore, Goren et al. (2010) performed granular simulations to present that initial dense packing of grains leads to initial pore dilatation, and loose packing does initial pore compaction.

Putting aside the above situation, we need certain simplified models. Since underground rocks in a seismogenic depth may have sufficiently low porosity, first we should consider the dilatation effect with shear. One simple assumption is dependence of the temporal rate of porosity increase on slip rate, as was assumed in several studies (Rudnicki & Chen (1988); Suzuki & Yamashita (2007)). In contrast, some experimental studies proposed that the temporal rate of porosity increase does not depend only on slip rate but also slip amount (Beeler et al. (1996); Marone et al. (1990)). From a practical standpoint, we adopt the former, more simple one.

In addition, beside the porosity changes with shear, chemical reaction such as pressure solution and precipitation, may occur within the fault zone. It should be time-dependent processes, independent of shear. Although many models have been suggested about it (e.g., Renard et al. (1999); Revil et al. (2006)), we try implementing the simplest one proposed by Gratier et al. (2003).

2.3 Typical values of material parameters

In the above relations, many material parameters appear. To evaluate them under a typical condition of underground seismogenic regions is essential for applications to fault dynamics.

First, referring to Clark (1966), we obtain the following values: the solid compressibility $\beta \sim 10^{-11} [\text{Pa}^{-1}]$, the thermal conductivity of the bulk (almost equal to the solid phase) $\lambda \simeq 2.0 \times$

$10^0 \text{ [Jm}^{-1}\text{s}^{-1}\text{K}^{-1}]$, the fluid compressibility $\beta_f \sim 10^{-9} \text{ [Pa}^{-1}]$, the thermal expansivity of the fluid $\alpha_f \sim 10^{-3} \text{ [K}^{-1}]$, and the thermal expansivity of the solid $\alpha \sim 10^{-5} \text{ [K}^{-1}]$.

The fluid parameters are calculated by assuming a pressure condition of 100 [MPa] and a temperature condition of 473 [K]. There is not much difference if the fluid composition is assumed to be pure H_2O or CO_2 . The notable difference of the magnitude of β and β_f means that we can look on the term $(\beta + \beta_f)$ as β_f . Likewise we are able to regard the term $(\alpha_f - \alpha)$ as α_f . Moreover, the multiplication of the bulk density ρ and the specific heat capacity c is approximately given by $3.0 \times 10^6 \text{ [Pa K}^{-1}]$ (Vosteen & Schellschmidt (2003)). The fluid viscosity ν is also approximated by 10^{-4} [Pa s] .

The remaining parameters of the permeability κ and the slip zone width w are difficult to characterize, although they are the controlling parameters of thermal pressurization. Unfortunately, many observations have revealed that they vary in several orders according to environments (e.g., Sibson (2003)). The porosity ϕ is also an ambiguous parameter. Therefore we regard the parameters as variables in this study.

The above typical values can be substituted into Inequality (15), via $A = (\alpha_f - \alpha)/[(\beta + \beta_f)\rho c]$, $S_t = \phi(\beta + \beta_f)$, $\omega = \kappa/[v\phi(\beta + \beta_f)]$ and $\Lambda\chi = A\lambda = [(\alpha_f - \alpha)\lambda]/[(\beta + \beta_f)\rho c]$. In particular, since A is a non-dimensional parameter, we can directly substitute the above typical value:

$$\left| \frac{d\mu}{dt} \right| \ll \frac{\mu}{\bar{\sigma}} \left| \frac{\tau_f v}{3w} - \frac{1}{S_t} \frac{d\phi}{dt} \right|_{pl} + \frac{c_{de}}{S_t} + \omega \nabla^2 p + \Lambda\chi \nabla^2 T \quad (16)$$

where $S_t \simeq 10^{-9} \phi \text{ [Pa}^{-1}]$, $\omega \simeq 10^{13} \kappa / \phi \text{ [m}^2 \text{ s}^{-1}]$, $\chi \simeq (2/3) \times 10^{-6} \text{ [m}^2 \text{ s}^{-1}]$ and $\Lambda\chi \simeq 2/3 \text{ [W m}^{-1} \text{ K}^{-1}]$.

3. Application to several cases

3.1 Model of undrained and adiabatic condition without porosity change and dehydration reaction

The comparison between thermal pressurization and frictional coefficient change in cases of undrained and adiabatic condition (no fluid flow and heat flow), no porosity changes, and no dehydration reactions is an easiest exercise. This situation would be applied to actual faults during short-time slip (details are described in section 4.1). Thus, in this section, we neglect the right-hand second, third, fourth and fifth terms of Inequality (16). Inequality (16) can be simplified as:

$$\left| \frac{d\mu}{dt} \right| \ll \frac{\mu^2 v}{3w} \quad (17)$$

Note that the absolute values of the normal stress and the pore pressure vanished by the assumption.

