Earthquake Source Parameters of Microearthquakes at Parkfield, CA, Determined Using the SAFOD Pilot Hole Seismic Array

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Abstract: We estimate the source parameters of 34 microearthquakes at Parkfield, CA, ranging in size from $M_{\text{L}}$-0.3 to $M_{\text{L}}$ 2.1, by analyzing seismograms recorded by the 32-level, 3-component seismic array installed in the SAFOD Pilot Hole. We succeeded in obtaining stable spectral ratios by stacking the ratios calculated from the moving windows taken along the record following the direct waves. These spectral ratios were inverted for seismic moments and corner frequencies using the multiple empirical Green's function approach. Both static stress drops and apparent stresses of microearthquakes at Parkfield do not largely differ from those reported for moderate and large earthquakes. It is likely that the dynamics of microearthquakes at Parkfield is similar to that of natural tectonic earthquakes in a macroscopic viewpoint. Half of the static stress drops are above 50 MPa, which are near the strength of the rock. This suggests that locally there can be high levels of stress even in active mature fault zones such as the San Andreas Fault.

1. Introduction

Static stress drop and radiated seismic energy are key parameters needed to understand the physics of earthquakes, investigate seismic source scaling relationships, and infer the local stress level in the crust. Recent work by Ide et al. (2003) suggests that propagation effects can contaminate measurements of source parameters even in the borehole recordings. One method for overcoming the problem is to use the spectral ratio method, which removes the propagation effects by deconvolving the smaller earthquake seismograms from those of the larger one. However, the deconvolution procedure is an unstable process, especially for higher frequencies, because small location differences result in the profound effects on the spectral ratio. This leads to large uncertainties in the estimations of corner frequencies.

In this study, we propose a method to determine a stable spectral ratio by stacking the ratios calculated from the moving windows taken along the record following the direct waves. We apply the method to microearthquakes occurring at Parkfield, CA, using the SAFOD Pilot Hole seismic array.

2. Data

In the summer of 2002, the Pilot Hole for the San Andreas Fault Observatory at Depth (SAFOD) was drilled to a depth of 2.2 km. The site lies just north of the rupture zone of the M 6 1966 Parkfield earthquake (Fig. 1). The seismic array consists of 32 levels of 3-component geophones (GS-20DM) at 40 meter spacing (856 to 2096 m depth). The sensors have a natural frequency of 15 Hz and damping constant of 0.57. The data were recorded at a sampling rate of 1kHz in July 2002 and then increased to 2kHz in December 12, 2002. On the basis of waveform similarity, we detected 34 events which classified into 14 groups and range in size from $M_{\text{L}}$ -0.3 to $M_{\text{L}}$ 2.1 (Fig. 1). These events are included in the cluster 9. Seismograms of the cluster 10 recorded at 428 m depth below mean sea level are shown in Fig. 1.
3. Method

We apply the spectral ratio method (Ide et al., 2003) to determine corner frequencies and seismic moments between the events within each cluster. As mentioned above, the deconvolution procedure is an unstable process, especially for higher frequencies, because small location differences result in the profound effects on the spectral ratio. According to Chaverria et al. (2003), the wavetrain recorded in the Pilot Hole is dominated by reflections and conversions and not random coda waves. So, we expect that the spectral ratios of the waves between P and S wave will also reflect the source, as will the waves following S wave. In fact, we succeeded in obtaining stable spectral ratios by stacking the ratios calculated from the successive windows taken along the record following the direct waves. In this study, we further stacked ratios obtained from each level of the array and component. This makes the ratio more stable (Fig. 2a) and permits us to estimate reliable source parameters.

