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# Modeling slip processes at the deeper part of the seismogenic zone using a constitutive law combining friction and flow laws

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The fault zone in the earth's crust is thought to consist of several regions from top to bottom: the upper frictional region, the brittle-ductile transition zone and the ductile region. The upper frictional region consists of the unstable frictional zone, the unstable-stable transition zone, and the stable frictional zone. Recent geological observations of fault rock suggest that at the deeper part of the seismogenic zone, co-seismic frictional slip coexists with interseismic flow processes. We propose a possible model for slip processes at the deeper part of the seismogenic zone in which the frictional slip and flow processes are connected in series. In this model, in the ductile region, power law creep is dominant. Around the unstable-stable transition zone, we assume that co-seismic frictional slip coexists with aseismic flow processes. We investigate simple 1-D and 2-D models where rate- and state-dependent friction coexists with power law creep that has a threshold stress. The results of numerical simulations show that the amount of slip during the interseismic period is greater in the case where friction coexists with power law creep than it is when only friction is at work. It is also found that, for the case where friction coexists with power law creep, frictional slip is largely inhibited in the ductile region.

## 1. Introduction

It is widely recognized that the lithosphere consists of two main regions different in their deformation style: the upper part controlled by friction law and the lower part controlled by plastic flow law. Transition from frictional slip to plastic flow is called brittle-ductile transition. On the other hand, earthquake generation processes are frictional instability on the fault zone. From the point of stability, the upper friction-dominated fault zone consists of mainly three zones: the upper unstable zone, the unstable-stable transition zone, and the lower stable zone (e.g., Tse and Rice, 1986; Blanpied *et al.*, 1998). The transition from unstable to stable frictional slip is expected to occur at about 300°C. The depth of this transition is thought to correspond to the cut-off depth of seismicity and is shallower than the depth of brittle-ductile transition.

The fault region from the unstable-stable transition to brittle-ductile transition significantly controls earthquake generation processes. However, this region is not well understood. It is thought that stationary slip occurs first in the stable frictional zone and the ductile region due to tectonic loading. Secondly, stress concentrates in the unstable-stable transition zone, along which accelerated slip widely occurs. Finally, accelerated slip localizes at some part of the unstable-stable transition zone, and nucleation begins at that point. Shibazaki (2002) investigated the fault model with a slip-dependent friction law which has the upper unstable zone, the unstable-stable transition zone, and the lower stable zone and found that acceleration of slip widely occurs along the unstable-stable transition zone.

Monitoring the fault region from the unstable-stable transition to brittle-ductile transition is thought to be a key factor in predicting large earthquakes (Aki, 1996; Iio *et al.*, 2002), although such monitoring is very difficult. For efficient monitoring, we must forecast slip processes through numerical simulations. To make such simulations, it is necessary to consider the following factors: (I) the geometry of deep extensions of earthquake faults, (II) tectonic loading processes, (III) fault-constitutive relations from the unstable-stable transition to brittle-ductile transition. In particular, constitutive relations from the unstable-stable transition to brittle-ductile transition are of fundamental importance.

Fault behavior from the unstable-stable transition to brittle-ductile transition is very complex. Scholz (1990) pointed out that the unstable-stable transition is closely related to the brittle-ductile transition; that is, the unstable-stable transition corresponds to the onset of plasticity of fault gouge. Recently, Takagi *et al.* (2000) examined small-scale ultramylonite and cataclasite bands developed in granitic rocks of the Hatagawa fault zone in the Abukuma Belt, northeast Japan. Cataclastic and plastic deformation features

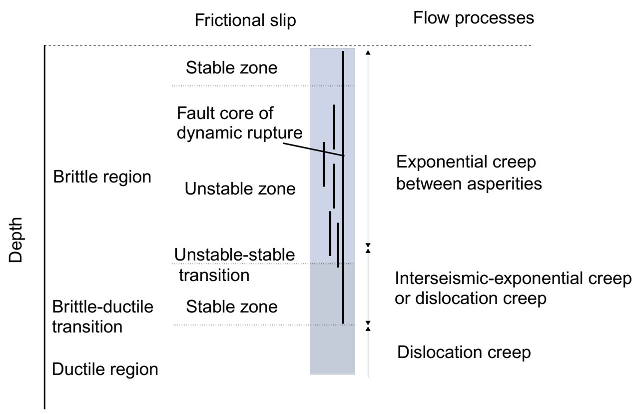


Fig. 1. Schematic model of the fault zone structure. Below the brittle-ductile transition, power law dislocation creep is dominant. From the unstable-stable to the brittle-ductile transition, there is broad interseismic exponential creep or dislocation creep in a fault zone.

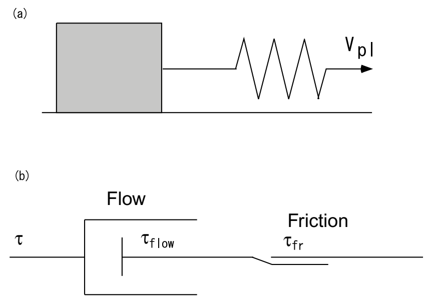


Fig. 2. (a) A spring and slider block system. (b) A fault zone model in which power law creep and a rate- and state-dependent friction law are connected in series.