Not only the pore pressure but the frictional coefficient μ alters during fault slip. There have been proposed so many processes and constitutive laws for the frictional coefficient (Bizzarri (2009) and references there in). By contrast, as a practical matter, simple velocity-dependent friction or slip-dependent friction are well used for boundary conditions in elastodynamic problems (e.g., Fukuyama & Madariaga (1998)).

3.1.1 Rate-strengthening friction vs thermal pressurization

When μ depends only on the slip velocity v , Inequality (17) is changed into:

$$\left| \frac{d\mu}{dv} \right| \ll \frac{\mu^2 v}{3w |dv/dt|} \quad (18)$$

Inequality (20) means that the thermal fluid pressurization must exceed in cases of constant slip velocity $dv/dt = 0$. If we perform frictional experiments for constant slip velocity using materials with pure velocity-dependent friction and confined pore fluid, friction evolution must be controlled by the thermal fluid pressurization.

In fact, several numerical and experimental researches of granular rheology have revealed that macroscopic friction of dry granular flow increases with flow rate (e.g., Hatano (2007); Jop et al. (2006)), which might be adopted as frictional characteristics of fault gouges with shear heating. In addition, several rock experiments have clarified that the frictional coefficient of rocks tend to have rate-strengthening characters with the sub-seismic slip rate in the range of $1 \text{ [m s}^{-1}] - 1 \text{ [cm s}^{-1}]$ (e.g., Tsutsumi & Shimamoto (1997); Weeks (1993)). Thus the “competition” between the rate-strengthening friction and the thermal pressurization of pore fluid is an important issue for fault dynamics.

In addition, for example, if the frictional coefficient has a logarithmic rate-strengthening character as many rock experiments revealed, Inequality (18) is modified as

$$\left| \frac{d\mu}{d\ln(v)} \right| \ll \frac{\mu^2 v^2}{3w |dv/dt|} \quad (19)$$

When we adopt the typical values $d\mu/d\ln(v) \simeq 0.01$ and $\mu \simeq 0.6$, we obtain

$$\left| \frac{dv}{dt} \right| \ll \frac{10v^2}{w} \quad (20)$$

The parameters in Inequality (18) are reduced to only three parameters.

3.1.2 Slip-dependent friction vs thermal pressurization

If μ depends only on the slip amount u , Inequality (17) is rewritten as:

$$\left| \frac{d\mu}{du} \right| \ll \frac{\mu^2}{3w} \quad (21)$$

Only three parameters remain in this case.

In general, earthquake breakdown processes are apparently interpreted as an initial slip-strengthening and the following slip-weakening behavior (e.g., Cocco & Tinti (2008); Ohnaka & Yamashita (1989)), both of which include many kinds of microscopic physical processes. The thermal pressurization of pore fluid might be one of a dominating process of phenomenological slip-weakening (Abercrombie & Rice (2005); Wibberley & Shimamoto (2005)). Whether apparent slip-weakening behavior in actual earthquakes is due to thermal pressurization or not, is not so easy to be judged from observations.

In order to provide a hint for this issue, we use Inequality (21). Assuming the typical values of $\mu \simeq 0.6$, we obtain

$$\left| \frac{d\mu}{du} \right| \ll \frac{0.1}{w} \quad (22)$$

Just two parameters remain: the slip-weakening rate of the frictional coefficient $d\mu/du$ and the width of the slip zone w .

It means that fault weakening by the thermal pressurization must exceed without a certain intense slip-strengthening of the frictional coefficient or intense slip-weakening owing to other mechanisms such as wearing (Matsu'ura et al. (1992)), flash heating of asperity contacts (Rice (2006)), and thermally-activated chemical reactions of rock minerals (Di Toro et al. (2004); Han et al. (2007)), dependent on the slip zone thickness w .

3.2 Model of undrained and adiabatic condition

As was discussed in Section 2.2, we assume a velocity-dependent pore dilatancy and time-dependent pore compaction.

With regard to the former, the temporal evolution of the porosity is given by

$$\left. \frac{d\phi}{dt} \right|_{pl} = Zv \quad (23)$$

where Z is a characteristic value for dilatation.

In respect to the latter, Gratier et al. (2003) provides a simple equation

$$\left. \frac{d\phi}{dt} \right|_{pl} = -\phi/X \quad (24)$$

where X is a characteristic value for compaction.

