

Stress Change in a Subducting Plate, due to Large Thrust Earthquakes, Plate Convergence and Viscoelastic Relaxation, and Its Possible Effect on Intraplate Normal-Faulting Earthquakes

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Abstract

We investigate the temporal change of the stress state in a subducting plate through the rupture process of a large thrust earthquake and the coseismic stress change, together with its postseismic changes due to plate convergence and viscoelastic relaxation process. The coseismic increase in the shear stress and the Coulomb failure stress below the the downdip edge of the main thrust zone still remains 20 years after the large earthquake, and may have enhanced the chance of occurrence of another large normal-faulting earthquake in the subducting plate.

Introduction

The south Pacific coastal region of Mexico, where the Cocos plate subducts beneath the North American plate, is one of the world's most seismically active zones. Large thrust earthquakes with low dip angles and shallow depths occur with relatively short recurrence time intervals. In addition to these, large intermediate-depth, normal-faulting earthquakes also take place in the subducting plate. While in other subduction zones this type of intraplate events take place near the trench or the outer rise some far updip of the thrust plane, most of normal-faulting events here occur mainly farther downdip in the subducted Cocos plate (Pardo & Suarez, 1995; Singh et al., 2000). There are a few remarkable exceptions, however. In 1997, a large, nearly-vertical, normal-faulting earthquake ($M_w=7.1$) took place right below the extensively ruptured, thrust fault of the 1985 Michoacan earthquake ($M_w=8.1$). Another large, obliquely-dipping normal-faulting earthquake ($M_w=7.5$) also occurred in 1999 just beneath the downdip edge of the thrust plane of the 1978 Oaxaca earthquake ($M_w=7.8$). The 1931 Oaxaca, normal-faulting earthquake ($M_w=7.8$) following the 1927-28 large thrust events (Singh et al.,1985) appears to have a similar location to the above two cases. The time interval between the two types of earthquakes is quite short as compared with the recurrence time of thrust events.

These situations lead us to suppose that there may be significant temporal change in the stress state in the subducting plate after the preceding large thrust events. The goal of the present study is to investigate the state of stress in the subducting plate, through the rupture process of the thrust earthquakes and the resultant coseismic stress change, together with postseismic changes due to plate convergence and viscoelastic relaxation process, and to see if these stress changes would enhance the chance of occurrence of the large normal-faulting earthquakes.

Previous Work

The dynamic rupture and coseismic stress change during the 1985 Michoacan earthquake have been calculated (Mikumo et al., 1999) from the distribution of kinematic slip over the fault plane with a dimension of 180 km x 140 km dipping at 14° , which had been estimated from waveform inversion of local strong-motion and teleseismic records (Mendoza & Hartzell, 1989). Four high

stress drop (stress decrease) zones with a maximum stress drop of 130 bars and negative stress drop (stress increase) zones have been identified on the fault. The maximum coseismic changes in the vertical shear stress and the Coulomb failure stress ($\mu' = 0.4$) reaches the order of 0.4-0.8 MPa in the subducting plate, about 30 km just beneath the high stress drop zone on the fault plane. The rupture starting point and the major part of the 1997 vertical fault are found to be located within this zone of maximum stress increase. The above evidence would suggest that the 1997 normal-faulting earthquake took place under the effects of possible stress transfer from the 1985 thrust earthquake to the interior of the subducting plate. Since the above calculations were for coseismic stress change due to a large thrust earthquake, it is necessary to estimate its postseismic stress change in the subducting plate, in subsequent studies.

Current Research

In the present study, we investigate the state of stress in the subducting Cocos plate since 1978, through the following procedures.

Rupture process of the 1978 Oaxaca earthquake

The 1978 thrust earthquake took place in the Oaxaca region of the Mexican subduction zone. It has been found from local seismic observations that its aftershocks were distributed over an area of 80 km (EW) x 65 km (NS) (Singh et al., 1980). The fault plane solution and the seismic moment has been obtained from teleseismic observations (Stewart et al., 1981), and the northward –dipping nodal plane at about 15° has been taken as the fault plane to be consistent with the depth distribution of aftershocks. The slip distribution on the fault has been calculated recently from kinematic waveform inversion of long-period P waves recorded at 10 WWSSN teleseismic stations with a good azimuthal coverage (Yagi, 2000). The results show that large slip with a maximum exceeding 7 m is concentrated around the central part of the fault, and that there are zones of medium slip around 1.5-2.0 m in the southeastern deeper fault section and in the northwestern shallower section. These are the fundamental information for the calculations that follow.

Coseismic stress change in the subducting plate

The next step is to estimate the coseismic stress change in and around the subducting plate due to the 1978 thrust earthquake, based on the slip distribution derived from the kinematic waveform inversion as observational constraints. We calculate dynamic change of all stress components due to the this earthquake, not only on its thrust fault plane but in the subducting plate, the overlying continental crust and uppermost mantle, and in the asthenosphere. The model used is an extension of a 3D dynamic model (Mikumo & Miyatake, 1993; Mikumo et al., 1998), which incorporates a shallow-dipping fault located on the upper interface of the subducting slab, and is embedded in a horizontally-layered velocity structure. Elastic wave velocities and densities are tentatively assumed to be 0, 5, and 10 % higher in the subducting slab than in the surrounding crust and mantle in the same layer. In this 3D model, calculations are made by solving elastodynamic equations under appropriate boundary conditions, with a second-order finite difference scheme. The estimated maximum stress drop on the 1978 fault reaches 22 MPa.

