Mechanism of deep low frequency earthquakes: Further evidence that deep non-volcanic tremor is generated by shear slip on the plate interface

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1 We study the mechanism of low frequency earthquakes (LFEs) in the Nankai Trough in western Shikoku, Japan. Precise locations have previously suggested that they represent shear slip on the plate boundary. In this paper we examine the mechanism of these events. Due to the low signal-to-noise ratio, we analyze stacked LFE waveforms and compare them with the waveforms of nearby earthquakes of known mechanism within the subducting Philippine Sea Plate. Analysis of both the focal mechanism using P-wave first-motions and the moment tensor using S waves indicates that LFEs represent shear slip on a low-angle thrust fault dipping to the northwest, namely the plate interface. Together with reports that deep tremor consists of a swarm of LFEs, our results suggest that deep tremor is generated directly by shear slip on the plate interface, and as such represents a seismic signature of the accompanying slow slip events. Citation: Ide, S., D. R. Shelly, and G. C. Beroza (2007), Mechanism of deep low frequency earthquakes: Further evidence that deep non-volcanic tremor is generated by shear slip on the plate interface, Geophys. Res. Lett., 34, L03308, doi:10.1029/2006GL028890.

1. Introduction

2 Deep, non-volcanic low-frequency tremors were discovered by Obara [2002] along the Nankai trough, Japan, where large (M ~ 8) earthquakes, such as the 1944 Tonankai and the 1946 Nankai earthquakes, have occurred repeatedly. Deep tremor consists of intermittent weak signals at relatively low frequency (1–8 Hz) that last as long as days to a few weeks once activity begins. The source of tremor is located near the down-dip limit of megathrust earthquakes in a belt-like distribution, suggesting the potential interaction with large inter-plate earthquakes. Many aspects of tremor, such as periodicity and migration, have been reported [Obara and Hirose, 2006]; however, the mechanism responsible for tremor generation has been unclear, in part due to the very low signal to noise (S/N) ratio of the tremor signal. In this area during the period of high tremor activity, slow changes in tilt have been detected [Hirose and Obara, 2005; Obara and Hirose, 2006]. Hirose and Obara [2005] interpreted these signals as originating from a slow slip event (SSE) on the plate interface. Strong temporal and spatial correlation between tremor and SSEs suggests that tremor may also originate on the plate interface.

3 While most of the tremor waveform has a chaotic appearance, there are periods with relatively impulsive arrivals, which have been identified by the Japan Meteorological Agency as a new class of events termed “low-frequency earthquakes” (LFEs) [Katsumata and Kamaya, 2003]. Tremor appears to be comprised of swarms of LFEs (D. R. Shelly et al., Non-volcanic tremor and low frequency earthquake swarms, submitted to Nature, 2007, hereinafter referred to as Shelly et al., submitted manuscript, 2007). Shelly et al. [2006] determined the hypocenters of LFEs using the double difference tomography and event relocation technique [Zhang and Thurber, 2003]. The hypocentral depths of the LFEs range from 30 km to 35 km, and the hypocenters fall on a surface that is approximately parallel to and ~7 km above the distribution of regular intraplate earthquakes, with a dip of 15°–20° to the northwest. The tomography reveals an area of high Vp/Vs anomaly between LFEs and intraplate earthquakes, suggesting the existence of pore fluids. Shelly et al. [2006] hypothesized that the reduction of effective stress due to high pore-fluid pressure may facilitate LFEs, tremor and SSEs.

4 The objective of this study is to determine the mechanism of LFEs and find whether it is consistent with this hypothesis. In short, the answer is yes. Independent analyses of P- and S-waves consistently show that the LFE moment tensor solution is shear slip on a low-angle thrust fault that has T and P axes azimuths parallel to the plate subduction direction. This mechanism is also consistent with fault models for SSEs determined by Hirose and Obara [2005].