Using both models for porosity changes, Inequality (16) is changed into:

$$\left| \frac{d\mu}{dt} \right| \ll \left| \frac{\mu^2 v}{3w} - \frac{\mu Z v}{\bar{\sigma} S_t} + \frac{\mu \phi}{\bar{\sigma} S_t X} + \frac{c_{de}}{S_t} \right| \quad (25)$$

Naturally, the right-hand second term (the dilatation term) and the right-hand third term (the compaction term) in Inequality (25) have sufficient potentials to alter the conditions described by the original Inequality (17). The dehydration term also has the potential. We can further introduce inequalities under limited assumptions like (18)-(22).

For example, Inequality (20) in case of the rate-strengthening friction is modified as:

$$\left| \frac{dv}{dt} \right| \ll \left| \frac{10v^2}{w} - \frac{60Zv^2}{\bar{\sigma} S_t} + \frac{60v\phi}{\bar{\sigma} S_t X} + \frac{c_{de}}{S_t} \right| \quad (26)$$

Moreover, Inequality (22) in case of the slip-dependent friction is modified as:

$$\left| \frac{d\mu}{du} \right| \ll \left| \frac{0.1}{w} - \frac{0.6Z}{\bar{\sigma} S_t} + \frac{0.6\phi}{\bar{\sigma} S_t X v} + \frac{c_{de}}{S_t} \right| \quad (27)$$

They have no simple parameter dependencies as Inequality (20)-(22).

4. Discussion

4.1 Requirement for neglecting fluid and heat diffusion

In Section 3.1-3.2, we ignore fluid and heat flow from slip zone. It is only valid in a sufficiently short time period.

Let us define the length of the time period in which we can ignore fluid and heat diffusion. With these terms, Inequality (17) is modified as:

$$\left| \frac{d\mu}{dt} \right| \ll \left| \frac{\mu^2 v}{3w} + \frac{\mu}{\bar{\sigma}} (\omega \nabla^2 p + \Lambda \chi \nabla^2 T) \right| \quad (28)$$

We can neglect the right-hand second term (fluid diffusion) of Equation (28) when

$$\Delta_t \ll \frac{w_{fld}^2}{4\omega} \quad (29)$$

and the right-hand third term (heat diffusion) when

$$\Delta_t \ll \frac{w_{heat}^2}{4\chi} \quad (30)$$

where Δ_t is a time scale for consideration, w_{fld} and w_{heat} are certain characteristic lengths for each process. Furthermore, since w_{fld} and w_{heat} can not fall below w , the conditions can be changed into

$$\Delta_t \ll \frac{w^2}{4\omega} \quad (31)$$

$$\Delta_t \ll \frac{w^2}{4\chi} \quad (32)$$

We can use Inequality (20), (22), (26) and (27), when both (31) and (32) are true.

Usually, under actual conditions, ω is several order larger than χ . For instance, even assuming quite low permeability $\kappa = 10^{-21} [\text{m}^2]$ and $\phi = 0.01$ as a typical value around slip zone, the fluid pressure diffusivity is $\omega \simeq 10^{-6} [\text{m}^2 \text{s}^{-1}]$, larger than the temperature diffusivity $\chi \simeq (2/3) \times 10^{-6} [\text{m}^2 \text{s}^{-1}]$ (see the last part of Section 2.3). It implies that Inequality (31) is a practical requirement for neglecting fluid and heat diffusion.

Besides, how large w in actual faults is another problem. Sibson (2003) reported coseismic shearing is localized in a region of less than 0.1 [m] by geological observations. A recent geochemical study on the Chelungpu fault revealed thermally-pressurized fluids might exist in the sheared bands with thickness of 0.02-0.15 [m] (Ishikawa et al. (2008)). Those studies may constrain the upper limit of w value ~ 0.1 [m]. In contrast, we have no idea to constrain the lower limit of w . Too small w breaks Inequality (31) in a practical time scale Δ_t .

For example, with one particular scale $w = 0.002$ [m] and $\omega = 10^{-6} [\text{m}^2 \text{s}^{-1}]$, Inequality (31) is turned into $\Delta_t \ll 1$ [s]. In this case, we can use (20), (22), (26) and (27) to consider whole slip processes in small earthquakes.

