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Low-frequency tremors associated with reverse faults in a shallow accretionary prism

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ABSTRACT

The shallow part of a seismogenic subduction zone is thought to play an important role in tsunami genesis during large interplate thrust earthquakes. Near the updip portion of the seismogenic zone along the Nankai trough, splay faults, which are major active reverse faults in the accretionary prism, likely rupture during large interplate earthquakes such as the 1944 M_w 8.2 Tonankai earthquake off Kii Peninsula. We observed low-frequency tremors associated with reverse faults in a shallow accretionary prism off Kii Peninsula at close range by using ocean bottom seismographs. The tremors were characterized by a dominant frequency range of 2–8 Hz and a lack of energy in the frequency range above 10 Hz. Their duration ranged from tens of seconds to a few minutes. Their source locations lay in three clusters on the landward slope of the Nankai trough. Activity in each cluster continued for from one day to two weeks. Many of the low-frequency tremors were located near the shallowest part of a major splay fault. The episodic activity of low-frequency tremors and of previously reported very-low-frequency earthquakes, which indicate reverse faulting in the shallow accretionary prism, suggests that the reverse faults in the accretionary prism are conditionally stable faults that can become unstable under sufficiently strong dynamic loading, such as that caused by a large earthquake. Such reverse faults, as typified by a splay fault, can rupture during large interplate earthquakes and generate large tsunamis.

1. Introduction

The extent of the seismogenic zone along the subduction thrust must be known to assess strong ground motions and tsunamis caused by large interplate earthquakes. In particular, the seaward extent of the updip limit of the seismogenic zone is crucial for tsunami generation. Along the Nankai trough, where the Philippine Sea plate subducts beneath southwestern Japan with a convergence rate of about 65 mm/yr (Miyazaki and Heki, 2001), large interplate thrust earthquakes of magnitude 8 class have occurred repeatedly with recurrence intervals of 100–200 years and generated large tsunamis (Ando, 1975). Although the shallow part of the thrust in the subduction zone is considered to be aseismic with stable sliding (Byrne et al., 1988), slip distribution models of the 1944 M_w 8.2 Tonankai earthquake, which was the last large event off Kii Peninsula, suggest that rather large slips (>1 m) occurred near the trough (Ichinose et al., 2003; Baba et al., 2006). These models support the hypothesis that slip has occurred along the splay fault, which is a major active reverse fault in the accretionary prism, during large interplate earthquakes, as proposed from seismic reflection surveys (Park et al., 2002; Moore et al., 2007).

Recent studies have shown anomalous seismic events called very-low-frequency (VLF) earthquakes around the updip portion of the seismogenic zone along the Nankai trough from on-land seismic network observations (Obara and Ito, 2005). The VLF earthquakes were characterized by a dominant frequency of about 10–20 s and a lack of energy at higher frequencies. Centroid moment tensor (CMT) solutions of the VLF earthquakes indicate reverse faulting in the shallow accretionary prism near the Nankai trough (Obara and Ito, 2005; Ito and Obara, 2006a). Most of the VLF earthquakes were observed after the 2004 off Kii Peninsula earthquake (M_w 7.3), a reverse-fault earthquake in the subducting Philippine Sea plate near the axis of the Nankai trough (Ito et al., 2005). In addition to the VLF earthquakes, low-frequency tremors were observed by ocean bottom seismographs (OBSs) deployed after the 2004 earthquake for aftershock observations (Sakai et al., 2007). These low-frequency tremors were characterized by a long duration of tens of seconds to several minutes (Sakai et al., 2007) and originated in the shallow accretionary prism (Nakamula et al., 2008). Although the CMT solutions of the VLF earthquakes indicate reverse faulting in the shallow accretionary prism (Obara and Ito, 2005; Ito and Obara, 2006a), the relation between these VLF earthquakes and crustal structure in the shallow accretionary prism has been unclear, because the earthquake locations determined by the on-land observations were not accurate enough for direct comparison with the crustal structure. Source locations with precisions comparable to the crustal

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structure in the shallow accretionary prism are necessary to understand the mechanism of this seismic activity characterized by low-frequency signals. Here we describe the episodic activity of low-frequency tremors related to reverse faults, as typified by the splay fault in the accretionary prism off Kii Peninsula observed at close range by OBSs, and propose that the splay fault might be a conditionally stable fault that can rupture during large interplate earthquakes.

2. Low-frequency tremors observed by OBS

Several OBS experiments were conducted from 2001 to 2005 to observe microseismicity along the Nankai trough (Obana et al., 2004, 2005, 2006, 2009) (Fig. 1). In most cases, the OBSs were equipped with a three-component 4.5–Hz short-period seismometer. The observation period of each experiment was up to 3 months. Data were collected continuously with a sampling frequency of 100 Hz. In a preliminary analysis to search for anomalous low-frequency tremors, we checked the raw velocity seismograms recorded during the 2005 experiment, which was conducted about six months after the 2004 off Kii Peninsula earthquake and which recorded many aftershocks of the 2004 earthquake (Obana et al., 2009).

