# Very low frequency earthquakes excited by the 2004 off the Kii peninsula earthquakes: A dynamic deformation process in the large accretionary prism

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Anomalous seismic events were observed after the occurrence of the foreshock (Mw=7.2) and the main shock (Mw=7.5) of the 2004 off the Kii peninsula earthquakes. These anomalous events are characterized by very low-frequency energy of around 10 seconds with almost no higher-frequency energy and are considered the same as the very low-frequency (VLF) earthquakes discovered by Ishihara (2003) in some places along the Nankai trough, southwest Japan. The VLF seismic activity is mainly coincident with the aftershock area of the 2004 off the Kii peninsula earthquakes; however a minor activity was also excited in the southern Kii channel area. The VLF seismograms sometimes include higher-frequency wave trains with amplitudes much smaller than that of regular aftershocks. This indicates that VLF earthquakes have different source properties from the regular earthquakes. The centroid moment tensor analysis for one of the larger events suggests that the source depth is very shallow and the focal mechanism is the reverse faulting. These features suggest that the event occurs on the well-developed reverse fault system in the large accretionary prism near the Nankai trough. The swarm activity of VLF earthquakes might be considered as a chain-like occurrence of slips on the reverse fault system and thus the signature of a dynamic deformation process in the accretionary prism.
**Key words:** Low-frequency earthquake, subduction zone, Nankai trough, accretionary prism, broadband seismometer.

## 1. Introduction

On the northwestern margin of the Philippine Sea, a young oceanic plate subducts beneath southwest Japan from the Nankai trough and mega-thrust earthquakes occur at intervals of about 100 years. Many slow earthquakes have been detected by the GPS and the broadband seismograph data monitoring system in some regions along the Nankai trough (Kawasaki, 2004). These are distributed in a stable-unstable transition zone on the plate boundary separately with rupture areas of huge mega-thrust earthquakes. Recently, short-term slow slip events have been discovered associated with the active non-volcanic tremors at the deeper extension of the locked zone in the western part of Shikoku area, southwest Japan (Obara *et al.*, 2004a). Such slow slip events might reflect coupling properties at the plate interface. To clarify the subduction process and evaluate the potential for coming mega-thrust earthquakes, it is important not only to understand the cause of the slow slip events but also to observe other seismic phenomena in the subduction zone.

Ishihara (2003) has discovered an anomalous type of seismic event near the trench axis along the Nankai trough by using the continuous broadband seismograph data of the National Research Institute for Earth Science and Disaster Prevention (NIED) F-net (Okada *et al.*, 2004). This anomalous event has only very low-frequency (VLF) energy of around 10 to 20 seconds and there is little or no high frequency content. Therefore these earthquakes are not detected by regional and global seismic observation networks and not listed on any earthquake catalogs. These earthquakes are distributed along the Nankai trough in the Tokai, Kii peninsula, Hyuga-nada, and Okinawa regions. Obara and Ito (2004) pointed out that the distribution of the VLF earthquake is rather concentrated in some clusters using the very dense broadband seismic network based on the array analysis technique. The seismic activity of each cluster usually continues over a period from one week to one month.

On September 5, 2004, Mj=7.1 (Mw=7.2) and Mj=7.4 (Mw=7.5) intra-slab earthquakes (Fig. 1) occurred successively in southeast of the Kii peninsula at 19:07 and 23:57 (JST), respectively. The epicenters are located just at the Nankai trough and the depth is around 20 km. The source mechanism of these earthquakes is reverse faulting with the compression axis oriented in north-south direction. Numerous aftershocks are distributed mainly on the land side of the trough axis and divided into several groups based on centroid moment tensor analysis (e.g. Ito *et al.*, 2005). Many aftershocks with reverse faulting focal mechanisms occurred inside the slab mantle at a depth of around 20 km. Some aftershocks with strike slip mechanisms occurred along a lineament with the northwest and southeast direction at depths shallower than 10 km inside the oceanic crust or perhaps in the sediment layer. The anomalous events occurred during the stage of decaying aftershock activity. These events are characterized by low frequency energy of around 10 seconds. They are very similar to the VLF earth-