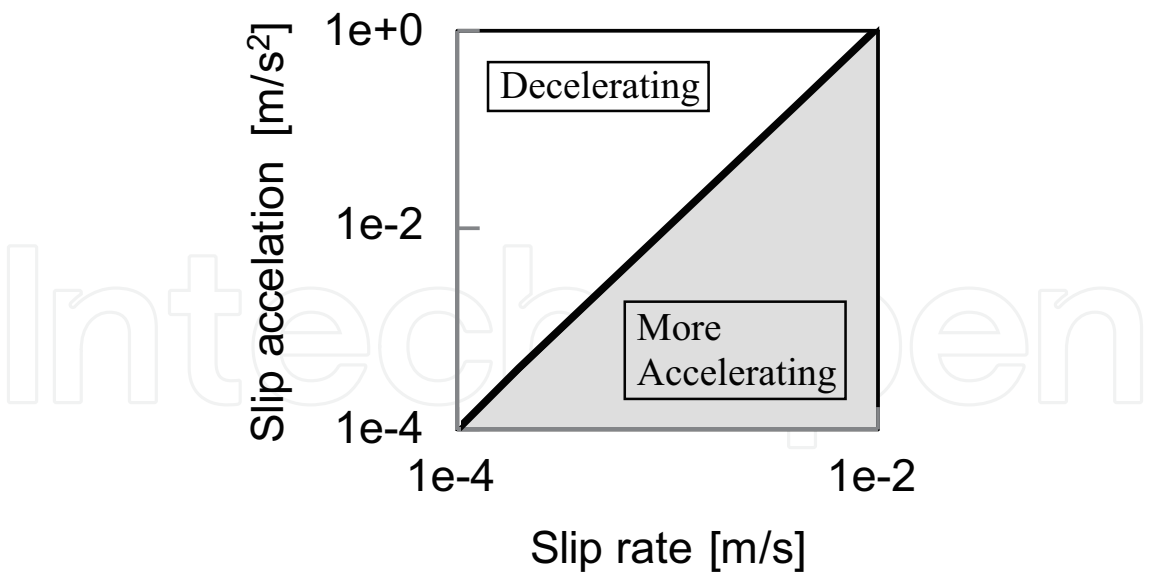


Fig. 5. The solid line displays a threshold level of the absolute value of slip acceleration as a function of sub-seismic slip rate, with $w = 1$ [cm]. When slip acceleration is above the threshold, slip will be decelerated owing to rate-strengthening friction. When it is below, slip will be accelerated due to the thermal pressurization of pore fluid.

4.2 Implications for actual earthquakes

4.2.1 Slip acceleration and deceleration with sub-seismic slip rate

As was described in section 3.1.1, frictional coefficient of rocks or fault gouges with sub-seismic slip rate may have rate-strengthening characters. Hence the “competition” between the rate-strengthening friction and thermal pressurization is a characteristic phenomenon during earthquakes especially in a slip acceleration period just before the slip rate reaches its maximum value.

Within the sufficiently short time under Inequalities (31) and (32), Inequality (20) would be a useful reference to understand fault behavior in this regime. As an example, Figure 5 presents a threshold level of slip acceleration whether slip is more accelerated by thermal pressurization or decelerated by rate-strengthening friction, when w is 1 [cm].

The Inequality and figure provide us qualitative implications about slip acceleration and deceleration during the sub-seismic slip regime. First, slip acceleration is originally loaded by external forces. Once slip rate reaches around the sub-seismic rate, the acceleration obeys the “competition”, namely evolves more or less along the threshold level of the “competition” described by Inequality (20). It means that slip acceleration process might have a broadly fixed pattern within the sub-seismic slip regime. Also, with respect to slip deceleration following high-speed seismic slip, similar consideration might be able to adopted.

4.2.2 Breakdown process with seismic slip rate

After the “competition” between the rate-strengthening friction and the thermal pressurization of pore fluid, slip rate may reach a seismic slip regime. Usually this regime accompanies the phenomenological slip-weakening of frictional coefficient. We can refer to

Inequality (22) to compare such the slip-weakening of frictional coefficient with the thermal pressurization. Figure 6 shows the meaning of Inequality (22).

With respect to the slip-weakening rate, for instance, experiments by Mizoguchi et al. (2009) using fault gouge obtained from Nojima fault, southwest Japan, show $d\mu/du \sim 10^{-2} [\text{m}^{-1}]$. Other experiments by Di Toro et al. (2004) using Arkansas novaculite, show $d\mu/du \sim 10^{-1} [\text{m}^{-1}]$. Those results fall on the shadow zone in Figure 6, which means Inequality (22) is true, even with the largest w in geological observations: $w \sim 0.1 [\text{m}]$.

It indicates that the thermal pressurization would necessarily dominate during the apparent slip-weakening behavior within the seismic slip regime, without the porosity evolution and the fluid/heat flow.

