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THREE-DIMENSIONAL NUMERICAL MODELING OF EARTHQUAKE MIGRATION ALONG A NORTHWESTERN PACIFIC SUBDUCTION SLAB

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Abstract: Three-dimensional numerical modeling has been performed to account for possible earthquake migration phenomena along a northwestern Pacific subduction slab, on the assumption that the lithosphere is a linear visco-elastic body, but the asthenosphere and the mesosphere respond to the applied stress as non-linear Newtonian materials obeying the power law of creep. On the basis of a three-dimensional thermal structure of the northwestern Pacific region, the preliminarily computed stress regimes show that: 1) to induce a stick-slip type trench event, prefailures at a depth of about 40 km in the front of the locked zone between two lithospheric plates are required; 2) the compositional density contrast due to phase change at typical depths is prerequisite of stress concentration to cause a dislocation type deep-focus earthquake; and 3) the co-seismic change in gravitational potential is a controlling factor for earthquake migration downward along the subduction slab.

Introduction

The northwestern Pacific region, particularly along the Japan trench-arc system is one of the most active zones in global seismicities. The monitored earthquakes in this region appear to migrate both down-dip along the subduction slab and laterally toward the inland forming a double seismic zone. Along the slab, there is also an aseismic gap between 300 and 500 km in depth (Goto *et al.*, 1987). On the other hand, Mogi (1973) investigated the correlation between shallow and deep earthquakes in the subduction zone, and indicated that deep events could occur within several years before or after a shallow event. It has also been shown (Loo *et al.*, 1991) from seismic observations that large deep events appear to take place successively downward, originating from an extremely large trench event, along a part of the Pacific plate subducting beneath the Japan Islands and the Japan Sea. Zhao *et al.* (1987) also suggested a close relationship between deep events occurring beneath the western Japan Sea and shallow events occurring in the North-China tectonic block. However, the mechanism of their intrinsic relation is still an open question. Previous qualitative analysis of great earthquake cycles along the Japan trench and troughs and their migration along the subduction slab as well as a three-dimensional modeling of thermal structure of the northwestern Pacific region (Fig. 1, Loo *et al.*, 1991) showed that both subduction plate dynamics and seismicities

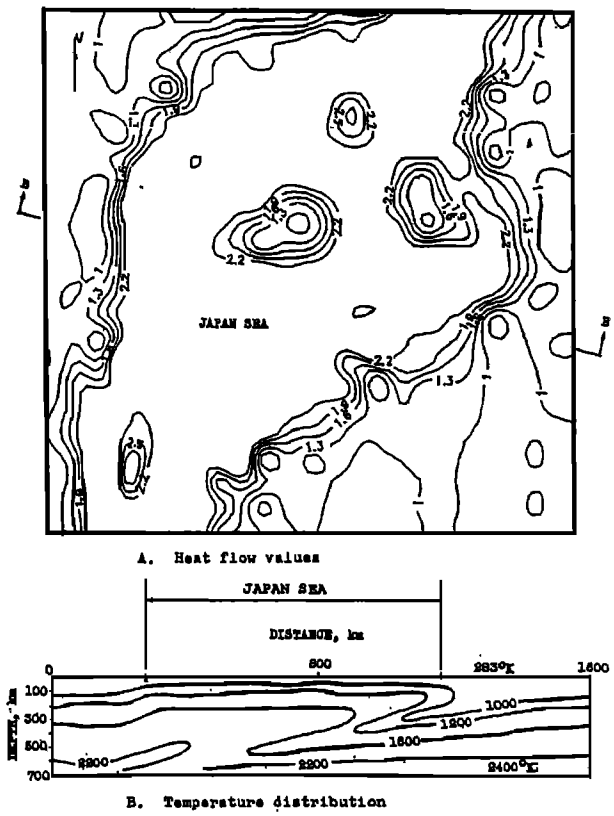

Fig. 1 Computed heat flow values in the Japan Sea region and the temperature distribution along a typical cross-section B–B with influence of the subducted slab (Loo *et al.*, 1991).

in the trench-arc system are well-correlated with the temperature distribution and also with the temperature-dependent phase changes along the subduction slab, leading to heterogeneous properties both in geomechanics and geochemistry (Rubie, 1989; Toksoz *et al.*, 1973).