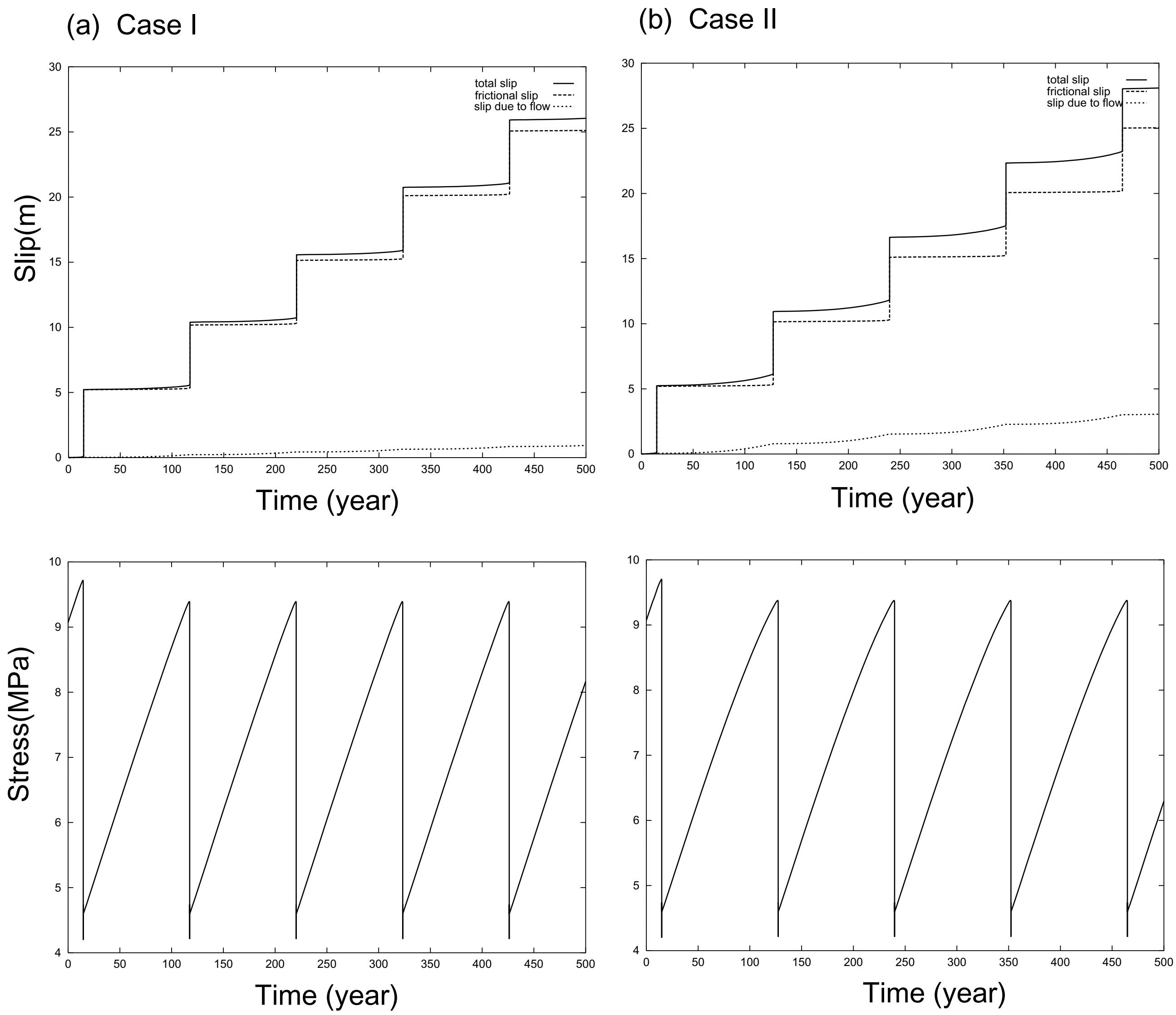


Fig. 3. Frictional slip, slip due to flow, total slip of frictional slip and slip due to flow, and shear stress in a a spring and slider block model using the constitutive law combining power law creep and a rate- and state-dependent friction law. (a) case I. The values of $a'_{flow}$ and $D_c$ are taken to be $8.8 \times 10^{-3}$ Pa and 0.03 m, respectively (b) case II. The values of $a'_{flow}$ and $D_c$ are taken to be $7.1 \times 10^{-3}$ Pa and 0.03 m. (c) case III. The values of $a'_{flow}$ and $D_c$ are taken to be $5.9 \times 10^{-3}$ Pa and 0.03 m, respectively (d) case IV. The values of $a'_{flow}$ and $D_c$ are taken to be $7.1 \times 10^{-3}$ Pa and 0.12 m.

closely coexist in the dark bands on the west of the Hatagawa fault zone. It was inferred that co-seismic frictional slip and aseismic plastic deformation have repeatedly taken place. Most recently, Shigematsu *et al.* (2001) found that ductile fracture occurs in granitic rocks of the Hatagawa fault zone. Tanaka (2000) also suggest that near the unstable-stable transition or stable frictional zone, a multi-mechanism deformation process occurs such as deformation mode changes from very slow plastic deformation to co-seismic frictional slip.

In general, to model earthquake generation processes, only the unstable-stable transition in frictional constitutive law is considered. However near the base of the seismogenic zone, it is possible that the stability depends on slip velocity. Shimamoto (1986) performed an experiment using Halite to investigate frictional behavior around the brittle-ductile transition. The results show the complex behavior where strength depends on strain: around the transitional regime, at a very low strain rate, strain rate strengthening occurs, at an intermediate strain rate, strain rate weakening occurs, and, at a high strain rate, strain rate strengthening occurs. These results suggest that at a very low strain rate, flow law is at work, and at an intermediate strain rate, frictional instability can occur. In the present study, we include this process into the model. However, we do not consider strain rate strengthening at a high strain rate since this paper mainly focuses on fault behavior in the inter- or pre-seismic period.

Recently, Chester (1995) proposed a rheologic model for wet crust considering a multi-mechanism description of friction. Reinen (2000) proposed a multi-mechanism constitutive law for serpentinite that combines a rate-dependent flow law and a rate- and state-dependent friction law proposed by Dieterich (1981) and Ruina (1983). Tanaka and Lockner (2001) also confirmed that power law creep with a threshold stress holds for montmorillonite clay gouge. It is possible that this kind of constitutive law, combining flow law and friction, holds from the unstable-stable transition to brittle-ductile transition.