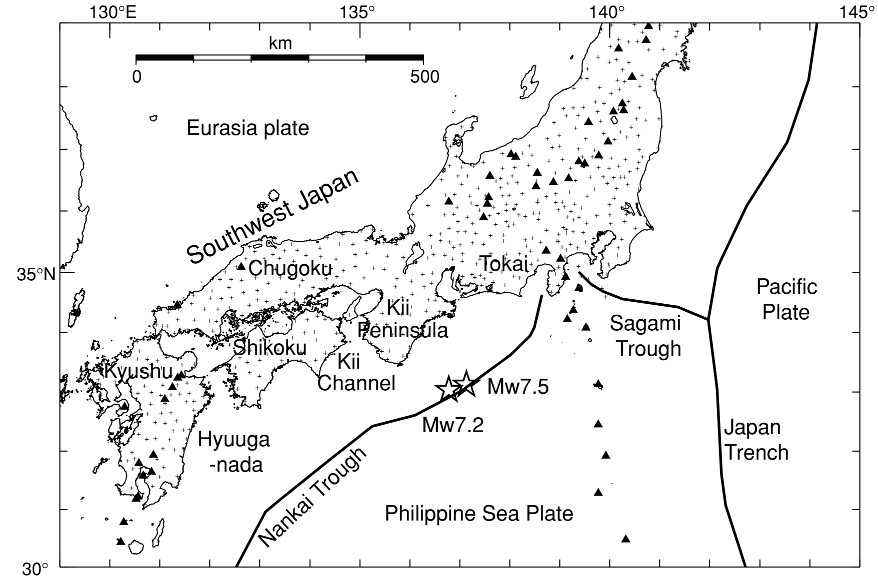


Fig. 1. Tectonic map around southwest Japan. Bold lines represent trench axes (plate boundaries). Both the Philippine Sea plate and Pacific plate subduct beneath the Eurasian plate in this area. Solid triangles denote Quaternary active volcanoes defined by the JMA and thin crosses indicate the NIED Hi-net seismic stations. Star symbols are two large earthquakes (Mw 7.2 and Mw 7.5) on September 8, 2004 southeast of the Kii-Peninsula.

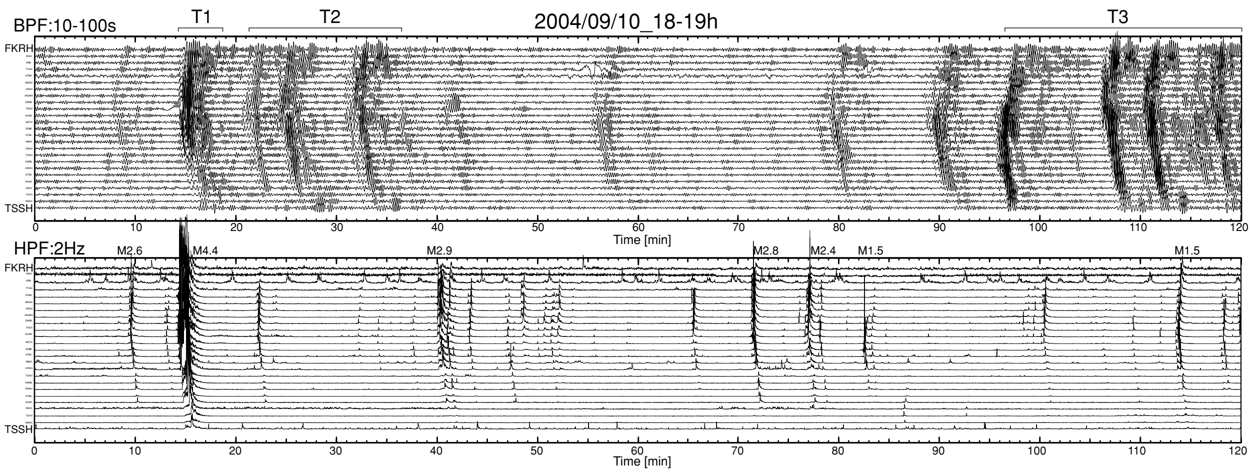


Fig. 2. Example of continuous broadband seismograms with a duration of 2 hours from 18:00 on September 10, 2004. The upper panel shows band-pass filtered seismograms with a pass band ranging from 10 to 100 seconds, and the lower panel shows root-mean-square traces using a high-pass filter with a corner frequency of 2 Hz. Figures attached with a letter M placed at envelope peaks in the lower panel are magnitudes of aftershocks listed in the JMA catalog. Traces from the top to bottom correspond to stations from east to west plotted by square symbols in Fig. 7. In the time period T1, an M4.4 regular aftershock excites the high-frequency body wave and the low-frequency surface wave, simultaneously. In the time period T2, there are some VLF events only in the low-frequency panel. In the time period T3, there are some wave trains only in the low-frequency panels with different patterns of phase arrival corresponding to the different sources. The first signal comes from the southern part of Kii Channel and the others are generated from the aftershock area southeast of the Kii Peninsula as shown in Fig. 7.