On the other hand, the rupture process of the 1999 Oaxaca earthquake has been analyzed from local strong-motion records (Hernandez et al., 2000) and with teleseismic waveforms (Yagi & Kikuchi, 2000), indicating a normal-faulting mechanism with a northward dip of about 50° .

Here we are looking at static changes of four stress components; $\Delta\sigma_{y'z'}$ (shear stress along the thrust fault), $\Delta\sigma_{y'y}$ (compressional stress in the direction of the thrust fault), $\Delta\sigma_{y'z''}$ (shear stress

along the normal fault), and $\Delta\sigma_{z'z'}$ (tensional stress perpendicular to the normal fault). From the last two components, the Coulomb failure stress $\Delta\sigma_{\text{cfs}} = \Delta\sigma_{y'z'} + \mu'\Delta\sigma_{z'z'}$ is also calculated, taking μ' , the apparent coefficient of friction for the effective pressure (e.g. King et al., 1994), to be in the range between 0.0 and 0.6. The estimated coseismic changes in the subducting plate are characterized by a few zones of stress increase and decrease beneath the 1978 thrust fault. It is found that the shear stress in the direction of the 1999 fault and the Coulomb failure stress for $\mu' = 0.4$ (Fig.1) show some increase from 0.5 to about 1.5 MPa beneath the downdip edge of the 1978 thrust plane, where the 1999 normal faulting earthquake took place. Although the coseismic stress change depends slightly on the location and the width of the 1978 fault, their patterns are not very much affected. Accordingly, the 1978 thrust earthquake appears to have provided, at least, some effects to enhance the chance of the 1999 normal-faulting earthquake. Several large aftershocks of the 1999 event occurred near the upper part of the mainshock fault, which had received stress increase from the 1978 event.

Postseismic stress change in the subducting plate

The postseismic stress changes that would affect the estimated coseismic change may come from the following tectonic processes : 1) further (forward) aseismic slip on the ruptured segment or the updip or downdip extension of the fault, 2) extensional stress (slab pull) from the subduction process, 3) stress accumulation due to the locking of the main thrust fault, 4) viscoelastic stress relaxation process in the overlying mantle and in the asthenosphere.

Evidence of further aseismic slip on the 1978 fault has not been obtained due to the lack of geodetic observations at that time, although it seems likely to have occurred. If it actually occurred on the major part of the fault with a few tens of percent of the coseismic slip, the postseismic increase of the shear stress beneath the thrust plane would enhance the coseismic stress change. Steady state subduction at a uniform rate of plate convergence, and the slab pull for such a shallow-dip slab in the Mexican subduction zone, would not generate appreciable stress change in the interior of the subducting plate. Accordingly, we will focus our attention to the last two effects to estimate the postseismic changes of the coseismic effects, without taking into account the absolute tectonic loading stress.

1) Postseismic stress accumulation

The stress accumulation in the subducting plate after the 1978 thrust event has been calculated by imposing hypothetical backward (normal) slip at a uniform rate (6 cm/yr) of plate convergence on the thrust plane, following the method adopted by previous workers (e.g. Savage, 1983; Matsu'ura & Sato, 1989; Dmowska et al., 1988; Taylor et al., 1996). The superposition of the backward slip on the steady state slip will lock the main thrust zone, yielding stress accumulation during the locking period. However, since the coseismic slip due to the 1978 event is quite heterogeneous, we assume that the fault segments with a slip smaller than a certain value corresponding to 6 cm/yr x 21 yrs had started free slipping before the 1999 event while the other segments with larger slip was still locked in 1999.

The stress state in 1999 in the subducting plate shows some change from that in 1978. The coseismic increase in the shear stress and the Coulomb failure stress beneath the downdip edge of the 1978 thrust fault diminishes to some extent, and hence the zone of stress increase shrinks by slight expansion of the adjacent zone of stress decrease but still well covers the 1999 normal fault zone. This pattern suggests that the effects of heterogeneous, coseismic stress change due to the 1978 event are large enough not to vanish even in 21 years.

2) Viscoelastic stress relaxation

To estimate the postseismic stress change, we included viscoelastic stress relaxation process in the overlying lower crust and uppermost mantle and in the asthenosphere. Calculations are made in the same 3D model as was used, assigning appropriate Maxwellian viscosities with relaxation

times ranging between 5 and 100 years to these portions, while assuming the subducting lithosphere as essentially an elastic slab. Boundary conditions are imposed for all stress components at the layer interfaces and the upper and bottom interfaces of the subducting slab. Preliminary results indicate that stress change due to the viscoelastic relaxation is less than 10 % for 21 years and the effects are not large enough to change the stress patterns.

