

# Modelling stress accumulation and crustal deformation associated with earthquake cycles at plate boundaries

Toshinori Sato<sup>(1)</sup> and Mitsuhiro Matsu'ura<sup>(2)</sup>

(1) Earthquake Research Institute, University of Tokyo, Tokyo, Japan (e-mail: satot@eri.u-tokyo.ac.jp, phone: +81-3-3812-2111 ext 5714, fax: +81-3-5689-7234).

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

## Abstract

We developed a kinematic earthquake cycle model applicable to transform fault zones, subduction zones, and collision zones on the basis of elastic dislocation theory. The crustal deformation associated with the periodic occurrence of inter-plate earthquakes is generally given by the superposition of viscoelastic responses to steady slip on the whole plate boundary, steady back slip on the seismic zone, and a sequence of periodic seismic slips. The essential points in the modelling are as follows. Interaction between adjacent plates can be naturally represented by the increase of discontinuity in tangential displacement across the plate boundary. Viscoelastic stress relaxation of the asthenosphere strongly affects the crustal deformation during inter-seismic period. The effect of gravity is essential in the case of subduction zones. Crustal deformation and stress accumulation due to steady plate subduction can not be neglected.

## Introduction

For long-term prediction of large earthquakes at plate boundaries, it is important to develop an earthquake cycle model which can quantitatively relate crustal movements to slip motion at plate boundaries. Savage and Prescott (1978[7]) proposed a kinematic earthquake cycle model for transform faults, and Matsu'ura and Sato (1989[1]) and Sato and Matsu'ura (1998[6]) made generalization of their model and developed a unified earthquake cycle model applicable to transform fault zones, subduction zones, and collision zones. This paper presents basic concepts of the earthquake cycle model following our previous works (Sato and Matsu'ura, 1988[3]; 1992[4]; 1993[5]; 1998[6]; Matsu'ura and Sato 1989[1]; 1997[2]).

## Earthquake cycle model

We represent interaction between two plates by the increase of discontinuity in tangential displacement across the plate boundary. The displacement discontinuity (dis-

location) is mathematically equivalent to the force system of a double couple without moment. The force system of a double couple has no net force and no net torque. In general, such a property must be satisfied for any force system acting on the plate boundary, because it is the internal force imposed by a dynamic process within the earth. We model a plate boundary by an infinitely long dislocation surface, which is not the approximation of an isolated plate boundary with a finite length, but the approximation of a sequence of various types of plate boundaries, which makes the circuit of the earth.

The lithosphere-asthenosphere system is modeled by a stratified viscoelastic half-space under gravity, which consists of an elastic (or high-viscosity) surface layer and a low-viscosity substratum. We assume that the viscoelastic layer behaves like a Maxwell fluid in shear and an elastic solid in bulk.

The periodic occurrence of inter-plate earthquakes can be regarded as a perturbation of the hypothetical steady slip motion proceeding on the whole plate boundary. Then the crustal deformation associated with the periodic occurrence of inter-plate earthquakes is given by the superposition of viscoelastic responses to the steady slip on the whole plate boundary, the steady back slip on the seismic zone, and the sequence of periodic seismic slips. The mathematical formulations of this process are shown in Matsu'ura and Sato (1989[1]), Sato and Matsu'ura (1992[4]; 1998[6]).

## Results of simulations

### Stress accumulation at a transform plate boundary

To demonstrate the importance of viscoelasticity of the asthenosphere, we simulate tectonic loading processes at a seismic zone on a transform plate boundary subject to steady relative plate motion (Matsu'ura and Sato 1997[2]). In this model, the seismic zone is represented by a locked patch with a finite length on an infinitely long plate interface. The simulation shows that stress accumulation on the seismic fault is partly due to viscous drag at the base of the lithosphere (base loading) and partly due to dislocation pile-ups at edges of fault (edge loading). Figure 1 shows accumulation of shear stress on the fault. The results indicate that the amount of accumulating stress during inter-seismic period due to the base loading depends strongly on the viscosity of the asthenosphere. For the realistic viscosity ( $10^{19} - 10^{20}$  Pa s), the amount is comparable to that due to the edge loading. This means that viscoelasticity of the asthenosphere is important for modelling of the loading process of earthquake cycles.

