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Distribution of Dynamic and Static Stress Changes during 2000 Tottori (Japan) Earthquake: Brief Interpretation of the Earthquake Sequences; Foreshocks, Mainshock and Aftershocks

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[1] The dynamic and static stress changes during the 2000 Tottori earthquake have been recovered from the results of waveform inversion. We use the DEM to solve the elastodynamic equation specifying the slip along the fault obtained by a kinematic fault model. The resulting shear stress distribution suggests an explanation of the foreshock and aftershock distributions. We conclude that the fault zone heterogeneity is strong and most of the foreshocks and aftershocks were located in the zone of negative stress drop and mainly in the area surrounding the asperity. This suggests that the asperity behaved as a barrier during the foreshocks and after the main shock the stress in the area surrounding the asperity increased and triggered most of the aftershocks. The foreshock distribution was confined to a finite localized zone in the central part of the fault, suggesting that this zone was bordered by barriers. *INDEX TERMS:* 7209 Seismology: Earthquake dynamics and mechanics; 7215 Seismology: Earthquake parameters; 7260 Seismology: Theory and modeling; 7223 Seismology: Seismic hazard assessment and prediction

1. Introduction

[2] Fault zone heterogeneity is now widely accepted in the study of earthquakes. The classical definition of asperities and barriers [e.g., *Kanamori and Stewart*, 1978; *Aki*, 1984], in which both terms are related to the absolute level of shear stress and strength distribution along the fault plane, is a simple as well as a robust description of such heterogeneity. This may also be important in controlling the number of foreshocks, i.e., the stronger the heterogeneity the greater the number of foreshocks [*Dodge and Beroza*, 1996]. Certainly the same concept is also valid for the number of aftershocks.

[3] The foreshock distribution is the manifestation of an earthquake nucleation [e.g., *Jones et al.*, 1982; *Dodge and Beroza*, 1996; *Ellsworth and Beroza*, 1998] and the aftershocks are triggered by the main shock, in response to the stress changes caused by the dynamic process of the earthquake. The physical understanding of the interaction between the foreshocks, main shock and aftershocks remains unresolved. Within this context, however, the study of *Harris* [1998], who reviewed many published works and presents a compilation of quantitative earthquake interaction studies from a stress change perspective, suggests that the stress changes may explain some aspects of these phenomena.

[4] The recent 2000 Tottori-ken Seibu earthquake (Mj = 7.3) provides us a good chance to study the problem of earthquake interaction. *Shibutani et al.* [2001] reported a swarm seismic activity including six moderate events (Mj = 5.1–5.4) that occurred in 1989, 1990 and 1997 in the same area of this earthquake. These authors carried out a temporary seismic observation in and around the source area and processed the data to determine the hypocenter locations of the preceding seismic activity, the main shocks and the aftershocks [*Joint Group for Dense Aftershock Observation of the 2000 Tottori-ken Seibu Earthquake*, 2001]. The relocated hypocenter distribution of the three preceding swarms as well as the 2000 activity determined by *Shibutani et al.* [2001] show that these events occurred on the same fault plane as the 2000 Tottori earthquake and were distributed on specific areas within the fault plane (Figure 1). In this context, we define the seismic activity of 1989, 1990 and 1997 as foreshocks because they broke weak zones on the same fault plane of the main event and could be the manifestation of nucleation of the Tottori earthquake.

[5] The first intuitive interpretation of this seismic activity preceding and succeeding the 2000 earthquake could be due to a possible strong heterogeneity over the fault plane, i.e., some of the strong patches on the fault behave as asperities and others as barriers. In order to explain some aspect of the spatial distribution of these foreshocks and aftershocks we recovered the dynamic and static stress drop as well as the relative fault strength distribution over the fault during the main shock from the results of waveform inversion.