Discussion

Temporal stress variations during a thrust earthquake cycle in and near a coupled subducted slab has been discussed on the basis of 1D and 2D finite element modeling (e.g. Dmowska et al., 1988; Taylor et al., 1996) including viscoelastic relaxation process. Their results show that the coseismic change in the uniaxial stress component below the thrust zone slowly recovers with time but still do not change its sign within the first half of the recurrence period. Gardi et al. (2000) also introduced a 2D finite element technique to model the subducting Cocos plate with an unbending and then-subhorizontal geometry, incorporating a plate convergence velocity and slab pull. The modeling results suggest the possibility that normal-faulting events could occur some time after a large thrust event in a wide zone of extensional stress below the downdip edge of the main thrust zone, in the form of flexural response of the overriding and subducting plates to the specific geometry. Although their results seem very sensitive to the geometry of the subducting slab, these could be an alternative explanation to the occurrence of intraplate normal faulting earthquakes, in the region where the subducting plate has actually this type of geometry. In this case, the two effects from the coseismic and postseismic stress changes estimated from our calculations and from the flexural response to the plate geometry would be complementary to cause normal faulting earthquakes in the subducting Cocos plate.

Conclusions

The present results from our stress estimates would suggest that the coseismic stress increase due to the 1978 thrust earthquake may have enhanced the chance of occurrence of the 1999 normal-faulting earthquake in the subducting Cocos plate. The estimated maximum increase in the shear stress and the Coulomb failure stress below the downdip portion of the main thrust zone is about 0.5 to 1.5 MPa. This magnitude is significantly larger than those so far reported (e.g. Harris, 1998). This may be due to the close proximity of the two events and large, heterogeneous stress drop during the thrust earthquake. The 1999 event took place in this zone. The postseismic changes during 20 years coming from the locking of the main thrust zone and also due to the viscoelastic stress relaxation do not seem to be large enough to overcome the effects of the coseismic change. If the coseismic and postseismic stress increase due to the 1978 earthquake actually triggered the 1999 event, one of its possible mechanisms might be stress corrosion; the subducting oceanic lithosphere may have involved several, preexisting weak planes, and one of these planes might have been reactivated and fractured due to stress corrosion under the increase of the applied stress there for 20 years.

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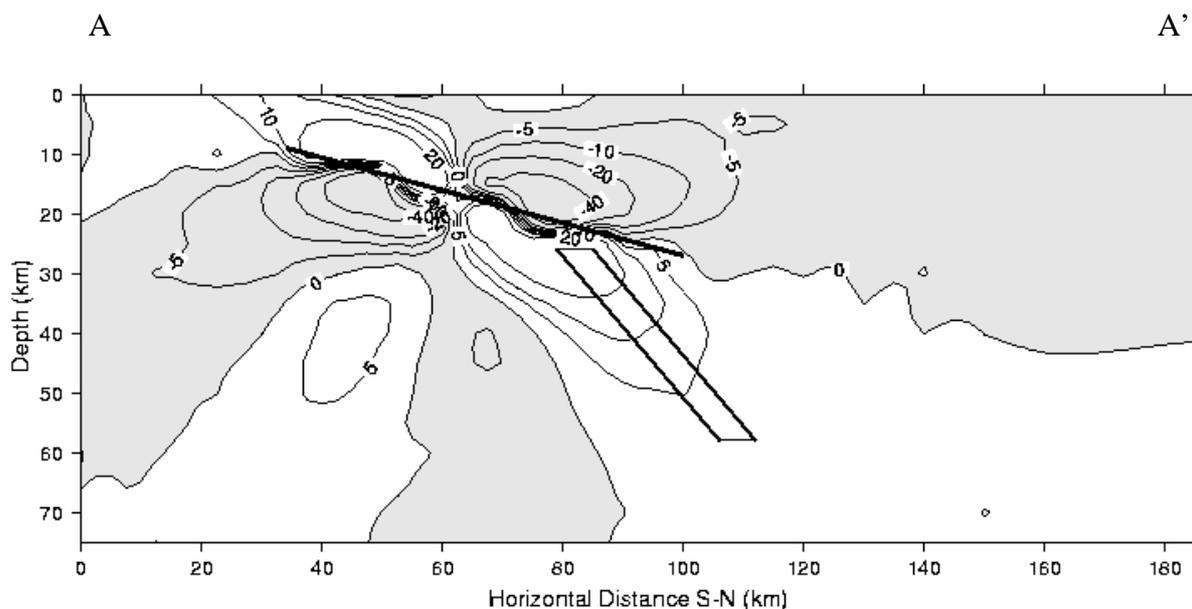


Fig. 1. Coseismic change of the Coulomb failure stress for $\mu' = 0.4$ due to the 1978 thrust earthquake, in the direction parallel to the 1999 normal fault. Grey and white area indicate the zones of stress decrease and increase, respectively, and the unit of numerals on contours is bars. Note that the 1999 fault zone (indicated by a rectangle) falls in the zone of stress increase due to the 1978 earthquake.