Physical modelling of tectonic loading processes at transcurrent plate boundaries

Chihiro Hashimoto and Mitsuhiro Matsu'ura

Department of Earth and Planetary Physics, University of Tokyo, Tokyo , Japan (e-mail: chihiro@gpsun01.geoph.s.u-tokyo.ac.jp; matsuura@geoph.s.u-tokyo.ac.jp, phone: +81-3-3812-2111 ext. 4290; 4318, fax: +81-3-3818-3247).

Abstract

We have constructed a physical model of tectonic loading processes at transcurrent plate boundaries by considering viscoelastic stress relaxation in the asthenosphere and spatial variation in fault constitutive parameters (peak strength and critical weakening displacement). With this model we have simulated the process of stress accumulation and release at a seismogenic region on a plate boundary, and obtained the following results. The increase of slip deficits in the seismogenic region with relatively high strength brings about stress concentration on its margin. The accumulated stress is released by unstable rupture if the critical weakening displacement D_c is small, and by stable slip if D_c is large. When a fault system consists of two high strength regions, interaction between them becomes essential in the stress accumulation and release process.

Introduction

The generation of large interplate earthquakes can be regarded as a process of tectonic stress accumulation and release, resulting from relative plate motion.The stress accumulation process essentially controls the subsequent stress release process, dynamic rupture propagation and stop, in the seismogenic region. So far it has been simply assumed that the tectonic stress accumulation uniformly proceeds in space and time in many earthquake simulation studies. The assumption of uniform loading is clearly contradict to the facts obtained through geodetic measurements (e.g., Lisowski et al., 1991 [1]; Thatcher, 1983 [2]). Matsu'ura and Sato (1997) [3] have constructed a kinematic model of tectonic loading by considering the effects of viscous drag at the base of the lithosphere and dislocation pile-ups at edges of a seismic fault. In the present study, first, we develop their model into a physical model by incorporating a fault constitutive relation between fault slip and shear stress into the kinematic model. Then, with this physical model, we simulate the process of tectonic loading at transcurrent plate boundaries.

Physical modelling

Given structure of the lithosphere-asthenosphere system and geometry of a plate boundary, we can describe the physical process of tectonic loading by coupled non-

linear equations, consisting of an internal viscoelastic stress function to fault slip on the plate boundary, the constitutive relation between fault slip and shear stress, and the relative plate motion. The lithosphere-asthenosphere system is modeled by an elastic surface layer overlying a Maxwellian viscoelastic half-space (Table 1). The constitutive equation of the surface layer is given by

$$\sigma_{ij} = \lambda^{(1)}\varepsilon_{kk}\delta_{ij} + 2\mu^{(1)}\varepsilon_{ij} \quad , \tag{1}$$

and that of the underlying viscoelastic half-space is given by

$$\dot{\sigma}_{ij} + \frac{\mu^{(2)}}{\eta}\left(\sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}\right) = \lambda^{(2)}\dot{\varepsilon}_{kk}\delta_{ij} + 2\mu^{(2)}\dot{\varepsilon}_{ij} \quad , \tag{2}$$

where σ_{ij}, ε_{ij}, and δ_{ij} are the stress tensor, the strain tensor, and the unit diagonal tensor, respectively. The dot indicates differentiation with respect to time. $\lambda^{(i)}$ and $\mu^{(i)}$ $(i = 1, 2)$ is Lamé elastic constants of each medium (the superscripts (1) and (2) correspond to the surface layer and the underlying half-space, respectively), and η is the viscosity of the underlying half-space.

	ρ [kg/m^3]	λ [GPa]	μ [GPa]	η [Pas]
Lithosphere	3000	40	40	–
Asthenosphere	3400	90	60	10^{19}

ρ : density, λ, μ : Lamé elastic constants, η : viscosity.

Table 1: Structural parameters.

The elastic lithosphere is divided into two parts by an infinitely long vertical interface, and interaction between these two parts is represented by the increase of tangential displacement discontinuity (fault slip) across the interface. We divide the fault slip w into the steady plate motion at a constant rate v_{pl} and its perturbation u :

$$w(\boldsymbol{x}, t) = v_{pl}t + u(\boldsymbol{x}, t) \quad . \tag{3}$$

The shear stress σ due to the fault slip w is obtained by the hereditary integral of the internal viscoelastic stress function $H(\boldsymbol{x}, t; \boldsymbol{\xi}, \tau)$ to a unit step slip on the plate boundary:

$$\sigma(\boldsymbol{x}, t) = \sigma_0(\boldsymbol{x}) + \int_0^t \int_{\Sigma_s} \frac{\partial u(\boldsymbol{\xi}, \tau)}{\partial \tau} H(\boldsymbol{x}, t - \tau; \boldsymbol{\xi}, 0) d\boldsymbol{\xi} d\tau \quad , \tag{4}$$

where the first and the second terms indicate the contributions from the steady plate motion and the slip perturbation, respectively.