2. Computation of the Dynamic Stress Changes During Earthquake Rupture

[6] For the computation of the dynamic and static shear stress changes during earthquake rupture we use the distribution of fault slip and the rupture time obtained from the inversion of strong motion waveforms. For this purpose we model the continuum surrounding the pre-existing fault as specified by the kinematic model and we solve the elastodynamic equation of motion of the continuum for a rupture along the fault plane. The slip distribution in space and time obtained by the kinematic fault model is used as a boundary condition along the pre-existing fault. The result of this calculation is the shear stress distribution in space and time from which the dynamic and static stress drop along the

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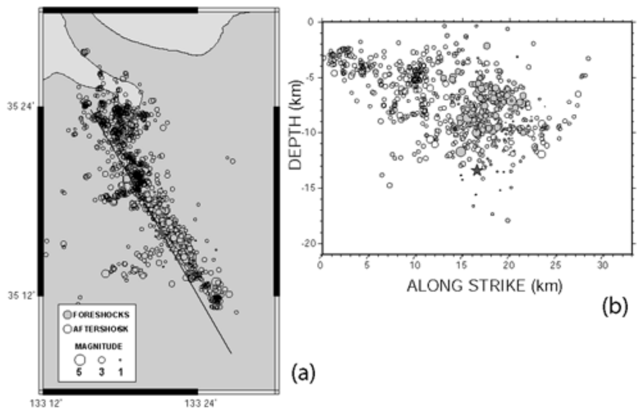

Figure 1. Comparison of the relocated hypocenter distribution of the seismic activity in 1989, 1990, 1997 (foreshocks) and 2000 (aftershocks) determined by *Shibutani et. al.* [2001]. The solid line and the start correspond to the fault plane and epicenter of the 2000 mainshock respectively (a) Map view; (b) Along the fault plane.

fault as well as the strength excess (relative fault strength defined as the difference between the peak shear stress and the assumed initial stress) are approximately estimated. This procedure, i.e., determination of the dynamic stress change from the results of kinematic waveform inversion, has been used by several authors [e.g., *Quin*, 1990; *Miyatake*, 1992; *Mikumo and Miyatake*, 1995; *Bouchon*, 1997; *Day et al.*, 1998], most of them using the finite-difference method. In the present paper, the volumetric discretization of the continuum is constructed using the 3D Discrete Element Method (DEM). This numerical technique models any orthotropic elastic solid. It is constructed by a three dimensional periodic truss-like structure using cubic elements. The method was successfully used to simulate the dynamic rupture process of the 1999 Chi-chi (Tawan) earthquake using a simplified 2D model [*Dalguer et al.*, 2001a, 2001b]. In the discrete dynamic model, masses are concentrated at nodal points. The solids are represented as an array of normal and diagonal elements linking lumped nodal masses. The dynamic analysis is performed using explicit numerical integration in the time domain. At each step of integration a nodal equilibrium equation (Equation 1) is solved by the central finite differences scheme

$$m\ddot{u}_i + c\dot{u}_i = f_i \tag{1}$$

where m denotes the nodal mass, c the damping constant, u_i a component of the nodal coordinates vector and f_i a component of the resulting forces at a nodal mass including elastic, external and frictional forces in direction i. In the current model, only the nodal points that coincide with the pre-existing fault have prescribed slip according to the kinematic slip model. The f_i components, that correspond to the stress along the fault, are calculated at each time step.

[7] The computation of the relative shear stress time history everywhere on the fault allows us to estimate the dynamic and static stress drop as well as the strength excess as shown in Figure 2. Since we do not know the absolute value of the initial stress distribution along the fault, we assumed that it is at the zero level. Therefore, the strength excess becomes the relative strength of the fault.

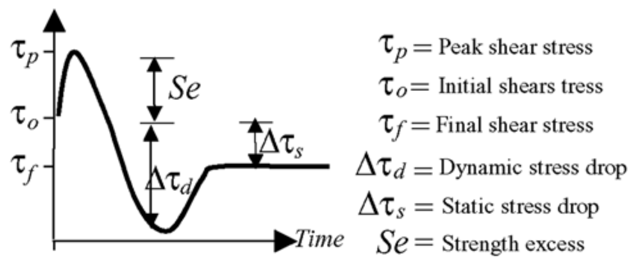

Figure 2. Characteristics shear stress time history and dynamic paramenetrs specification.