### Crustal deformation associated with earthquake cycles in subduction zones

To demonstrate the importance of effects of steady plate subduction and viscoelasticity of the asthenosphere, we compute the crustal deformation cycle associated with the periodic occurrence of inter-plate earthquakes (Matsu'ura and Sato 1989[1]; Sato and Matsu'ura 1992[4]; 1998[6]). The computation was done for two representative cases, Case I and II. In Case I the seismic zone extends through the entire thickness of the lithosphere, and in Case II the seismic zone extends from surface to the half depth of the lithosphere. Figure 2 shows vertical movements at a fixed point during three earthquake cycles. The fixed point is located on the continental side at 100 km

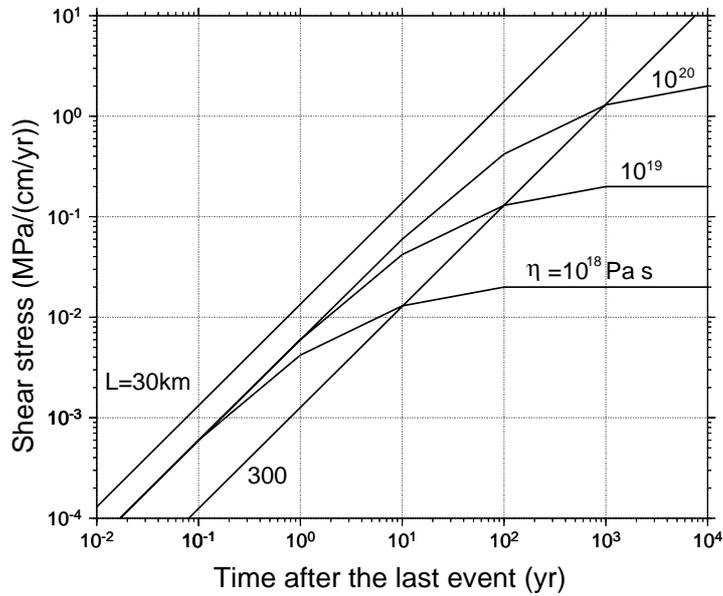


Figure 1: Accumulation of shear stress on a fault due to the edge loading (straight lines) and base loading (curved lines) after the occurrence of a large inter-plate earthquake. The shear stress is normalized by a relative plate velocity.  $L$  and  $\eta$  indicate the fault length and the viscosity of the asthenosphere, respectively.

distance from the trench axis. The results indicate that the permanent deformation due to steady plate subduction (broken lines) is not negligible, and that the effects of viscoelastic stress relaxation in the asthenosphere is remarkable in the post-seismic period. In Case II, especially, the viscoelastic model shows subsiding motion in the post-seismic period. The elastic model neglecting the effects of steady plate subduction (dotted lines), on the other hand, shows rising motion at a constant rate in the same period. These mean that the effects of steady plate subduction and viscoelastic stress relaxation in the asthenosphere are essential in the modelling of earthquake cycles.

## Acknowledgments

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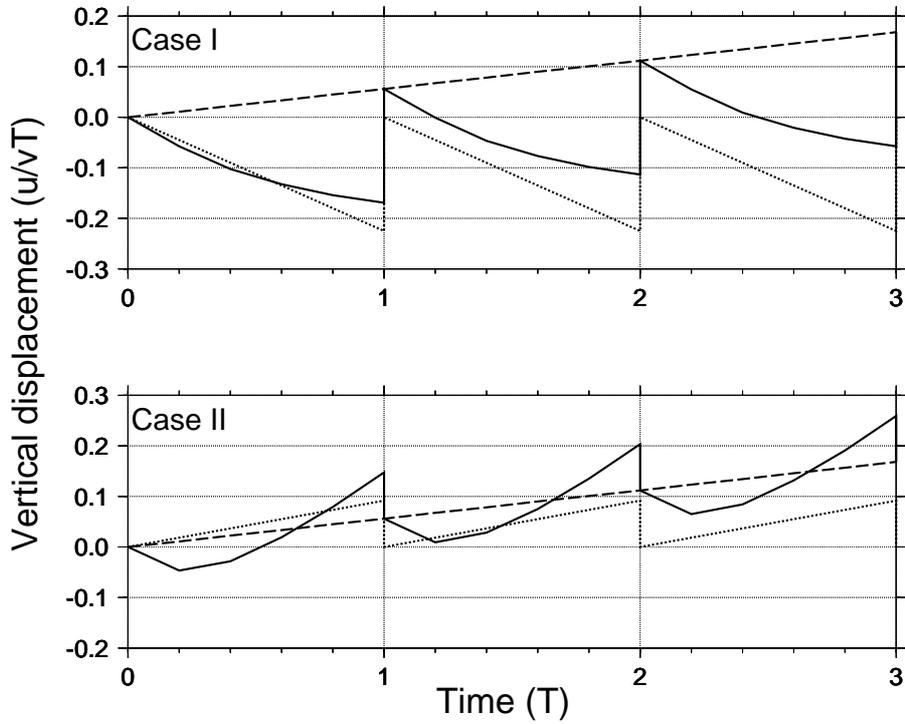


Figure 2: Vertical movements at a fixed point during three earthquake cycles (solid lines).  $T$  indicates the recurrence time of earthquakes. The displacements are normalized by  $vT$ , where  $v$  is a relative plate velocity. Broken lines indicate vertical displacements due to steady plate subduction. Dotted lines indicate vertical displacements for the elastic model, in which the effects of steady plate subduction and viscoelasticity of the asthenosphere are neglected.

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