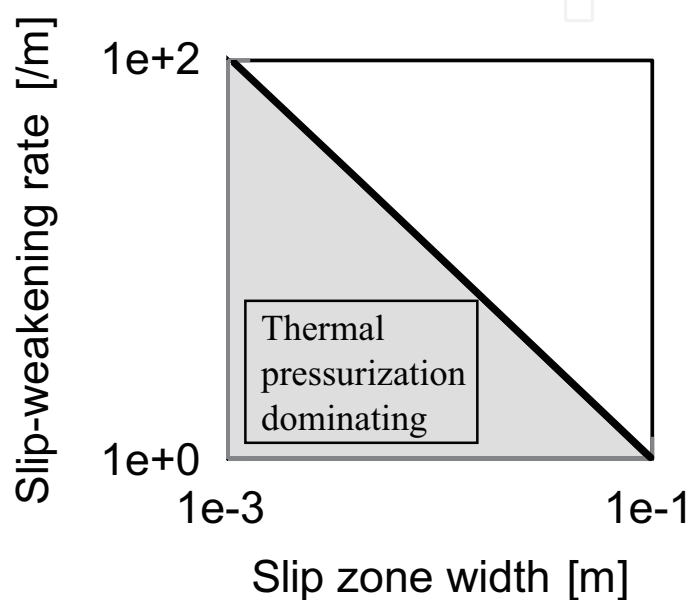


Fig. 6. The solid line represents a threshold level of slip-weakening rate of frictional coefficient $d\mu/du$ as a function of the slip zone width w . Within the shadow zone, the thermal pressurization dominates the slip-stress evolution.

5. Conclusion

We derived inequalities for comparing the change of pore pressure with that of frictional coefficient during fault slip.

The condition in which the effects of the pore pressure change on friction can exceed is represented as Ineqation (12) or (15). Substituting the typical values of rock materials for the inequality, we obtain Inequality (16). Some easy relations are further obtained by the assumptions of no porosity evolution, no dehydration reaction, and a short-time period as Inequality (31) and (32): “rate-strengthening friction vs thermal pressurization” (Inequality (20)) or “slip-dependent friction vs thermal pressurization” (Inequality (22)).

From the easy relations, we obtain a qualitative implication for slip acceleration and deceleration with sub-seismic slip rate. Slip acceleration, originally due to external forces, might have a fixed way owing to the competition between the rate-strengthening friction and the thermal pressurization. Slip deceleration does the same. In addition, the thermal

pressurization would necessarily dominate the apparent slip-weakening behavior in the seismic slip regime under the undrained and adiabatic condition with no porosity evolution and no dehydration reaction.

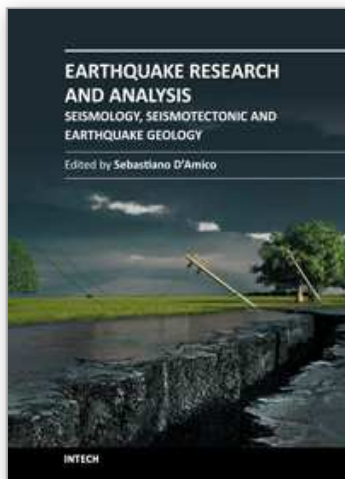
6. References

- Abercrombie, R. E. & Rice, J. R. (2005). Can observations of earthquake scaling constrain slip weakening?, *Geophys. J. Int.* 162(2): 406–424.
URL: <http://blackwell-synergy.com/doi/abs/10.1111/j.1365-246X.2005.02579.x>
- Andrews, D. J. (2002). A fault constitutive relation accounting for thermal pressurization of pore fluid, *J. Geophys. Res.* 107(B12).
URL: <http://www.agu.org/pubs/crossref/2002/2002JB001942.shtml>
- Aydin, A. (1978). Small faults formed as deformation bands in sandstone, *Pure Appl. Geophys.* 116: 913–930.
URL: <http://www.springerlink.com/index/10.1007/BF00876546>
- Balsamo, F. & Storti, F. (2010). Grain size and permeability evolution of soft-sediment extensional sub-seismic and seismic fault zones in high-porosity sediments from the Croton basin, southern Apennines, Italy, *Marine Petro. Geol.* 27(4): 822–837.
URL: <http://linkinghub.elsevier.com/retrieve/pii/S0264817209002141>
- Beeler, N. M., Tullis, T. E., Blanpied, M. L. & Weeks, J. D. (1996). Frictional behavior of large displacement experimental faults, *J. Geophys. Res.* 101(B4): 8697–8715.
URL: <http://www.agu.org/pubs/crossref/1996/96JB00411.shtml>
- Bizzarri, A. (2009). What Does Control Earthquake Ruptures and Dynamic Faulting? A Review of Different Competing Mechanisms, *Pure Appl. Geophys.* 166(5-7): 741–776.
URL: <http://www.springerlink.com/index/10.1007/s00024-009-0494-1>
- Bizzarri, A. & Cocco, M. (2006). A thermal pressurization model for the spontaneous dynamic rupture propagation on a three-dimensional fault: 1. Methodological approach, *J. Geophys. Res.* 111(B5).
URL: <http://www.agu.org/pubs/crossref/2006/2005JB003862.shtml>
- Brace, W. F. & Martin, R. J. (1968). A test of the law of effective stress for crystalline rocks of low porosity, *Int. J. Rock Mech. Min. Sci.* 5: 415–426.
- Brantut, N., Schubnel, A., Corvisier, J. & Sarout, J. (2010). Thermochemical pressurization of faults during coseismic slip, *J. Geophys. Res.* 115(B5): 1–17.
URL: <http://www.agu.org/pubs/crossref/2010/2009JB006533.shtml>
- Cardwell, R. K., Chinn, D. S., Moore, G. F. & Turcotte, D. L. (1978). Frictional heating on a fault zone with finite thickness, *Geophys. J. R. Astr. Soc.* 52: 525–530.
- Clark, S. P. (ed.) (1966). *Handbook of physical constants*, The Geological Society of America, New York.
- Cocco, M. & Tinti, E. (2008). Scale dependence in the dynamics of earthquake propagation: Evidence from seismological and geological observations, *Earth Planet. Sci. Lett.* 273(1-2): 123–131.
URL: <http://linkinghub.elsevier.com/retrieve/pii/S0012821X08003956>
- Collettini, C., De Paola, N. & Faulkner, D. (2009). Insights on the geometry and mechanics of the Umbria–Marche earthquakes (Central Italy) from the integration of field and laboratory data, *Tectonophysics* 476(1-2): 99–109.
URL: <http://linkinghub.elsevier.com/retrieve/pii/S004019510800396X>