Concerning a modeling of the earthquake cycles and nucleation processes, a lot of studies have been done with a rate- and state-dependent friction law considering the

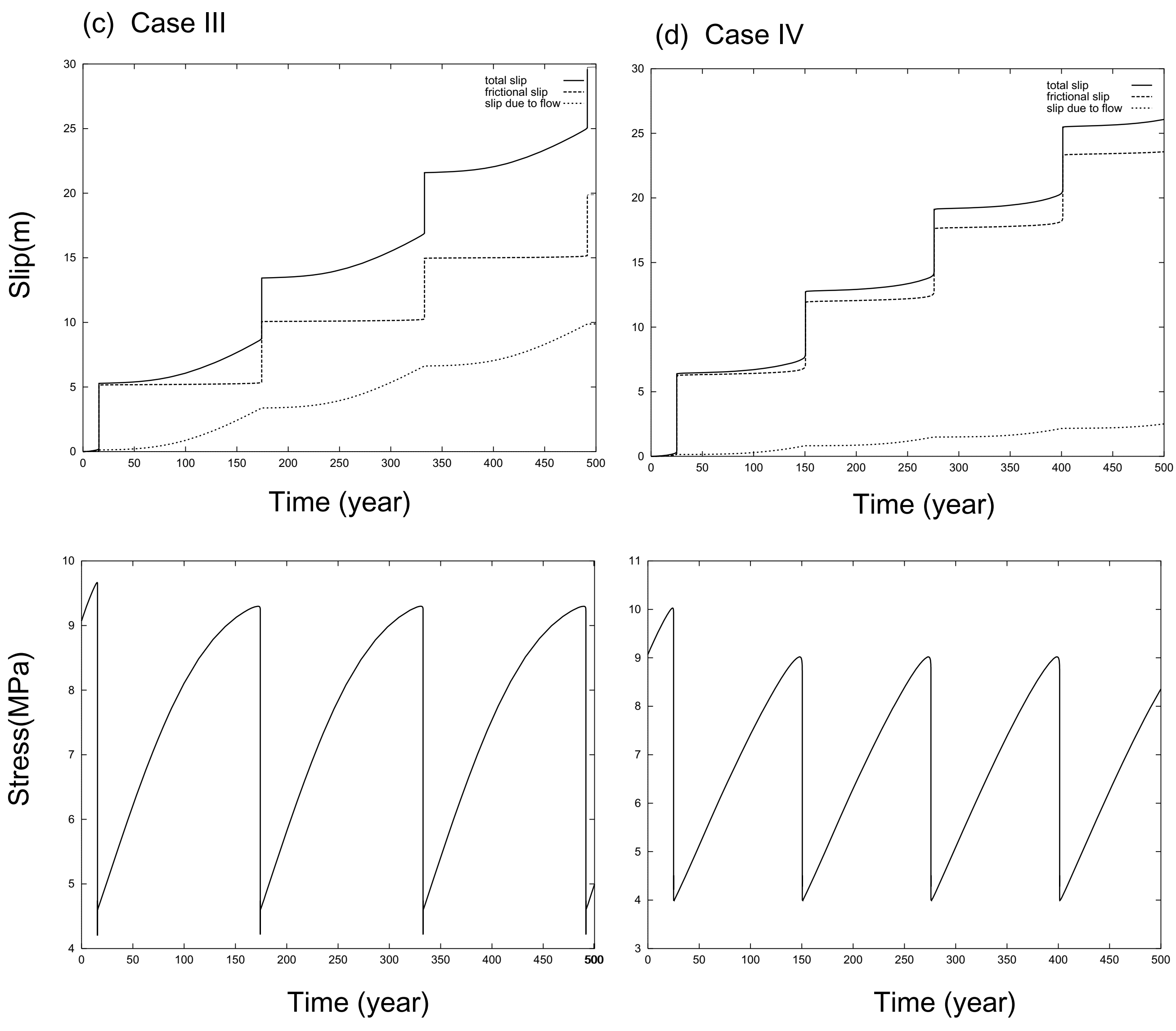


Fig. 3. (continued).

unstable-stable transition (e.g., Tse and Rice, 1986; Rice, 1993; Stuart and Tullis, 1995; Tullis, 1996; Kato and Hirasawa, 1997). Lapusta *et al.* (2000) developed a sophisticated model for earthquake cycles for a strike-slip fault, which rigorously includes the effect of the inertia. Ben-Zion and Rice (1997) investigated a strike-slip fault model in which the constitutive law, combining flow law, and friction, is used. However, the role of flow processes were not examined in detail.

This paper proposes a possible model for slip processes at the deeper part of a seismogenic zone, in which friction and flow processes are connected in series. We investigate simple 1-D and 2-D fault models in which a rate- and state-dependent friction coexists with power law creep with a threshold stress assuming the width of the fault zone is constant and the strain rate of the fault zone is constant.

## 2. Model

### 2.1 Conceptual model

Figure 1 shows our conceptual model of a fault zone. From geological and seismological observations, it is found that shear deformation is localized into a narrow zone beneath a seismogenic fault (Iio and Kobayashi, 2002). Therefore, the existence of a narrow shear zone in the ductile region is assumed. Two kinds of flow processes are also assumed: high-temperature power law creep and low-temperature exponential law creep (Kohlstedt *et al.*, 1995).

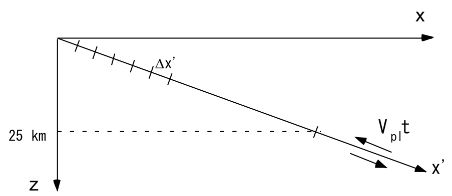


Fig. 4. Model space of thrust fault in a 2-D elastic half space. Below the depth of 25 km, uniform slip $V_{pl}t$ is given. The fault plane is divided into equal segments of $\Delta x'$.