Tectonic outline

In this study, we assume that the interface between the oceanic subduction plate and continental plate is locked as a sticking patch above a 40 km depth. The basalt-eclogite phase change at this depth range will increase density from 5% (Vetter *et al.*, 1979) to 10% (Kaula,1980), which may be responsible for stress concentration at the bottom of the coupled zone. Below the depth, olivine readily metamorphoses to serpentine by hydrothermal alteration processes and dehydrates later to promote local melting and plastic deformation, arc magma could be derived from melted quartz-eclogite of the subduction slab at a depth of 100 km with a density decrease from 3.45 to 3.0 g/cm^3 (Hsui *et al.*, 1983) acting as a buoyancy force. This may explain why the volcanic front is located at a

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site about 100 km above the slab. At depths of 200-250 km, there is a low velocity zone, which could be due to a compositional change (Kaula, 1980). This portion of the slab will then undergo creeping flows causing only small earthquakes. The aseismic gap between 300 and 500 km depth is a transition zone of olivine-spinel-postspinel resulting in a density increase at both ends of the gap (Goto *et al.*, 1987; Ito and Takahashi, 1989). In addition, there is an anomalously low velocity region overlying the same gap (Suyehiro *et al.*, 1983). Therefore, such ends are triple junctions of density discontinuity existing between the slab and the surrounding mantle, which may be favorable to accumulate creep strains and/or elastic strains released from nearby shocks along the slab.

Based on these phenomena, a three-dimensional, elasto-visco-plastic model is established and solved numerically to study the mechanism of earthquakes migration along a subduction slab with a uniform thickness of 100 km and a dip angle of 30°.

Constitutional relations and parameter selections

Assuming both the overthrusting and underthrusting lithospheres at a depth less than 40 km to be visco-elastic, the relation of strain rate to deviatoric stress for the viscous component can be written linearly as

$$S_{ij} = 2\eta\dot{\varepsilon}^V \qquad i,j = x,y,z \tag{1}$$

where η is the viscosity and $\dot{\varepsilon}^V$ is the viscous strain rate. For the asthenosphere and the mesosphere, a nonlinear relationship between the creep rate, stress and temperature is described by the equation:

$$\bar{\dot{\varepsilon}} = \frac{2B}{T}\bar{\sigma}^n exp(-H/RT) \tag{2}$$

where B is a numerical constant determined experimentally, T is the absolute temperature, H is the activation energy (function of pressure), R is the gas constant and power n commonly has a value ranging from 2 to 6 as a function of depth and temperature (Yuen, 1978).

A general incremental initial strain procedure has been adopted to solve thermo-elasto-visco-plastic problems. It is assumed valid to extend the general uniaxial creep law to the multiaxial cases (Kraus, 1980) at any point in the creeping body. For a specified time increment, the components of the creep strain increment are proportional and parallel to the corresponding stress deviators.

A set of linear and non-linear discrete equations of the creep deformation, Equations (3) and (4), are solved by the use of the principle of additivity of elastic, plastic and viscous strains, as well as a series of piesewise linear equations. A variable tangential modulus for the primary creep and a secant modulus for the secondary creep are used to represent the energy dissipation (Kraus, 1980).

The visco-elastic deformation for the materials above a depth of 40 km, with elastic constants, yields

$$\begin{aligned}\int \underline{B}^T \underline{D}\,\underline{\varepsilon}_k dv + \int \underline{N}^T \underline{n}\,\underline{D}\,\underline{\varepsilon}_k ds \\ = \int \underline{N}^T \underline{X}_k dv + \int \underline{N}^T \underline{T}_k ds \\ + \int \underline{B}^T \underline{D} \sum_{j=1}^{k} \Delta\underline{\varepsilon}_k^V dv + \int \underline{N}^T \underline{n}\,\underline{D} \sum_{j=1}^{k} \Delta\underline{\varepsilon}_k^V ds\end{aligned} \tag{3}$$