2. Events and Data

5 We study LFEs identified by the JMA in western Shikoku, Japan using the relocated catalog of Shelly et al. [2006]. In the present study we use records of high-sensitivity seismometers maintained by the National Research Institute for Earth Science and Disaster Prevention (NIED), Earthquake Research Institute, the University of Tokyo, and Kochi University. The distribution of LFEs is spatially clustered. We focus on one of these clusters in an area of 5 km × 15 km (Figure 1). This cluster of LFEs has a linear northwest (N35°–45°W) trending alignment, which is comparable to the relative plate motion direction in this area (N43°W) from NUVEL-1A [DeMets et al., 1994]. The dip angle is approximately 15°.

6 In this study area intraplate earthquakes within the downgoing Philippine Sea Plate are also present, but are approximately 7 km deeper than the LFEs (Figure 1). We
determine the focal mechanism (strike, dip, and rake angles) and the scalar seismic moment for ten of these intraplate earthquakes using polarities and amplitudes of P-waves (Table S1 of the auxiliary material). Although the hypocenters of these events are close to each other, the mechanisms are quite diverse, which helps in constraining the polarities and mechanisms of the LFEs.

[7] Are the mechanisms of LFEs equally diverse? To address this issue, we calculate cross correlation functions for S-wave arrivals between LFE events that are separated by less than 3 km and compare the distribution of maximum positive and negative peaks (Figure 2a). Since the mechanisms of intraplate earthquakes are diverse, negative correlations are often stronger than positive correlations (Figure 2b). If the mechanism diversity is comparable to that for the intraplate earthquakes, we should observe strong negative peaks at many stations; however, for the LFEs we observe no such distribution of negative peaks. Although the low S/N ratio leads to weak correlations, they are predominantly positive with a complete lack of strong negative correlations over the many stations used in the analysis. This suggests that the mechanisms of LFEs are very similar and justifies our focus on a specific event to investigate the mechanism of LFEs more generally.

[8] Because the individual original records are noisy, we use stacking to improve the S/N ratio. As Shelly et al. [2006] explained, the body wave arrivals of LFEs are similar and have good correlations between different events. Once the large-amplitude S-waves are aligned, they were also able to successfully identify and align the P-waves using cross correlation.

[9] For the stacking procedure, we let $u^0_k(t_i)$ denote the velocity records of a reference LFE at time $t_i$ where $k = 1–3$ denotes a component. We chose waveforms of LFEs with maximum cross correlation peaks larger than 0.7, after bandpass filtering between 1 and 8 Hz. These waveforms, $u^k(t_n)$, $(n=1,\ldots,N)$, are aligned using cross correlation and the stacked waveforms for the reference event, $u^0(t_i)$, are written as,

\begin{equation}
\overline{u^0_k(t_i)} = \sum_{n=0}^{N} u^k(t_i) / \sum_j (\overline{u^0_k(t_j)})^2.
\end{equation}

Figure 3 shows the P-wave portion of the stacked waveforms compared with two intraplate earthquakes. The reference event is the one that occurred at 06:50:24 on 19 April, 2005 (JST). Although we analyze the stacked waveforms for the LFEs, we use the amplitude information from the reference event as determined using equation (2). The stacked waveforms of different stations do not share a common shape due to wave propagation effects caused by local structure near the stations. On the other hand the

Figure 1. (top) Map showing the study area and the locations of LFEs (crosses) and regular intraplate earthquakes (circles), determined by Shelly et al. [2006]. The study area of southwest Shikoku is shown in the inset. The mechanisms of ten intraplate earthquakes are shown by beach-balls (lower hemisphere projection). Star represents the reference LFE, 20050419065024. Triangles are stations. (bottom) Cross sectional view of the hypocenter distribution within the thick gray rectangular.

Figure 2. Comparison of the maximum and minimum of cross correlation functions (a) between the reference LFE, 20050419065024, and all LFEs within 3 km of it, and (b) between the intraplate events shown in Figure 1. Cross correlation functions are calculated for three component waveforms bandpass-filtered between 1 and 8 Hz. Size of symbol scales with S/N ratio in dB.

waveforms of LFEs and intraplate earthquakes are similar for each station, because the effect of path differences is dominated by effects in the neighborhood of the receiver, which is common to the two types of events.