- Di Toro, G., Goldsby, D. L. & Tullis, T. E. (2004). Friction falls towards zero in quartz rock as slip velocity approaches seismic rates, *Nature* 427: 436–439.
URL: <http://www.ncbi.nlm.nih.gov/pubmed/14749829>
- Dieterich, J. H. & Kilgore, B. D. (1994). Direct observation of frictional contacts: New insights for state-dependent properties, *Pure Appl. Geophys.* 143(1-3): 283–302.
URL: <http://www.springerlink.com/index/10.1007/BF00874332>
- Fialko, Y. (2004). Temperature fields generated by the elastodynamic propagation of shear cracks in the Earth, *J. Geophys. Res.* 109(B1).
URL: <http://www.agu.org/pubs/crossref/2004/2003JB002497.shtml>
- Fukuyama, E. & Madariaga, R. (1998). Rupture dynamics of a planar fault in a 3D elastic medium: Rate- and slip- weakening friction, *Bull. Seis. Soc. Am.* 88(1): 1–17.
- Goren, L., Aharonov, E., Sparks, D. & Toussaint, R. (2010). Pore pressure evolution in deforming granular material: A general formulation and the infinitely stiff approximation, *J. Geophys. Res.* 115(B9).
URL: <http://www.agu.org/pubs/crossref/2010/2009JB007191.shtml>
- Gratier, J.-P., Favreau, P. & Renard, F. (2003). Modeling fluid transfer along California faults when integrating pressure solution crack sealing and compaction processes, *J. Geophys. Res.* 108(B2).
URL: <http://www.agu.org/pubs/crossref/2003/2001JB000380.shtml>
- Han, R., Shimamoto, T., Hirose, T., Ree, J.-H. & Ando, J.-I. (2007). Ultralow friction of carbonate faults caused by thermal decomposition, *Science* 316: 878–881.
URL: <http://www.ncbi.nlm.nih.gov/pubmed/17495168>
- Handin, J., Hager, R. V., Friedman, M. & Feather, J. N. (1963). Experimental deformation of sedimentary rocks under confining pressure; pore pressure tests, *Bull. Am. Assoc. Petro. Geol.* 47(5): 717–755.
- Hatano, T. (2007). Power-law friction in closely packed granular materials, *Phys. Rev. E* 75(6).
URL: <http://link.aps.org/doi/10.1103/PhysRevE.75.060301>
- Hirono, T., Fujimoto, K., Yokoyama, T., Hamada, Y., Tanikawa, W., Tadai, O., Mishima, T., Tanimizu, M., Lin, W., Soh, W. & Song, S.-R. (2008). Clay mineral reactions caused by frictional heating during an earthquake: An example from the Taiwan Chelungpu fault, *Geophys. Res. Lett.* 35.
URL: <http://www.agu.org/pubs/crossref/2008/2008GL034476.shtml>
- Hirose, T. & Bystricky, M. (2007). Extreme dynamic weakening of faults during dehydration by coseismic shear heating, *Geophys. Res. Lett.* 34(14).
URL: <http://www.agu.org/pubs/crossref/2007/2007GL030049.shtml>
- Ishikawa, T., Tanimizu, M., Nagaishi, K., Matsuoka, J., Tadai, O., Sakaguchi, M., Hirono, T., Mishima, T., Tanikawa, W., Lin, W., Kikuta, H., Soh, W. & Song, S.-R. (2008). Coseismic fluid-rock interactions at high temperatures in the Chelungpu fault, *Nature Geoscience* 1: 679–683.
URL: <http://www.nature.com/doi/10.1038/ngeo308>
- Jop, P., Forterre, Y. & Pouliquen, O. (2006). A constitutive law for dense granular flows., *Nature* 441: 727–730.
URL: <http://www.ncbi.nlm.nih.gov/pubmed/16760972>
- Lachenbruch, A. H. (1980). Frictional Heating, Fluid Pressure, and the Resistance to Fault Motion, *J. Geophys. Res.* 85(B11): 6097–6112.
URL: <http://www.agu.org/pubs/crossref/1980/JB085iB11p06097.shtml>