3. Estimation of the Relative Fault Strength, Dynamic and Static Stress Drop for the 2000 Tottori Earthquake

[8] For the estimation of these dynamic parameters we follow the procedure described above. The distribution of fault slip of the 2000 Tottori earthquake obtained from the inversion of strong motion waveforms calculated by *Iwata et al.* [2000] was used. The kinematic source model is briefly described as follow: [*Iwata et al.*, 2000] 1) The slip model was obtained by inverting the bandpass filtered strong ground motion velocity of 0.1 to 1.0 Hz; 2) the fault was divided into subfaults with 3 × 3 km^2; 3) each subfault motion is obtained by the response of a point dislocation source placed at the center of the subfault; 4) The slip-time history on each subfault was characterized using six time windows having a duration of 1 sec, each 0.5 sec apart; 5) The rupture velocity of the first time window was selected to be 2.3 km/s with radial propagation; 6) the fault plane with strike N150E and dip 90° is 33 km long and 21 km down dip; 7) the rupture initiates at a depth of 13.4 km; 8) The results presented by *Iwata et al.* [2000] shows that the slips mainly occurred at the shallower part, the largest slip occurred at the asperity area with almost 3 m left lateral slip, the asperity area is defined in Figure 3 as the zone of higher stress drop than surrounding areas.

[9] For the shear stress calculation we adopted the fault plane defined above by the kinematic model, that is, a grid size of the DEM is equal to 3 km. The velocity structure is shown in Table 1.

[10] The distribution of the dynamic and static stress drop calculated using the DEM is shown in Figure 3a. In order to validate these results we also evaluated both distributions using the discrete Fourier transform approach presented by *Bouchon* [1997], as shown in Figure 3b, in which we used subfaults of size 0.5 × 0.5km. On account of the difference between grid sizes used in the two models, the approach of

Table 1. Velocity Structure

Depth (km)	Vp (km/s)	Vs (km/s)	ρ (kg/m^3)
0	5.5	3.179	2600
2	6.05	3.497	2700
16	6.6	3.815	2800
38	8.03	4.624	3100

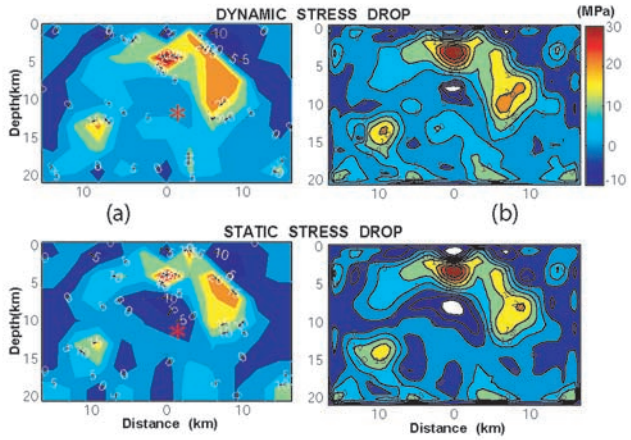

Figure 3. Distribution of the dynamic and static stress drop: (a) calculated using the DEM; (b) calculated using the approach of *Bouchon* [1997].