In the ductile region, dislocation creep will be dominant, whereas from the unstable-stable transition to the stable zone, inter-seismic exponential creep or dislocation creep can occur. In this model, during the interseismic period, plastic deformation occurs in the shear zone from the unstable-stable transition to the stable zone. In the co-seismic period, frictional slip occurs at the very narrow fault core in the shear zone from the unstable-stable transition to the stable zone.

Scholz (1990) proposes a model in which, from the unstable-stable transition zone to brittle-ductile transition zone, ductile deformation coexists with adhesive wear that causes a stable frictional slip. In his model, mylonites begin to form just below the unstable-stable transition zone. The present model is very similar to Scholz's model. The only difference is that this model assumes that even around the unstable-stable transition zone, ductile deformation can occur; that is, unstable frictional slip coexists with interseismic flow processes. This region is considered to model the geological observations by Takagi *et al.* (2000) and Shigematsu *et al.* (2001). At present, there are very few direct observations of fault rocks around the unstable-stable transition or brittle ductile transition. Therefore, it is not certain whether this model is generally applicable.

For simplicity, it is assumed that the width of the fault zone is constant and that the strain rate $\dot{\varepsilon}$ of the fault zone is constant in the fault zone. When the width of the fault zone is equal to $W$, the amount of relative displacement becomes $W\varepsilon$. To construct a realistic model of the shear zone, it is necessary to consider shear localization of the fault zone. However, it is quite difficult to do this sort of numerical modeling. Although this model is very simple, it is useful for considering the role of flow processes on faulting at the present stage. We consider a model in which friction, exponential creep, and power law creep are connected in series. In this case, in the ductile region, power law creep will be dominant. In the unstable-stable transition zone, unstable frictional slip coexists with interseismic flow processes.

Shear stress along the fault equals frictional stress $\tau_f$, flow

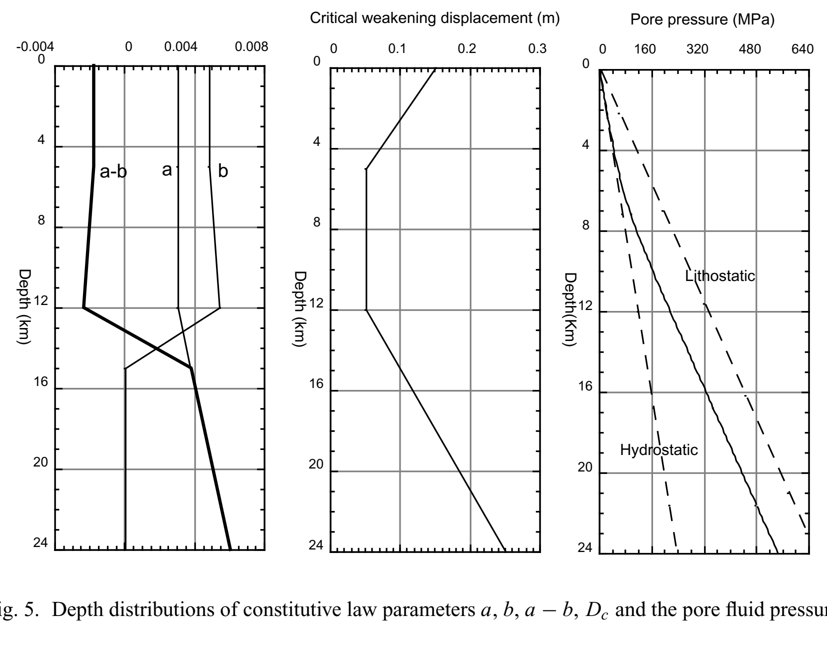


Fig. 5. Depth distributions of constitutive law parameters $a$, $b$, $a-b$, $D_c$ and the pore fluid pressure.

stress due to dislocation creep $\tau_d$, and Peierls stress $\tau_p$:

$$\tau = \tau_f = \tau_d = \tau_p. \quad (1)$$

Total relative displacement is the sum of frictional slip $u_{fr}$, slip due to power law creep $\varepsilon_d$, and slip due to exponential creep (Peierls stress) $\varepsilon_p$:

$$u = u_{fr} + W\varepsilon_d + W\varepsilon_p. \quad (2)$$

### 2.2 Flow laws

Considering the thermal activation process, the strain rate can be expressed as

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \sinh(-G^*/kT) \quad (3)$$

where $G^*$ is the stress-dependent Gibbs free energy of activation for the thermally activated process of dislocation glide, and $k$ is the Boltzmann constant. $G^*$ depends on the functional type of the obstacle (Kocks *et al.*, 1975). In the simplest case, $G^*$ can be expressed by

$$G^* = \Delta G(1 - \tau_p/\tau_{th}) \quad (4)$$

where $\Delta G$ is the value of $G^*$ at zero shear stress. Then, shear stress (Peierls stress) becomes

$$\tau_p = \tau_{th} + \tau_0 kT/\Delta G \sinh^{-1}(\dot{\varepsilon}/\dot{\varepsilon}_0). \quad (5)$$

If $\dot{\varepsilon}/\dot{\varepsilon} \gg 0$, this form becomes

$$\tau_p = \tau_{th} + \tau_0 kT/\Delta G \log(\dot{\varepsilon}/\dot{\varepsilon}_0). \quad (6)$$

This kind of creep process is at work at high stress and low temperature. Therefore, it is possible that exponential creep is at work above the brittle-ductile transition.