In our problem the distribution of the fault slip w on the interface is unknown. What we know is the relation between the fault slip and the shear stress, that defines the frictional properties of the fault surface. We assume the constitutive relation between the fault slip w defined by Eq. (3) and the shear stress σ defined by Eq. (4) as a function of position:

$$\sigma(\boldsymbol{x}, t) = f\left[w(\boldsymbol{x}, t); \boldsymbol{x}\right] \quad . \tag{5}$$

The physical process of stress accumulation on the plate interface is essentially governed by the coupled nonlinear system that consists of Eqs. (3), (4), and (5).

Numerical simulations

In the present study we take a simple slip-weakening constitutive relation with the following form:

$$f(w) = \begin{cases} -\frac{\sigma_p}{2w_o^3} w(w^2 - 3w_o^2), & (0 \le w < w_o) \\ \sigma_p \left(\frac{w}{w_o}\right)^{\frac{w_o}{w_c}} \exp\left[\frac{w_o}{w_c}\left(1 - \frac{w}{w_o}\right)\right], & (w_o \le w) \end{cases} . \quad (6)$$

Here, σ_p , w_o , and w_c are the position-dependent parameters, related with two key parameters; the breakdown strength drop $\Delta\sigma_p$ and the critical weakening displacement D_c. We simulate the processes of stress accumulation and release in some representative cases with different values of these parameters by solving the coupled nonlinear equations, and obtained the following results.

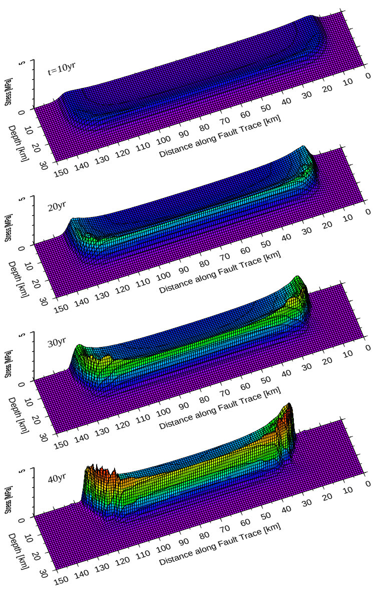

Figure 1: Stress accumulation on the uniform-strength fault with the effective length of 100 km. The relative plate velocity is 50 mm/yr. The increase of slip deficits in the seismogenic region brings about stress concentration on its margin. The system becomes unstable at $t = 40$ yr .

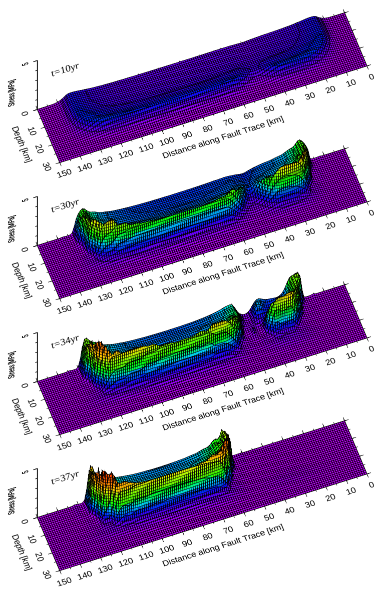

Figure 2: Stress accumulation on the fault system with a narrow weak zone. The total length of the fault system is 100 km. First, the smaller fault becomes unstable, and then, a few years later, the larger fault becomes unstable.

The increase of slip deficits in the seismogenic region with relatively high strength brings about stress concentration on its margin (Fig.1). The rate of stress accumu-

lation is nearly inversely proportional to the effective length of seismogenic regions. The accumulated stress is released by unstable rupture if the critical weakening displacement D_c is small, and by stable slip if D_c is large. When the seismogenic region is divided into two sub-regions with different sizes by a narrow zone, the sudden stress release in the smaller fault accelerates the stress accumulation in the larger fault (Fig. 2). This indicates the importance of interaction between adjacent seismic faults in the stress accumulation and release process.

References

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