Bouchon leads to sharper plots than those resulting from the DEM. But in general both sets of results are consistent. So, the resolution of the stress distribution is not significantly affected by the grid size. For the purpose of the paper, the general characteristic of the stress change is very well represented in low frequency analysis. Therefore, it is

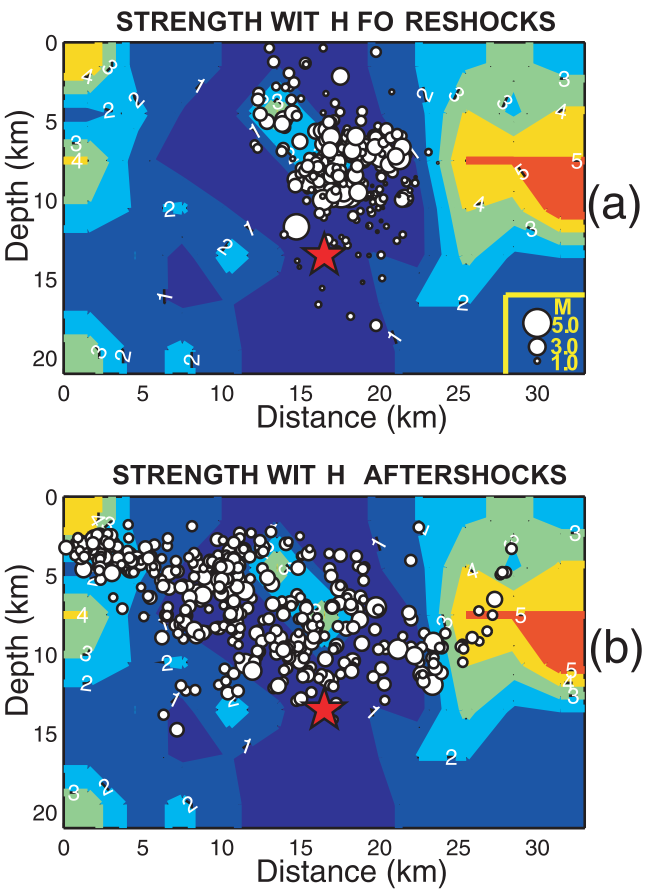

Figure 4. Comparison of the strength excess distribution with: (a) swarm seismic activity in 1989, 1990, 1997 (foreshocks) and (b) aftershocks.

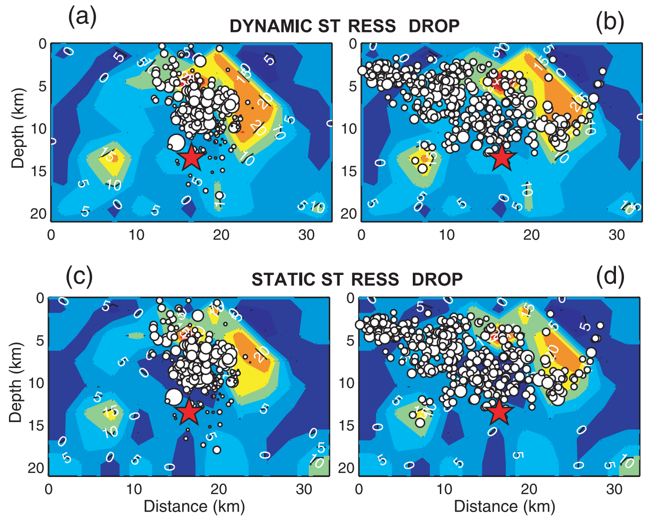

Figure 5. Comparison of the swarm seismic activity in 1989, 1990, 1997 (foreshocks) and aftershocks with the dynamic and static stress drop distribution; (a) foreshocks and dynamic stress drop; (b) aftershocks and dynamic stress drop; (c) foreshocks and static stress drop; (d) aftershocks and static stress drop.

confirmed that the DEM may be reliably used in the analysis of this problem.

[11] From Figure 3 we can observe that there is a localized asperity in the upper central part of the fault. The maximum stress drop is 30 MPa in the asperity zone; while the dynamic stress drop shows negative values near the free-surface and at the left and right sides of the fault. This suggests that the stress continuously accumulates during the rupture process (hardening). The static stress drops in the asperities zone are very close to the dynamic stress drops, but at the center of the fault and in the surrounding area of the asperities the stress is negative (max. -10 Mpa), indicating that the stress in the asperity zone has been completely released but in the surrounding area the stress increases after the rupture process of the earthquake.