In the ductile region, due to high temperature, the flow law obeys the following power law dislocation creep:

$$\tau_d = a_{flow}(\dot{\varepsilon}/\dot{\varepsilon}_1)^{1/n} \exp(Q/nRT) \quad (7)$$

where $Q$ is the activation energy. In some cases, a threshold stress (internal stress) $\tau_{th}$ is required to properly explain the experimental results (e.g. Poirier, 1985):

$$\tau_d = \tau_{th} + a_{flow}(\dot{\varepsilon}/\dot{\varepsilon}_1)^{1/n} \exp(Q/nRT). \quad (8)$$

### 2.3 Rate- and state-dependent friction law

This study investigates the Ruina-Dieterich rate- and state-dependent friction laws (Ruina, 1983). In the Ruina-Dieterich friction law, frictional resistance depends on both slip velocity and state:

$$\tau_{fr} = \sigma_n^{eff}\{\mu_* + a\ln(\nu/\nu_*) + b\Theta\} \quad (9)$$

where $\sigma_n^{eff}$ is the effective normal stress, $\mu_*$ is the base friction for steady-state slip at a reference velocity $\nu_*$, $\nu$ is the instantaneous sliding velocity, and $\Theta$ is a state variable that characterizes the evolving state of the sliding surfaces. In recent studies by Heslot *et al.* (1994), Nakatani (2001), and Rice *et al.* (2001), $a\ln(\nu/\nu_*)$ has been interepreted as a thermal activation process working between asperities. In the Ruina-Dieterich friction law, a state variable can be written as

$$\partial\Theta/\partial t = -(\nu/D_c)\{\Theta + \ln(\nu/\nu_*)\} \quad (10)$$

where $D_c$ is a characteristic displacement scaling the evolution of the state variable.

## 3. Example of Numerical Simulation

In general, it is necessary to consider the frictional slip process, the exponential creep process and the power law creep process. However, since this system of processes is quite non-linear and it is not easy to obtain the solution, we investigate a simple case where a rate- and state-dependent friction, expressed by Eqs. (9) and (10), coexists with power law creep that has a threshold stress, expressed by Eq. (8).

### 3.1 1-D spring and slider block system model

First, we consider a spring and slider block system (Fig. 2(a)) in order to investigate the role of creep processes in the fault model in which a rate- and state-dependent friction and power law creep with a threshold stress are con-

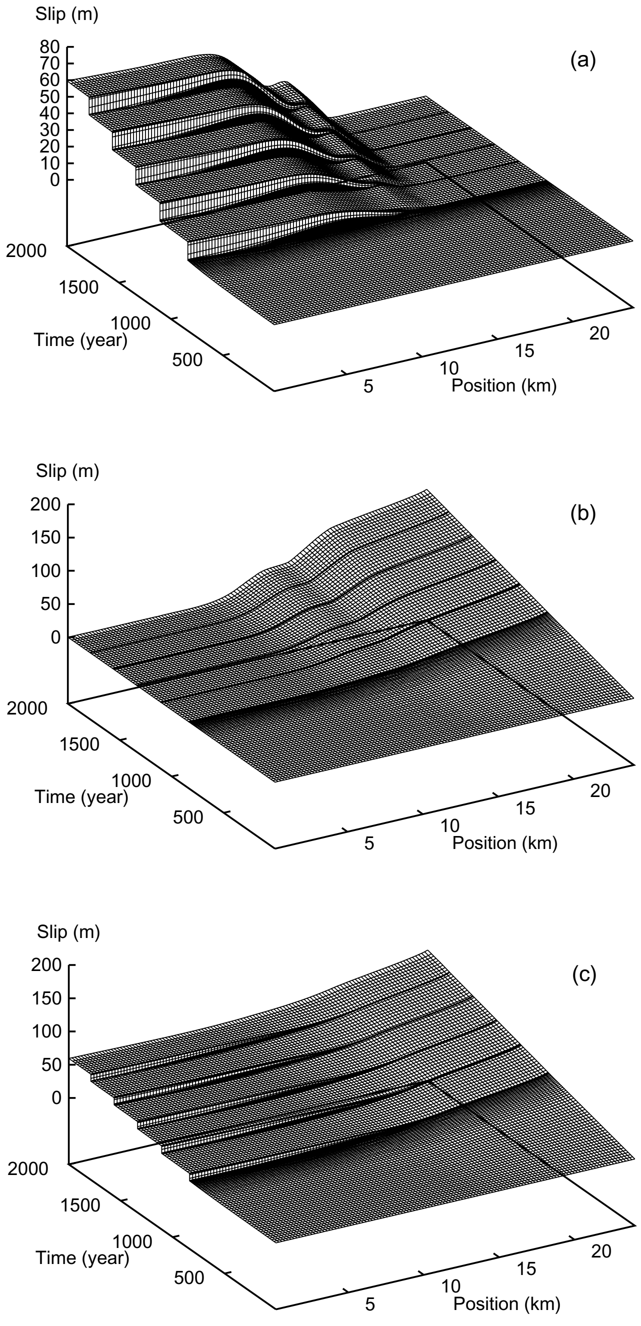


Fig. 6. Slip histories for several earthquake cycles. (a) Frictional slip. (b) Slip caused by power law creep. (c) Sum of frictional slip and slip caused by power law creep.