We determine the source radius from the corner frequency using the circular crack model of Sato and Hirasawa (1973). The static stress drop is then calculated by the formula of Eshelby (1957). Following Ide et al. (2003), we derived attenuation function at each level of the array and component by taking the ratio between the observed and calculated spectrum. By the average of the functions over all events of the cluster, we obtain the average attenuation function, which is assumed to represent the propagation effects between the source and station. We calculate the radiated seismic energy from spectra corrected by the attenuation function.
4. Results

The observed spectral ratios were well modeled by the omega square model (Fig. 2b). The estimated static stress drops range from approximately 0.5 to 120 MPa (Fig. 3a), where they do not vary with seismic moment. Our result is consistent with other previous study using deep borehole data that there is no breakdown in the constant stress drop scaling over the wide range of magnitude. The apparent stresses, defined as the rigidity multiplied by the ratio between radiated energy and seismic moment, range from approximately 0.1 to 20 MPa (Fig. 3b). Each data set in the previous studies shows the apparent stress scales with seismic moment. However, Ide and Beroza (2001) and Ide et al. (2003) have shown that most of the observed size dependence can be attributed to artifacts arising from underestimation of energy due to a finite recording bandwidth or inadequate corrections for path effects, and concluded that the apparent stress is almost constant over a wide range of magnitude in seismic moment. Our result is consistent with their conclusion.

The estimated static stress drops seem to be high end of the compilation, where half of them are in excess of 10 MPa and some are above 50 MPa. Assuming hydrostatic pore pressures, laboratory-derived coefficients of friction (0.6<\(\mu\)<0.85), and a vertical stress \(S_V\) equal to the overburden pressure, the Coulomb failure criterion predicts a maximum shear stress of 43-54 MPa in a strike-slip faulting environments at a depth of 5 km. If we consider that the maximum shear stress is a good approximation of the average shear stress acting on the fault plane to cause slip, the static stress drops of some events are near the strength of the rock. The San Andreas fault has long been thought to be significantly weak as evidenced by the lack of heat flow anomaly adjacent to the fault, and the shear strength of the fault has been predicted about 20 MPa or less (e.g., Brune et al., 1969). High stress drop microearthquakes might suggest that locally there can be high levels of stress even in active mature fault zones.

![Figure 3.](image)

Figure 3. (a) Static stress drop versus seismic moment. (b) Apparent stress versus seismic moment. The results of this study are plotted as solid circles. Gray circles represent lower limits of the apparent stress.

4. Discussion and Conclusions

We have shown that both static stress drops and apparent stresses of microearthquakes at Parkfield do not depend on earthquake size, and are similar to those reported for moderate and large earthquakes. It is likely that natural tectonic earthquakes are self-similar over a wide range of earthquake size and the dynamics of small and large natural tectonic earthquakes are similar in a macroscopic viewpoint.

Bridging the gap between laboratory friction experiments and seismological measures of earthquake sources makes it possible to use the laboratory results as a basis for models of
earthquake generation process. It should be noted that the earthquakes studied in this study include events with dimensions less than 10 m, approaching those in laboratory studies (about 1 m). Further analysis of microearthquakes at Parkfield is expected to narrow the gap between laboratory experiments and natural tectonic earthquakes.

Based on the recurrence interval of repeating microearthquakes in Parkfield, Nadeau and Johnson (1998) derived the scaling relation for displacements, source dimensions, and static stress drops with seismic moment. The implied stress drops decrease from ~2000 MPa to 100 MPa for $M$ from ~0 to 3. Their scaling relation is shown by a broken line in Fig. 3a, which are much higher than our estimations. Failure of repeating earthquakes is often thought to occur on a strong fault patch (asperity) embedded in an aseismically creeping fault plane. According to an asperity model, the small strong asperity patch is surrounded by a much weaker fault that creeps under the influence of tectonic stress. When the asperity patch ruptures, the surrounding area slips as it is dynamically loaded by the stress release of the asperity patch. Based on this asperity model, our estimated source sizes correspond to the latter, while source dimensions by Nadeau and Johnson (1998) can be considered as the former. If so, the stress drop averaged over the asperity patch should be higher than that over the entire slip surface. This might explain the discrepancy seen in Fig. 3a, but it is unlikely that the stress drops exceed the strength of the rock. Although several models have been proposed to resolve the stress drop question at Parkfield, it remains unresolved. We should re-examine the asperity model based on the results obtained in this study.

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6. References