3. **P-Wave First-Motions**

   [11] To constrain the focal mechanism, we make a plot of P-wave first-motion polarities based on a comparison between the waveforms of LFEs and earthquakes that have clear polarities. For example, the polarity is clearly up at KWBH, because intraplate events #4 and #8 have up and down polarities, respectively, and these waveforms are quite similar. We qualitatively compare waveforms at several stations and obtain the polarity distribution on the focal sphere (Figure 3).

   [12] Since the mechanisms of all LFEs are similar (Figure 2), we attempt to merge all polarity information from individual LFEs to form a composite mechanism using an automated polarity determination method. The polarity of LFEs can be estimated using cross correlation measurements with intraplate events of known mechanism. We measure the maximum and the minimum of the cross correlation functions between vertical P-waves of the LFEs and intraplate events shown in Figure 1 in the frequency range between 1 and 8 Hz. When the absolute value of either the maximum or the minimum is larger than 0.5 and the difference between them exceeds 0.1, we automatically assign a polarity based on that of the intraplate event. Despite generally poor S/N ratios, some LFE waveforms have a detectable P-wave for which the polarity can be extracted by comparing the waveform with multiple intraplate events. In Figure 3 we plot those polarities determined with at least two intraplate events.

   [13] Figure 3 shows up polarities in the northwest and down polarities in the southeast. Although the observation directions of the automated analysis are almost evenly distributed on focal sphere except for the near-horizontal southeast direction (largely offshore), few polarities are determined in the northeast and southwest direction. This suggests that this direction is close to one of the nodal planes of P-wave radiation. Overall the data are consistent with shear slip on a low angle thrust fault dipping to the northwest.

4. **Empirical Moment Tensor Inversion**

   [14] Next, we analyze S waves, which are generally the dominant arrival in the LFEs. The waveform similarity between LFEs and intraplate earthquakes holds for S-waves, too, and indicates that they share similar propagation effects. Therefore we use the intraplate earthquake records as empirical Green's functions to determine the LFE mechanisms.

mechanisms. We apply a modified version of their method as follows. There are $N$ earthquakes, each of which has a different moment tensor $M_i$ expressed by a set of basis moment tensors $M_1, M_2, \ldots, M_5$, and coefficients $m_{ij}$,

$$M^i = M_0^i \sum_{j=1}^5 m_{ij} M_j,$$

where $M_0^i$ is the seismic moment of $i$-th earthquake. The waveform of this event $u_i(t_k)$ is considered as the summation of impulse response functions $u_i(t_k)$ from the basis moment tensors $M_j$, convolved with a source time function. When we analyze them for frequencies lower than the characteristic frequency of the event, the source time function can be neglected and we can approximate the waveform with some unknown error $e_i(t_k)$ as

$$u_i(t_k) = M_0^i \sum_{j=1}^5 m_{ij} u_j(t_k) + e_i(t_k) (i = 1, \ldots, I).$$

If the number of events $I$ is larger than 5 and errors are Gaussian, the above equations can be used to invert $u_i(t_k)$ for $u_i(t_k)$ using least squares.

[16] Once $u_i(t_k)$ are determined for many stations, we use them and the records of a target event $u_i(t_k)$ to determine the moment tensor of the target event. The observation equation for a station is written as

$$u_i(t_k) = \sum_{l} s_l(t_k - t_l) \sum_{j=1}^5 m_{lj} u_j(t_l) + e_i(t_k),$$

where $s(t_k)$ is a source time function that is normalized so that the summation $\sum s(t_k)$ is unity. $m_{ij}$ are five unknown parameters and $e_i(t_k)$ are errors. Assuming that the errors are Gaussian, we solve the observation equations (5) for all stations simultaneously as a least-squares problem to determine the parameters $m^i_{ij}$ and the corresponding moment tensor,