Several low-frequency tremors were recorded on these seismograms. They were characterized by a dominant frequency range of 2–8 Hz and a lack of energy in the frequency range above 10 Hz (Fig. 2c). Given the frequency characteristic of the 4.5-Hz short-period seismometer in the OBSs, the dominant frequency range of the tremors might be lower than that observed. The duration of the signals reached up to a few hundreds of seconds. These characteristics are similar to those of the tremors observed during the aftershock observations of the 2004 off Kii Peninsula earthquake (Sakai et al., 2007), and we consider them to be key to the detection of low-frequency tremors along the Nankai trough.

On the basis of the preliminary analysis, we searched for events with a dominant frequency range of 2–8 Hz and duration of longer than 10 s using the short-term/long-term amplitude ratio of the vertical-component seismograms. Next, we carefully examined the detected events to eliminate regular earthquakes or T-phase signals, which are sound waves traveling in the ocean with a dominant frequency range similar to the low-frequency tremors. Finally, we identified several low-frequency tremors during the 2003 and 2005 OBS experiments off Kii Peninsula (Fig. 2). During OBS experiments off Kii Peninsula from 2001 to 2002 and an experiment off Shikoku in 2004 (Fig. 1), no low-frequency tremors were detected. The low-frequency tremors did not release energy in a frequency range higher than 10 Hz (Fig. 2b and c), whereas regular earthquakes usually release energy in that frequency range. Moreover, although the lower limit of the dominant frequency of regular earthquakes is about 4 Hz, the low-frequency tremors released energy at a significantly lower frequency. The duration of the low-frequency tremors ranged from tens of seconds to a few minutes. In most cases, it was difficult to identify the onset of the signals in the seismograms (Fig. 2d and e), but for some events, the onset of a small signal, apparently the P-wave arrival, could be seen before the large-amplitude low-frequency signals. This suggests that the large-amplitude signals of the low-frequency tremors correspond to S-wave arrivals.

3. Source locations of low-frequency tremors

We estimated source locations of the low-frequency tremors observed in 2003, which seemed to be within the OBS network, by using the differential arrival times between OBSs, based on cross-correlations of the envelope seismograms. Because the onsets of the signals were not clear, it was difficult to use absolute arrival times. We obtained the envelopes by the following procedure. First, we filtered the vertical-component raw velocity seismograms (Fig. 3a) using a band-pass filter with cutoff frequencies of 2 and 8 Hz (Fig. 3b); then we converted the filtered seismograms to envelopes, which are the root-mean-square amplitudes with a smoothing time of 1 s (Fig. 3c). We then used pairs of envelopes with a length of 150 s to calculate the cross-correlation function. We obtained the differential times between the OBSs as the lag time with the maximum cross-correlation coefficient

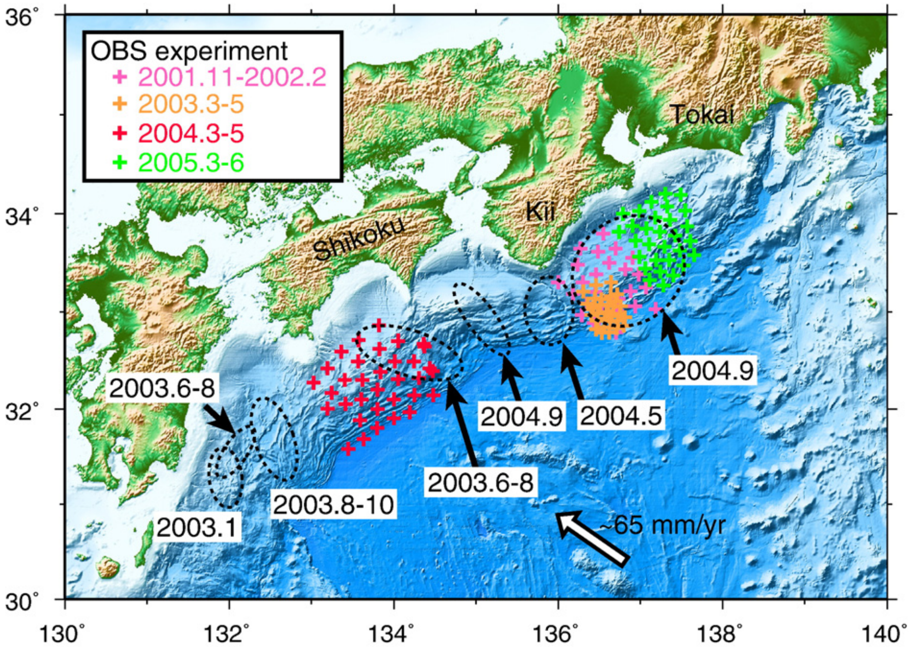

Fig. 1. OBS experiments (Obana et al., 2004, 2005, 2006, 2009) and VLF activities (Obara and Ito, 2005) along the Nankai trough. Colored crosses show the OBS locations of each experiment. Dashed ellipses enclose VLF activity clusters. The year and month(s) of both the OBS experiments and the VLF activity clusters are indicated. The open arrow is the convergence vector of the Philippine Sea plate relative to southwestern Japan (Miyazaki and Heki, 2001).