- Mandl, G., Jong, L. N. J. & Maltha, A. (1977). Shear zones in granular material, *Rock Mech. Roch Eng.* 9: 95–144.
URL: <http://www.springerlink.com/index/10.1007/BF01237876>
- Marone, C., Cocco, M., Richardson, E. & Tinti, E. (2009). The critical slip distance for seismic and aseismic fault zones of finite width, in E. Fukuyama (ed.), *Fault-zone properties and earthquake rupture dynamics*, Academic press, chapter 6, pp. 135–162.
- Marone, C., Raleigh, C. B. & Scholz, C. H. (1990). Frictional Behavior and Constitutive Modeling of Simulated Fault Gouge, *J. Geophys. Res.* 95(B5): 7007–7025.
URL: <http://www.agu.org/pubs/crossref/1990/JB095iB05p07007.shtml>
- Matsu'ura, M., Kataoka, H. & Shibazaki, B. (1992). Slip-dependent friction law and nucleation processes in earthquake rupture, *Tectonophysics* 211(1-4): 135–148.
URL: <http://linkinghub.elsevier.com/retrieve/pii/004019519290056C>
- Mitsui, Y. & Hirahara, K. (2009a). Coseismic thermal pressurization can notably prolong earthquake recurrence intervals on weak rate and state friction faults: Numerical experiments using different constitutive equations, *J. Geophys. Res.* 114(B9).
URL: <http://www.agu.org/pubs/crossref/2009/2008JB006220.shtml>
- Mitsui, Y. & Hirahara, K. (2009b). Interseismic pore compaction suppresses earthquake occurrence and causes faster apparent fault loading, *Geophys. Res. Lett.* 36(20).
URL: <http://www.agu.org/pubs/crossref/2009/2009GL039932.shtml>
- Mizoguchi, K., Hirose, T., Shimamoto, T. & Fukuyama, E. (2009). High-velocity frictional behavior and microstructure evolution of fault gouge obtained from Nojima fault, southwest Japan, *Tectonophysics* 471(3-4): 285–296.
URL: <http://linkinghub.elsevier.com/retrieve/pii/S0040195109001292>
- Noda, H. & Shimamoto, T. (2005). Thermal Pressurization and Slip-Weakening Distance of a Fault: An Example of the Hanaore Fault, Southwest Japan, *Bull. Seis. Soc. Am.* 95(4): 1224–1233.
URL: <http://bssa.geoscienceworld.org/cgi/doi/10.1785/0120040089>
- Ohnaka, M. & Yamashita, T. (1989). A Cohesive Zone Model for Dynamic Shear Faulting Based on Experimentally Inferred Constitutive Relation and Strong Motion Source Parameters, *J. Geophys. Res.* 94(B4): 4089–4104.
URL: <http://www.agu.org/pubs/crossref/1989/JB094iB04p04089.shtml>
- Renard, F., Park, A., Ortoleva, P. & Gratier, J.-P. (1999). An integrated model for transitional pressure solution in sandstones, *Tectonophysics* 312(2-4): 97–115.
URL: <http://linkinghub.elsevier.com/retrieve/pii/S0040195199002024>
- Revil, A., Leroy, P., Ghorbani, A., Florsch, N. & Niemeijer, A. R. (2006). Compaction of quartz sands by pressure solution using a Cole-Cole distribution of relaxation times, *J. Geophys. Res.* 111(B9).
URL: <http://www.agu.org/pubs/crossref/2006/2005JB004151.shtml>
- Rice, J. R. (2006). Heating and weakening of faults during earthquake slip, *J. Geophys. Res.* 111(B5).
URL: <http://www.agu.org/pubs/crossref/2006/2005JB004006.shtml>
- Rudnicki, J. W. (1986). Slip on an impermeable fault in fluid-saturated rock mass, in S. Das, J. Boatwright & C. H. Scholz (eds), *Earthquake source mechanics*, Vol. 6 of AGU *Geophysical Monograph* 37, pp. 81–89.
- Rudnicki, J. W. & Chen, C.-H. (1988). Stabilization of rapid frictional slip on a weakening fault by dilatant hardening, *J. Geophys. Res.* 93(B5): 4745–4757.