For the elasto-visco-plastic deformation of the materials below the depth of 40 km, a similar equation results except

$$\underline{D} = \underline{D}_k^{eq} \tag{4}$$

where $\underline{B}$ is a matrix relating strain and nodal displacement, $\underline{D}$ is an elastic matrix; after a yield point but before failure, the elastic modulus E in $\underline{D}$ is replaced by tangential modulus, E_T. $\underline{D}_k^{eq}$ is a softened elasto-plastic matrix in which the Poisson's ratio ν_S and the secant modulus E_S are used instead of ν and E to form the equivalent matrix. $\underline{\varepsilon}_k$ is the total strain at time increment k, $\underline{\varepsilon}^V$ is a viscous strain matrix, $\underline{N}$ is a shape function matrix, $\underline{n}$ is a constant matrix relating the boundary force $\underline{T}$ to stress and $\underline{X}$ is the body force vector. Detailed derivations for these two equations are described in a separate paper (Loo *et al.*, 1989).

The parameters and constants used here, as shown in Tables I and II, are selected on the basis of a computed temperature distribution (See Fig. 1, Loo *et al.*, 1991) and possible phase changes with variations in density at different depths, as discussed earlier in Tectonic outline. The temperature of the subduction slab is lower than that of its surroundings, varying with depth from 200 to 600°C. The Japan island region is assumed to be a previously failed zone with a lower modulus than that assigned in the Table II in order to avoid overstressing due to plate motion.

For pure visco-plastic materials, the Poisson's ratio is 0.5, but for actual rocks, hard minerals act as elastic components during plastic deformation, and then the effective Poisson's ratio for an elasto-visco-plastic rock is less than 0.5 as selected for calculation.

Model and computation procedures

Fig. 2 shows the thickness variation of the lithosphere which overlays a uniformly layered mantle to form a three-dimensional model. The dip angle of the underthrusting slab is taken to be 30°. The dimensions of the model space are 1600 km long, 1500 km wide and 700 km deep, which is divided into 2040 elements.

To calculate the time-dependent stress regime, let creep strain to be zero at time $t = 0$. Initial stress is applied through the body force and the converging plate motion at a rate of 10 cm/yr. Then, we use the initial stresses to calculate the creep strain increment during the first time step. Making use of Eqs. (3) and (4) and repeating these processes, one can get the combined effective stresses due to both the viscous relaxation and the elastic accumulation at any time.

Once the stress condition at any location reaches the estimated rock creep failure strength at the corresponding depth and temperature, which are shown in Table I & II, its elastic modulus has been tentatively reduced to 1/10 of the assigned

Table I Material parameters within the subduction slab

	Depth km						
Parameters	40	100	200	300	400	500	600
E, dyn/cm^2 ($\times 10^{12}$)	1.5	1.2	1.6	2.5	2.45	3.2	4.12
ν	0.27	0.4	0.38	0.32	0.32	0.32	0.3
ρ, g/cm^3	3.46	3.12	3.0	3.6	3.8	4.2	4.1
T, °K	600	950	1050	1100	1350	1600	1700
Rock creep failure strength, MPa	300	240	260	600	750	900	1100
n	2	3	3.5	4.0	4.5	5	5.5

Table II Material parameters outside the subduction slab

	Depth km						
Parameters	40	100	200	300	400	500	600
E, dyn/cm^2 ($\times 10^{12}$)	1.3	1.0	1.2	1.88	2.46	2.7	3.08
ν	0.4	0.42	0.42	0.42	0.45	0.45	0.4
ρ, g/cm^3	2.85	3.01	2.90	3.47	3.74	3.86	3.95
T, °K	800	1100	1400	1600	1900	2100	2300
Rock creep failure strength, MPa	180	200	220	400	500	600	800
n	3.0	3.5	4.0	4.5	5.0	5.5	6.0