$$M^0 = \sum_{j=1}^5 m^0_{ij} M_j.$$

[17] Using ten intraplate events in Figure 1, we obtained synthetic waveforms for the basis moment tensors at ten stations within an epicentral distance of approximately 30 km. The waveforms of different events must first be aligned on the arrival times of S-waves. Therefore, we first apply a bandpass filter (1–5 Hz) for all waveforms, calculate the cross correlation of waveforms with those from the first event, and arrange them based on the time that gives the maximum of the absolute value of the cross correlation function. Then, the estimated waveforms from the basis moment tensors are used to determine the moment tensor of the LFEs. The data are the S-wave portions of the three components of the stacked signals.

[18] Figure 4 shows the beach ball of the calculated moment tensor and comparison between the data and calculated waveforms. The best double couple solution is (strike = 279°; dip = 25°, and rake = 151°). The seismic moment of the reference LFE is measured to be 2.9 x 10$^{11}$ N-m ($M_w$ 1.6), which is significantly larger than would be estimated based on the JMA magnitude of this event,
The source time function is chosen empirically as an isosceles triangle of 0.3 s. There is also some ambiguity about the timing of data and calculated waveforms, which we modified empirically to improve the variance reduction, which is defined as,

$$VR = 1 - \sum_k \| e(t_k) \|^2 / \sum_k \| u^k(t_k) \|^2. \quad (7)$$

The final VR is 49%, which is far from perfect. Although the large amplitude waves are well explained by the calculated ones, stations with small amplitudes are often not fit well. This is attributable to relatively large noise for these components, the assumption that the LFE and intraplate events share the same path and site effects, and the estimation errors of synthetic waveforms for the basis moment tensors.

To investigate solution stability, we carried out the inversion using different subsets of eight of the ten stations. The different combination of stations yields slightly different solutions as shown in Figure 4; however, in most case, $P$ and $T$-axes are within 30° in azimuth. These are almost parallel to the direction of relative plate motion (N43°W), suggesting that the LFEs act to accommodate the subduction of the Philippine Sea Plate. The dip angle is better constrained, with a shallow angle from 15° to 25°, which is also consistent with the dip angle of the LFE cluster, 15°. The sign of the non-double couple component is not stable, hence this component is not considered well constrained and may be zero. In summary, all possible mechanisms are consistent with the independently determined $P$-wave first-motion distribution (Figure 3), which enhances the reliability of this solution.

5. Discussion and Conclusion

We analyze the waveforms of LFEs in western Shikoku, Japan, to estimate the mechanism of these events. We increase the S/N ratios of the LFEs by stacking similar events. The combination of LFEs and intraplate events enable us to constrain the LFE mechanisms using both $P$-wave polarity and $S$ waveforms. While the intraplate events have a variety of mechanisms, the mechanisms of the LFEs are nearly identical. Therefore, we can estimate a moment tensor solution that represents the general mechanism of LFEs. The resultant moment tensor is a shallow dipping thrust fault that is entirely consistent with the subduction of the Philippine Sea Plate.

Hirose and Obara [2005] determined the fault plane for six SSEs, two of which partially overlap our study area. Figure 4b shows the focal mechanisms of these events. All three mechanisms in Figure 4 are similar low angle thrust faults. The difference of the strike and rake angles is not significant considering the errors in the two solutions. We conclude that the moment tensor solution for the LFE is consistent with the SSE mechanisms.

Shelly et al. (submitted manuscript, 2007) demonstrated that deep tremor in western Shikoku can be represented as a swarm of LFEs. Thus, SSEs, LFEs, and deep tremor appear to be different manifestations of the same process, viz. relatively slow, but accelerated shear slip on the plate interface. The strategic location of these episodic accelerated slip events, which are directly down-dip of the locked zone, mean that it will be important to monitor them closely and to understand better their earthquake triggering potential, including their relationship to the megathrust earthquake recurrence.

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