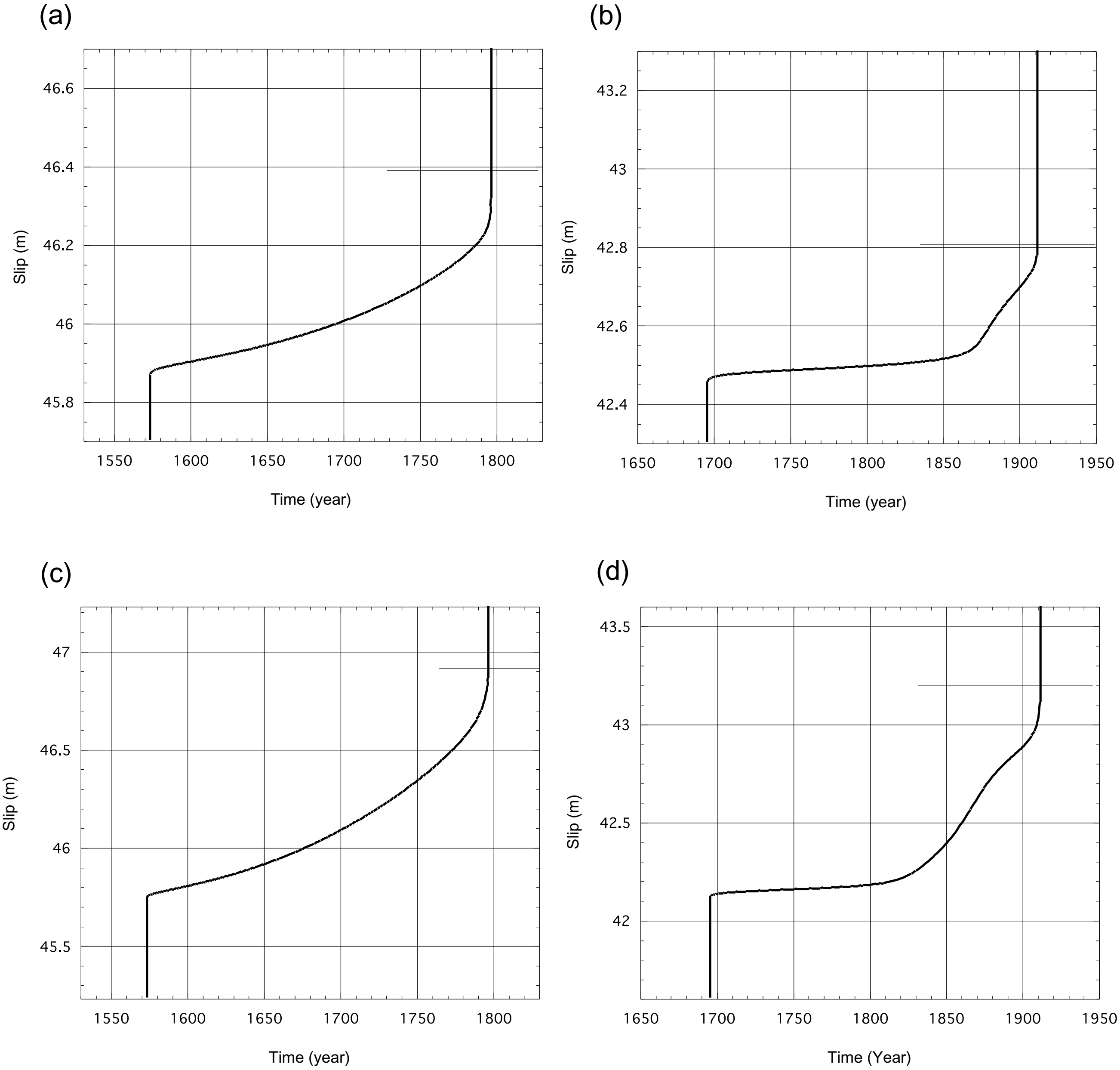


Fig. 7. Changes in slip with time at a depth of 9.5 km (a) and 10.3 km (c) for the case where friction coexists with a power law creep and at a depth of 9.5 km (b) and 10.3 km (d) for the case where only friciton is at work.

nected in series (Fig. 2(b)). The shear stress on the fault is accumulated by the delay of the fault slip from the displacement of a loading point. We solve the following system:

$$\tau = \tau_{fr} = \tau_d$$
$$u = u_{fr} + W\varepsilon_d$$
$$\tau = k(V_{pl}t - u) - \mu/2\nu_s du/dt \qquad (11)$$

where $\tau_{fr}$ is a frictional stress expressed by Eqs. (9) and (10), $\tau_d$ is flow stress due to dislocation creep expressed by an Eq. (8), $V_{pl}$ is the relative velocity of the plate motion, $\mu$ is the rigidity, $\nu_s$ is the shear wave velocity, and $k$ is the spring constant. We solve this system using the Runge-Kutta method with an adaptive time step size control (Press *et al.*, 1992) which Kato and Hirasawa (1997) originally used. This model is very similar to that of Reinen (2000). In her study, the velocity step is given in $V_{pl}$. This study fixes the value of $V_{pl}$.

In Figs. 3(a)–(c), we show the results of numerical simulations changing the parameter $a'_{flow} = a_{flow}\exp(Q/nRT)/\dot{\varepsilon}_1^n$. The values of $a$, $b$, $\sigma_n^{eff}$, and $D_c$ are set to be 0.03, 0.06, 100 MPa, and 0.03 m, respectively. The values of $V_{pl}$, $k$, $\mu$, and $\nu_s$ are set to be 0.05 m/year, 1.0 MPa/m, 30 GPa, and 3500 m/s, respectively. The values of the threshold stress $\tau_{th}$, $n$, and $W$ are set to be $0.9\mu_*\sigma_n^{eff}$, 5, 10 m.

A small value increases aseismic slip during the interseismic period. If $a'_{flow}$ is large, shear stress increases almost linearly with time. However, if $a'_{flow}$ is small, before instability, a stage appears in which the increasing rate of stress becomes small, which causes an inter-seismic precursory slip. When shear stress reaches the maximum value, then shear stress drops abruptly. Figure 3(d) shows a case where the critical weakening displacement $D_c$ is large. In this case, after shear stress reaches the maximum value, shear stress drops gradually at first, after which shear stress drops rapidly. Gradual shear stress drops cause a precursory slip just before instability.