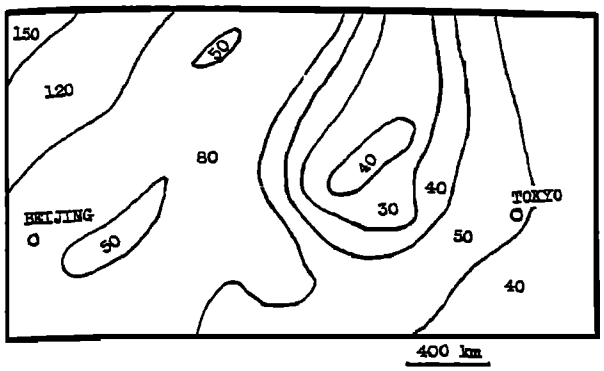

Fig. 2 Top View of a three-dimensional creep model in the northwestern China and Japan Sea area, consisting of 6 uniformly layered astheno- and meso-spheres as well as a lithosphere varying in thickness (km) as shown in various regions indicated by numerals.

value to indicate a stress drop, and then recalculate the elastic stress as well as the effective creep stresses in order to estimate the post-seismic stress and hence to simulate the possible earthquake migration. Of course, such a reduction of elastic modulus can be varied to match the observed stress drop during earthquakes.

Preliminary results and discussion

Before the failure of the locked region, stresses generally nucleate at both the front of the locked region and the location where crustal thickness changes. They are responsible for shallow shocks at a depth range of about 40 km. That is to say, buried ruptures at this typical depth instantaneously extends upward to cause shallow trench events. After a large stress drop during a shallow trench event, and due to a reduction of the elastic modulus of these failed regions, resulting stress conditions including the creeping loss are redistributed as shown in Fig. 3, indicating the stresses migrating stepwise downward along the slab toward the depths of 300 and 500 km, which are located at triple junctions of compositional density contrast.

Fig. 4 shows the effective stress change with time at different depths in the subducted slab, which has been calculated on the basis of the three-dimensional model described here. The time increment is taken to be 1 yr. The right-hand side indicates the behaviors of creep relaxation, while the left-hand includes the change of the elastic stress due to the occurrence of the shallow and deep events, in addition to the creep relaxation. The stepwise increase of the stress at different depths below 100 km is due to the indirect effects from these shocks. It is noticed that the stress drop during these shocks increases with depth. Since the creep failure strength of rocks increases with depth as shown in Table I (Loo *et al.*, 1990), it may be understood that the deeper the focal depth is, the higher the stress drop will be as shown in Fig. 4. The lack of elastic shocks at 400 km is probably due to the lack of concentration of creep stress at this depth, where there is almost no compositional density contrast.

It should also be noticed that the change in the stress drop and hence the triggering of earthquakes migrates downward from the shallower portion to the depth of 500 km. From the figure, one can also see that the duration of stress relaxation is longer and the energy dissipation is lower in the deeper zone than those in the shallower one. Therefore, the imposed elastic stress resulting from the nearby shocks will compensate for

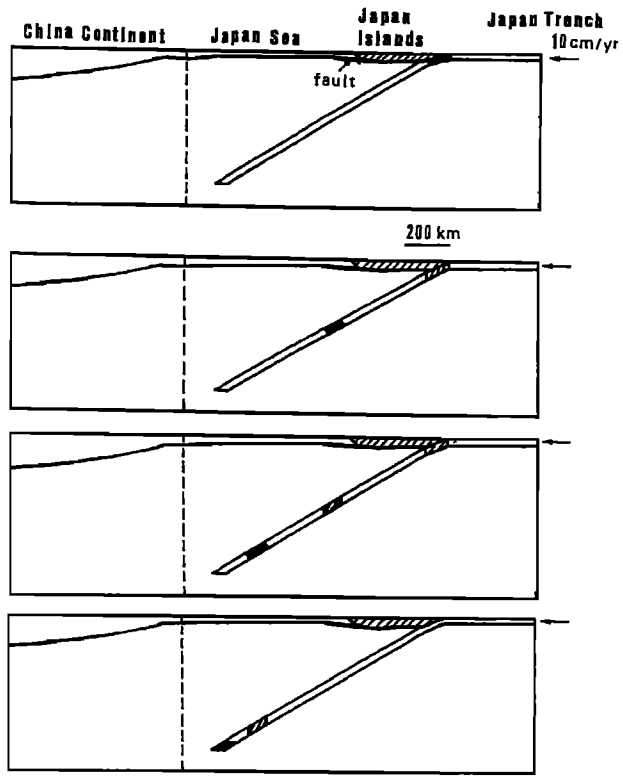

Fig. 3 Stress migration along the subduction slab along a typical section crossing the Japan Sea with body force and plate motion.
Hatched area: failed zone,
Solid area: high stress zone

the loss of creep relaxation, leading to an increase in shearing stress with time in the deeper region which will be favorable for earthquake development.