- Segall, P. & Rice, J. R. (2006). Does shear heating of pore fluid contribute to earthquake nucleation?, *J. Geophys. Res.* 111(B9).
URL: <http://www.agu.org/pubs/crossref/2006/2005JB004129.shtml>
- Shibazaki, B. (2005). Nucleation process with dilatant hardening on a fluid-infiltrated strike-slip fault model using a rate- and state-dependent friction law, *J. Geophys. Res.* 110(B11).
URL: <http://www.agu.org/pubs/crossref/2005/2005JB003741.shtml>
- Sibson, R. H. (1973). Interactions between Temperature and Pore-Fluid Pressure during Earthquake Faulting and a Mechanism for Partial or Total Stress Relief, *Nature* 243: 66–68.
- Sibson, R. H. (2003). Thickness of the Seismic Slip Zone, *Bull. Seis. Soc. Am.* 93(3): 1169–1178.
URL: <http://bssa.geoscienceworld.org/cgi/doi/10.1785/0120020061>
- Suzuki, T. & Yamashita, T. (2007). Understanding of slip-weakening and -strengthening in a single framework of modeling and its seismological implications, *Geophys. Res. Lett.* 34(13).
URL: <http://www.agu.org/pubs/crossref/2007/2007GL030260.shtml>
- Tanikawa, W., Sakaguchi, M., Tadaï, O. & Hirose, T. (2010). Influence of fault slip rate on shear-induced permeability, *J. Geophys. Res.* 115(B7).
URL: <http://www.agu.org/pubs/crossref/2010/2009JB007013.shtml>
- Terzaghi, K. (1943). *Theoretical soil mechanics*, John Wiley & Sons.
- Tsutsumi, A. & Shimamoto, T. (1997). High-velocity frictional properties of gabbro, *Geophys. Res. Lett.* 24(6): 699.
URL: <http://www.agu.org/pubs/crossref/1997/97GL00503.shtml>
- Ujiie, K., Kameyama, M. & Yamaguchi, A. (2010). Geological record of thermal pressurization and earthquake instability of subduction thrusts, *Tectonophysics* 485(1-4): 260–268.
URL: <http://linkinghub.elsevier.com/retrieve/pii/S0040195110000065>
- Vosteen, H. D. & Schellschmidt, R. (2003). Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rock, *Phys. Chem. Earth* 28(9-11): 499–509.
URL: <http://linkinghub.elsevier.com/retrieve/pii/S147470650300069X>
- Weeks, J. D. (1993). Constitutive Laws for High-Velocity Frictional Sliding and Their Influence on Stress Drop During Unstable Slip, *J. Geophys. Res.* 98(B10): 17637–17648.
URL: <http://www.agu.org/pubs/crossref/1993/93JB00356.shtml>
- Wibberley, C. A. J. & Shimamoto, T. (2005). Earthquake slip weakening and asperities explained by thermal pressurization, *Nature* 436: 689–692.
URL: <http://www.ncbi.nlm.nih.gov/pubmed/16079843>
- Zhang, S. & Tullis, T. E. (1998). The effect of fault slip on permeability and permeability anisotropy in quartz gouge, *Tectonophysics* 295(1-2): 41–52.
URL: <http://linkinghub.elsevier.com/retrieve/pii/S0040195198001140>



Earthquake Research and Analysis - Seismology, Seismotectonic and Earthquake Geology

Edited by Dr Sebastiano D'Amico

ISBN 978-953-307-991-2

Hard cover, 370 pages

Publisher InTech

Published online 08, February, 2012

Published in print edition February, 2012

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How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Yuta Mitsui (2012). Change of Pore Fluid Pressure Versus Frictional Coefficient During Fault Slip, Earthquake Research and Analysis - Seismology, Seismotectonic and Earthquake Geology, Dr Sebastiano D'Amico (Ed.), ISBN: 978-953-307-991-2, InTech, Available from: <http://www.intechopen.com/books/earthquake-research-and-analysis-seismology-seismotectonic-and-earthquake-geology/change-of-pore-fluid-pressure-versus-frictional-coefficient-during-fault-slip>

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