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Determining changes in the state of stress associated with an earthquake via combined focal mechanism and moment tensor analysis: Application to the 2013 Awaji Island earthquake, Japan

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ABSTRACT

One approach that can be used to evaluate the potential for an earthquake occurrence is the detection of the stress concentration at an earthquake fault. While the stress fields for pre- and post-seismic event stages differ, this change cannot provide information regarding the potential for an earthquake. Here, we propose a detection method for states of stress that uses focal mechanism data from microearthquakes. The state of stress can be defined both by the background stress and by a moment tensor equivalent to the stress concentration. We applied this method to actual focal mechanism data from the 2013 Awaji Island earthquake (M6.3), Japan, and the results showed the presence of stress concentration around the earthquake fault before the mainshock. In addition, the regional differential stress was shown to be about 13 MPa. The magnitude of the obtained stress concentration in the focal area and the high dip angle of the mainshock fault imply that the faulting occurred in the crust where it was overpressurized to a level near the lithostatic pressure.

1. Introduction

An earthquake occurs when the shear stress applied to a fault exceeds its interfacial shear strength. The stress released by such a seismic event can be estimated from the seismic waves radiated by the earthquake, although it is difficult to ascertain whether the major contributing factor is the stress concentration or the shear strength decline on the fault. An additional important factor in determining the potential for seismic activity is the absolute magnitude of differential stress applied to a fault area from an external source; however, such measurements can be problematic because the analysis of focal mechanisms can resolve only deviatoric stresses.

The directions of principal stresses and stress ratio (i.e., $\Phi = (\boldsymbol{\sigma}_2 - \boldsymbol{\sigma}_3) / (\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_3)$, where $\boldsymbol{\sigma}_1$, $\boldsymbol{\sigma}_2$, and $\boldsymbol{\sigma}_3$ are the maximum, moderate, and minimum principal stresses, respectively) are parameters that are used to denote the deviatoric stress field, which is estimated from focal mechanism data because of undetermined traction strength on a fault plane (Angelier, 1979, 1984; Michael, 1984). Inversion techniques developed by pioneering studies have allowed many researchers to estimate the deviatoric stress field successfully. Spatial and temporal variations of stress fields around earthquake faults, such as those that have been investigated in several different regions and thus exhibit significant variation, may provide further insight into this subject. There are two approaches that can be used to estimate the spatially varying stress fields, as shown in the schematic diagram in Fig. 1. One approach assumes that the stress field is composed of many small areas, and each area is under a homogeneous stress field (e.g., Hardebeck and Michael, 2006). The second approach models the heterogeneous stress field as a combination of homogeneous regional stress and moment tensors to recreate the spatial variation of stress (Matsumoto et al., 2012). The former approach can estimate the parameters at each divided area. Therefore, the resolution for the estimation is defined as the size of the area, which can be appropriately determined based on the amount of data and their quality. However, a spatial binning problem arises during the process of determining the size of an area to which uniform stress should be applied. The latter approach can directly fit data to the spatial heterogeneous stress field without the binning problem because the field is modeled as a combination of the regional stress tensor and moment tensors as stress sources. If the existence of an inelastic deformation source such as faulting or magma intrusion in a target area is known, the latter approach may be advantageous. By using the former approach, numerous studies have estimated the stress field around the San Andreas Fault, which is one of the best targets for investigating the stress field because of its heterogeneous stress field caused by the high strain rate and high seismic activity around the fault. These studies

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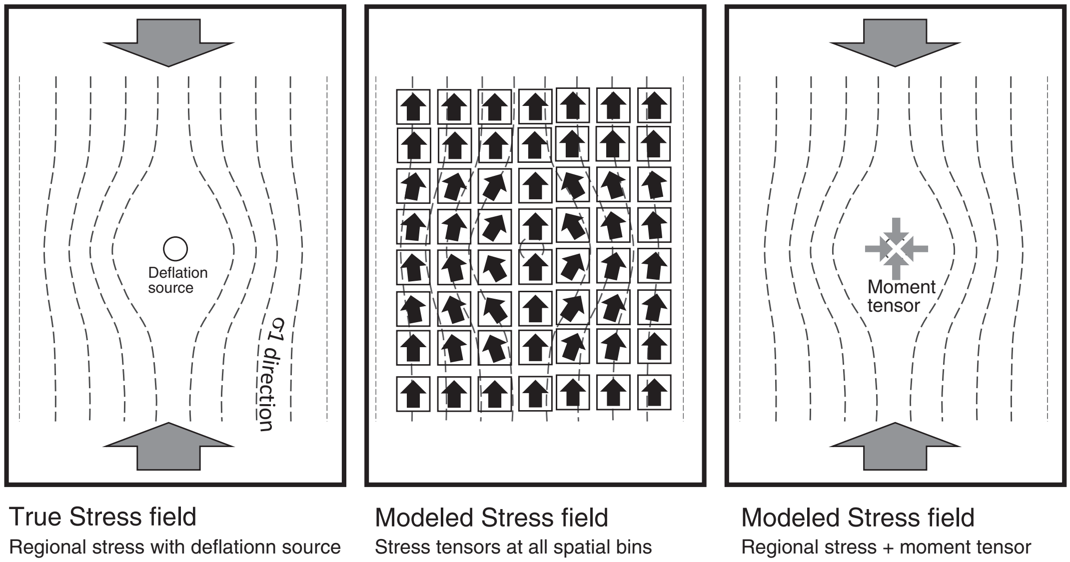