### 3.2 2-D thrust fault model

Next, we consider a thrust fault in 2-D elastic half-space as illustrated in Fig. 4. The fault plane is located along the $x'$ axis. The dip angle is taken to be 20°. The free surface is located on the $z = 0$ plane. A fault plane is divided into cells with a length of $\Delta x'$. The $i$-cell occupies the region $(i-1)\Delta x' \le x' \le i\Delta x'$ $(i = 1, \ldots, M)$. For simplicity, we consider only the slip in the $x'$ direction. The shear stress $\tau_i$ on the $i$-cell on the fault in the $x'$ direction is accumulated by the delay of the fault slip $u_i$ from relative plate or micro-plate motion. The shear stress $\tau_i$ on the $i$-cell on the fault is accumulated by the delay of the fault slip $u_j$ from relative plate motion $V_{pl}t$. We solve the following system using the Runge-Kutta method with an adaptive time step size control (Press *et al.*, 1992):

$$\begin{aligned}\tau_i &= \tau_{fr,i} = \tau_{d,i}\\ u_i &= u_{fr,i} + W\varepsilon_{d,i}\\ \tau_i &= \sum_j k_{ij}(V_{pl}t - u_j) - \mu/2v_s du_i/dt \qquad (12)\end{aligned}$$

where $k_{ij}$ is the elastostatic kernel, which is the stress at the center of the $i$-cell caused by the uniform slip of the $j$-cell. Solving the equation of equilibrium and a constitutive relation, we can obtain stress and slip histories with the increase of relative plate motion.

Depth distributions of constitutive law parameters in Eqs. (9) and (10), and pore fluid pressure are shown in Fig. 5. The effective normal stress $\sigma_n^{eff}$ is defined as the difference between the lithostatic pressure and the pore fluid pressure. The values of the threshold stress $\tau_{th}$, the activation energy $Q$, $\dot{\varepsilon}_1$, $n$, and $W$ are set to be $0.9\mu_*\sigma_n^{eff}$, 120 kJ/mol, 1, 3, and 10 m. The depth distribution of temperature given by Iio and Kobayashi (2002) is used. In this simulation, we have selected the parameters of flow law such that co-seismic frictional slip coexists with the inter-seismic flow process at the deeper part of the seismogenic zone.

Figure 6 shows the result of the numerical simulations: displacement due to frictional slip, displacement due to flow, and total displacement. In this case, in the ductile region, slip due to power law creep is dominant. After an earthquake rupture, afterslip migrates downward to the ductile region. However, frictional slip is largely inhibited in the ductile region. There is a large discrepancy between the amount of fault slip at the Earth's surface and that at a depth of 25 km. This is caused by the difference in base frictional stress and threshold stress of the flow law $\mu^*\sigma_n^{eff} - \tau_{th} = 0.1\mu^*\sigma_n^{eff}$. If base frictional stress is equal to threshold stress of the flow law, the discrepancy disappears.

Figure 7 shows the changes in slip with time at depths of 9.5 km and 10.3 km for case I where friction coexists with a power law creep and for case II, where only friction is at work. The amount of slip during the inter-seismic period in case I is greater than that in case II. Figure 8 shows the changes in slip with time at depths of 20 km for case I and case II. It can be seen that frictional slip is largely inhibited in the ductile region for case I. The numerical results of this study are similar to those obtained by Kato and Hirasawa (1997). However, there are significant differences between these results and Kato and Hirasawa's for slip processes at the deeper part of the fault zone.

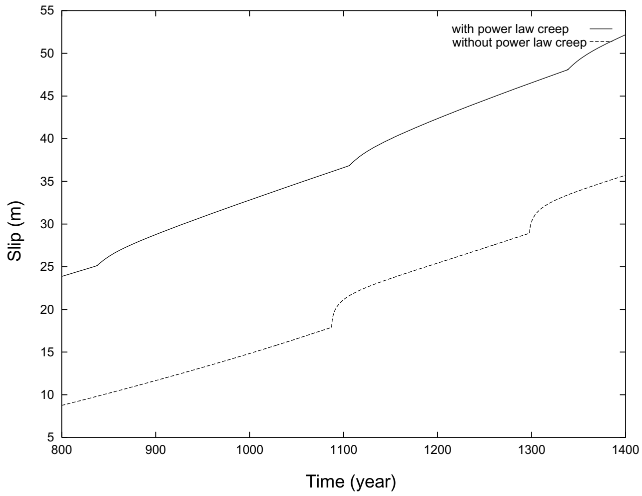


Fig. 8. Changes in slip with time at a depth of 20 km for the case where friction coexists with a power law creep and for the case where only friction is at work.

## 4. Conclusions

In the modeling of slip processes at the deeper part of the seismogenic zone, competing mechanisms of flow and friction are of fundamental importance. We proposed a model in which friction, exponential creep, and power law creep processes are connected in series. In the ductile region of this model, power law dislocation creep is dominant and stationary flow proceeds. At the lower part of the seismogenic zone, frictional slip coexists with the inter-seismic flow processes of the fault zone.

We investigated a simple case where a rate- and state-dependent friction coexists with power law creep that has a threshold stress. First, we considered a spring and slider block system in order to examine the role of flow processes on faulting. The results of the numerical simulations show that large flow increases inter-seismic slip. Next, we considered a thrust fault in 2-D elastic half-space. The results of the numerical simulations show that the amount of slip during the inter-seismic period at the deeper part of the seismogenic zone is greater in the case where friction coexists with power law creep than in the case where only friction is at work. It was also found that frictional slip is largely inhibited in the ductile region in the case where friction coexists with power law creep.

Our model assumes that the strain rate of the fault zone is constant and does not consider shear localization in a fault zone. The shear localization process may be a significant cause of slip acceleration. In future studies, it is necessary to investigate this process in order to develop a realistic model of slip acceleration at the deeper part of the fault zone.