Conclusions

A possible mechanism of earthquake migration along the subduction slab is proposed: that strains are accumulated gradually in the locked region near the trench down to a depth of about 40 km, and then buried slips would start at the tip of some portions of the locked region to load the interface so as to produce a trench event. This mechanism is different from triggering of inland shallow shocks as suggested by Rydelek *et al.* (1990). Such a rapid and large displacement is resisted by the elastic components of both lithospheric, asthenospheric and mesospheric media to induce stress migration both laterally and downward, which is responsible for shallow and deep earthquakes development respectively. The suddenly imposed elastic stress in the asthenosphere will be relaxed more rapidly than in the mesosphere of high viscosity. This allows mainly downward stress migration along the slab which acts as a stress guide for earthquakes migration resulting from the co-seismic change in gravitational potential (Loo *et al.*, 1990).

Although the mechanism responsible for shallow earthquakes is believed to be frictional sliding, frictional processes should become impossible at deeper zones. Since intermediate and deep-focus earthquakes are mainly located at junctions of compositional density contrast appropriate for stress accumulation to accelerate creeping and then to produce an equivalent dislocation for seismic source, which is different from that suggested

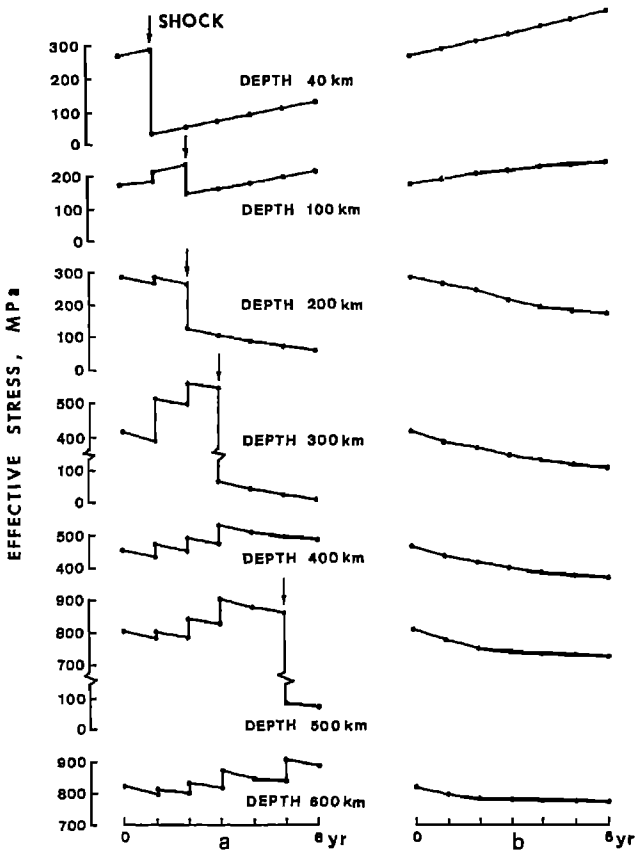

Fig. 4 Effective stress versus time in the subduction slab without body force and boundary loading.
a. with shock influence
b. without shock influence

by Burnley *et al.* (1991) and Kirby *et al.* (1991), mechanical failure should occur only during olivine-spinel transformation.

The grid size of the numerical model is about 100×100×100 km, and the time increment in this calculation is 1 yr, which are not small enough to investigate the source mechanism sufficiently and to deal with the stress migration rate in detail. To meet these requirements, further refined grids and time increments are necessary, and such an advanced study will be taken place in the near future. However, our preliminary conclusion on the importance of compositional density contrast which controls the development of intermediate and deep earthquakes would not be altered significantly.

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