Fig. 1. Comparison of approaches for inverting the stress field from the focal mechanism dataset. Two-dimensional (2D) schematic figures express the stress field by the regional compression and deflation source in a medium (left); estimation of the stress field at every spatial bin (middle); estimation by combining regional stress and the moment tensor (right). Dashed line denotes the direction of maximum principal stress (σ1) in the region. Gray arrow in the left figure indicates the compression stress. Solid arrow in the middle figure shows the estimated principal stress direction and the spatial bin (small rectangle) where the stress field is assumed to be uniform. The parameter represents a stress tensor at each spatial bin. The total number of parameters is 5 × the number of bins. The stress field is modeled by the regional stress tensor and the moment tensor (gray arrows) in the right-hand case. The number of parameters is 5 + 5 (for one moment tensor).

estimated fault strength because stress heterogeneity depends on loading stress, fault behavior, and fault strength (Hardebeck and Hauksson, 2001; Hardebeck and Michael, 2004; Townend and Zoback, 2001, 2004; Zoback et al., 1987). Differential stress has also been estimated in many other regions by analyzing spatial and temporal changes in stress associated with large earthquake occurrences (e.g., Hasegawa et al., 2011; Holt et al., 2013; Wesson and Boyd, 2007; Yang et al., 2013). However, the spatial binning problem creates difficulties when evaluating the fault strength (Hardebeck and Michael, 2004; Townend and Zoback, 2004). In addition, stress fields in the case of stress concentration at a fault prior to an earthquake have not been discussed. Bouchon et al. (1998) and Spudich et al. (1998) have shown that precise estimation of the stress levels on an earthquake fault associated with faulting can be performed by using co-seismic radiated waves. Although both of these previous studies obtained detailed conditions of the fault, it is also necessary to analyze the stress around a fault in order to determine the potential for seismic activity in an area.

At present, it is difficult to determine the conditions prior to an earthquake occurrence. However, we believe that the states of stress before and after an earthquake, in addition to the absolute stress level, are key factors that can be obtained with the appropriate techniques. In this paper, we report on a new method that can be used to determine whether the major factor for an earthquake occurrence is the stress concentration or the strength weakening at an earthquake fault. This new method is an extension of that reported by Matsumoto et al. (2012), who modeled the heterogeneous stress field as a combination of homogeneous regional stress and moment tensors to recreate the spatial variation of stress. The method proposed in this paper estimates the stress condition at an earthquake fault and the absolute differential stress, and it was applied to an actual dataset of the seismicity before and after the 2013 Awaji Island earthquake (M6.3) in southwestern Japan. This region is located southeast of the aftershock area for the 1995 Kobe earthquake (M7.2).

2. Modeling the state of stress around a fault

The stress field in an area depends on the properties of the medium, the boundary conditions between the medium and surrounding regions, and any mechanical sources of stress concentration that exist in the medium. For simplicity, we considered a medium with a spatially variable stress field that is attributable to two major factors: loading stress to the medium from outside the target area and inelastic deformation. Inelastic deformation distorts the stress field around the deformed area, which can affect the stress concentration at the edge of a fault that resulted from an earlier slip event. Here, we evaluated the state of stress around a fault by using a simplified model that examines the differences between a pre- and post-earthquake stress field. First, we considered two end-member cases for the state of stress: one with a high uniform differential stress in the entire medium (case 1) and another in which the differential stress concentrates along a fault because of stress relaxation in the surrounding medium (case 2). The excess stress due to stress concentration was assumed to be equivalent to the amount of stress released during an earthquake. Differential stress profiles along the fault were constant for case 1 and high at the fault for case 2, as shown schematically in Fig. 2A. A possible cause for the situation described in case 2 is non-seismic slip at the extension of the fault's slip direction, with the regional stress sustained only by the fault strength. For example, stress concentration can occur in a fault in a "locked region" such as at a plate boundary. An area on a plate boundary in which strain is accumulated by stable plate subduction is detectable as back slip (Savage, 1983). Although global positioning system (GPS) data cannot be used for direct estimation of the stress concentration, many studies have used these types of data to evaluate the stress concentration from strain anomalies at plate boundaries. For example, Nishimura et al. (2000) estimated the spatial distribution of seismic coupling on the plate interface of the subducting Pacific plate by inversion to co- and post-seismic strain rate data.

In the given examples, when an earthquake occurs at a fault, the associated differential stress decreases and the surrounding stress field changes, although the cause of the earthquake occurrence may be different for each case. For example, in case 1, the fault strength could have been reduced as a result of fluid injection at high pressure, as proposed by Sibson (1992), whereas in case 2, stress relaxation in the surrounding medium could have imparted stress on the fault that exceeded its strength and led to the faulting. Thus, the post-earthquake stress profiles for each scenario are different, as shown in Fig. 2B. In case 1, the stress on the fault decreases and concentrates at its edges because of the occurrence of a finite amount of slip, whereas for case 2, the stress