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## References

Aki, K., Scale-dependence in earthquake phenomena and its relevance to earthquake prediction, *Proc. Natl. Acad. Sci. USA*, **93**, 3740–3747, 1996.

Ben-Zion, Y. and J. R. Rice, Dynamic simulations of slip on a smooth fault in an elastic solid, *J. Geophys. Res.*, **102**, 17,771–17,785, 1997.

Blanpied, M. L., C. J. Marone, D. A. Lockner, J. D. Byerlee, and D. P. King, Quantitative measure of the variation in fault rheology due to fluid-rock interactions, *J. Geophys. Res.*, **103**, 9691–9712, 1998.

Chester, F. M., A rheologic model for wet crust applied to strike-slip faults, *J. Geophys. Res.*, **100**, 13,033–13,044, 1995.

Dieterich, J. H., Constitutive properties of faults with simulated gouge, in *Mechanical Behavior of Crustal Rocks, Geophysical Monograph Series, vol. 24*, edited by N. L. Carter, M. Friedman, J. M. Logan, and D. W. Stearns, Ameican Geophysical Union, Washington, D.C., pp. 103–120, 1981.

Heslot, F., T. Baumberger, B. Perrin, B. Caroli, and C. Caroli, Creep, stick-slip, and dry friction dynamics: Experiments and a heuristic model, *Phys. Rev. E*, **49**, 4973–4988, 1994.

Iio, Y. and Y. Kobayashi, Is the plastic flow uniformly distributed below the seismogenic region?, *Earth Planets Space*, **54**, this issue, 1085–1090, 2002.

Iio, Y., Y. Kobayashi, and T. Tada, Large earthquakes initiate by the acceleration of slips on the downward extensions of seismogenic faults, *Earth Planet. Sci. Lett.*, 2002 (in press).

Kato, N. and T. Hirasawa, A numerical study on seismic coupling along subduction zones using a laboratory-derived friction law, *Phys. Earth Planet. Inter.*, **102**, 51–68, 1997.

Kocks, W. F., A. S. Argon, and M. F. Ashby, Thermodynamics and kinetics of slip, *Progr. Mater. Sci.*, **19**, 291, 1975.

Kohlstedt, D. L., B. Evans, and S. J. Mackwell, Strength of the lithosphere: constraints imposed by laboratory experiments, *J. Geophys. Res.*, **100**, 17,587–17,602, 1995.

Lapusta, N., J. Rice, Y. Ben-Zion, and G. Zheng, Elastodynamic analysis for slow tectonic loading with spontaneous rupture episodes on faults with rate- and state-dependent friction, *J. Geophys. Res.*, **105**, 23,765–23,789, 2000.

Nakatani, M., Conceptual and physical clarification of rate and state dependent friction law: Thermally activated rheology of frictional sliding, *J. Geophys. Res.*, **106**, 13,347–13,380, 2001.

Poirier, J. P., Creep of crystals, Cambridge University Press, Cambridge, 1985.

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, Numerical recipes in Fortran: the art of scientific computing, second edition, Cambridge University Press, 1992.

Reinen, L. A., Slip styles in a spring-slider model with a laboratory-derived constitutive law for serpentinite, *Geophys. Res. Lett.*, **27**, 2037–2040, 2000.

Rice, J. R., Spatio-temporal complexity of slip on a fault, *J. Geophys. Res.*, **98**, 9885–9907, 1993.

Rice, J. R., N. Lapusta, and K. Ranjith, Rate and dependent friction and the stability of sliding between elastically deformable solids, *J. Mech. Phys. Solids.*, **49**, 1865–1898, 2001.

Ruina, A. L., Slip instability and state variable friction laws, *J. Geophys. Res.*, **88**, 10,359–10,370, 1983.

Scholz, C. H., The mechanics of earthquakes and faulting, Cambridge University Press, 1990.

Shibazaki, B., Nucleation of large earthquakes determined by the seismic-aseismic boundary: agreement between models and observations, *Phys. Earth Planet. Inter.*, 2002 (in press).

Shigematsu, N., K. Fujimoto, T. Ohtani, T. Tomita, and K. Omura, Plastic deformation and fracturing: a case study in the Hatagawa fault zone, in *Proceedings of International Symposium on Slip and Flow Processes in and below the Seismogenic Region*, pp. 265–272, Sendai, Japan, 2001.

Shimamoto, T., A transition between frictional slip and ductile flow undergoing large shearing deformation at room temperature, *Science*, **231**, 711–714, 1986.

Stuart, W. D. and T. E. Tullis, Fault model for preseismic deformation at Parkfield, California, *J. Geophys. Res.*, **100**, 24,079–24,099, 1995.

Takagi, H., K. Goto, and N. Shigematsu, Ultramylonite bands derived from cataclastic and pseudotachylyte in granites, Northeast Japan, *J. Struct. Geol.*, **22**, 1325–1339, 2000.

Tanaka, H., Competitive mechanisms between flow and friction within a fault zone during dynamic slip; a model based on distribution and characteristics of intrafault materials, Programme and abstracts, *Seism. Soc. Japan*, **C35**, 2000 (in Japanese).

Tanaka, H. and D. A. Lockner, Nonlinear viscous behavior of montmorillonite clay minerals under hydrostatic conditions with low strain rate, and its implication for fault creep (in preparation).

Tse, S. T. and J. R. Rice, Crustal earthquake instability in relation to the depth variation of frictional slip properties, *J. Geophys. Res.*, **91**, 9452–9472, 1986.

Tullis, T. E., Rock friction and its implications for earthquake prediction examined via models of Parkfield earthquakes, *Proc. Natl. Acad. Sci. USA*, **93**, 3803–3810, 1996.

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