[12] Figure 4 shows the strength excess distribution along the fault. Maximum values occur at the left and right sides of the fault, reaching around around 5 MPa. The minimum values take place in all the central fringe of the fault except in a small portion between depths of 4 and 9 km where moderate strength excess of 4 MPa is determined. It suggests that the tectonic shear stress had reached close to the level of the critical stress before the earthquake in almost all the central fringe of the fault.

4. Foreshocks and Aftershocks Associated with the Stress Distribution Along the Fault of the 2000 Tottori Earthquake

[13] The seismic activity that occurred in 1989, 1990 and 1997 preceding the 2000 Tottori earthquake is a clear evidence of foreshock distribution of the main shock, as explained in the introduction of the present paper. In order to explain some aspects of the spatial distribution of these foreshocks as well as the aftershocks we can associate them with the dynamic and static stress distribution calculated in the previous section. In Figures 4 and 5 we compare the

foreshock and aftershock locations with the strength excess and stress drop distribution, respectively.

[14] From Figure 4a we can observe that the foreshock distribution was confined to a finite zone localized in the central part of the fault. Most of these events are located in the zone where the strength excess is very small. This suggests that the surrouding zones with larger strength excess behaved as barriers, being possibly responsible for arresting the rupture in the 1989, 1990 and 1997 events. From Figures 5a and 5c, we can observe that this confined zone is located below the asperity in the area where the dynamic stress drop is almost zero and the static stress drop is negative. The central zone where the dynamic stress drop has almost zero values, implies that in this zone the stress had been relaxed or dropped during the previous seismic activity. But a question arises why does this foreshock seismic activity occur in this confined zone? And why the existence of this confined zone? Does the main shock was triggered by the stress changes from this previous swarm seismic activity? *Shibutani et al.* [2001] suggests that the 2000 Tottori earthquake and the preceding seismic activity might have been triggered by crustal fluids because this source area is located between the Daison Volcano, which was active during the Pleistocene, and the Yokata monogenic volcanic cluster, which was active in the early Pleistocene. *Ohmi and Obara* [2001] reported that several deep low-frequency earthquakes were found near the source area. If we observe the static stress drop distribution of Figures 5c and 5d, this confined zone has considerable negative static stress drop in which the biggest aftershocks took place. In Figure 4b it may also be observed that the aftershocks also occurred in this confined zone and on the left side of the fault. Apparently the right side, which presents the largest values of strength excess, was the strongest barrier also for aftershock. It seems that this confined zone became very active because the stress accumulation tends to reaches very fast to the yielding stress, producing continuously the relaxed stress in foreshocks or aftershocks. Probably this zone will continue to be active.

5. Conclusions

[15] The paper uses a sound analytical method to estimate the distribution of stress drop and strength excess associated with the 2000 Tottori earthquake. This analysis leads to a quantitative estimate of the stress change in the main asperity. Furthermore, the stress-change distributions are related to the foreshock and aftershock distributions.

[16] From the stress distribution, we conclude that the fault zone heterogeneity is very strong; it may also be an important factor that controls the seismic activity in the source area of the 2000 Tottori earthquake. It was found that most of the foreshocks and aftershocks are located mainly in the surrounding area of the main asperity. It suggests that the asperity was a barrier during the foreshocks, and after the main shock, the stress in the area surrounding the asperity increased and triggered most of the aftershocks. An interesting thing is that the foreshocks occurred predominantly in a confined zone of negative stress drop and minimal strength excess. This is suggestive of foreshock occurrence in a zone of the fault in which the stresses are continuously being relaxed, but which rupture cannot easily break out of.

[17] From the analysis it is not clear whether the main shock was triggered by stress changes from the foreshocks, but certainly the foreshock distribution is one of the most obvious manifestation of earthquake nucleation, so that earthquake prediction might require more detailed knowledge of the stress and strength distributions on faults.

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