quakes discovered by Ishihara (2003) in other areas along the Nankai trough. In this paper, the seismic activity of the VLF earthquakes is investigated and compared with regular aftershocks of the 2004 off the Kii peninsula earthquakes.

## 2. Characteristics of VLF Earthquakes

### 2.1 Seismograms

The frequency content of the VLF earthquakes is clearly different from regular aftershocks. Figure 2 shows an example of continuous broadband seismograms including VLF earthquakes. The upper panel shows band-pass filtered seismograms with a pass band ranging from 10 to 100 seconds and the lower panel indicates higher-frequency envelope seismograms with a corner frequency of 2 Hz. The plotted seismograms are the output from the north-south component of the high-sensitivity accelerometer, which is installed in every Hi-net borehole observation well (Okada *et al.*, 2004). The direct current component of the accelerometer is used as the tiltmeter, which is very useful to detect and analyze the slow slip events accompanied by non-volcanic tremors in western part of Shikoku, southwest Japan (Obara *et al.*, 2004a). More than 700 tiltmeters cover the Japan Islands with an average spacing of 25 km. The set direction is corrected by using the estimated orientation of borehole sensors (Shiomi *et al.*, 2003).

The wave train in the time period T1 in Fig. 2 at around

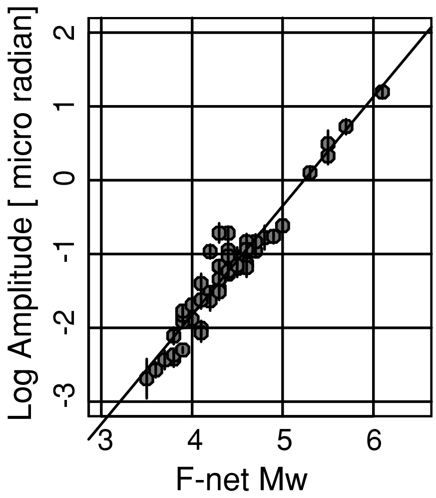


Fig. 3. Comparison between the moment magnitude determined by NIED F-net and the amplitude in a period range from 10 to 100 seconds for regular aftershocks. The amplitude averaged from 10 stations in Kii Peninsula region is plotted. Vertical bars indicate the standard deviation in the observed amplitudes.

18:15 on September 10 is recognized in both frequency plots. This event is a regular aftershock (M4.4) including both high-frequency body waves and low-frequency surface waves. There are 7 aftershocks during the 2 hours listed in the Japan Meteorological Agency (JMA) catalog and their waveforms are recognized only in the high-frequency envelope chart except for the M4.4 event. Also there are some small spike-like signals on the high-frequency envelope chart without any phases in low-frequency band. These are considered as regular micro-aftershocks, which are too small to be detected by JMA. On the other hand, we can see some wave trains only in the low-frequency component panel without corresponding high-frequency signals during the time period T2 and T3 in Fig. 2. These are the VLF earthquakes. In the time period T3, there are some different patterns in the arrival alignment, which are due to different source regions as described later. The low-frequency wave trains are very similar in neighboring stations and this similarity is used in the epicentral determination process. The apparent velocity of the coherent signals is about 3.8 km/s, so the very low-frequency signal is considered as a surface wave.

### 2.2 Seismicity

The VLF earthquakes started on September 8, 2004 three days after the occurrence of the foreshock and the main shock of the 2004 off the Kii peninsula earthquakes. These events are not included in any earthquake catalog, therefore continuous broadband seismograph data were used to detect them by monitoring low-frequency seismic energy. Magnitudes of the VLF events are roughly estimated by comparing amplitudes observed in the period range from 10 to 100 seconds with amplitudes from regular aftershocks. Figure 3 shows the relationship between the amplitudes in the low-frequency band ranging from 10 to 100 seconds and the moment magnitude determined by NIED F-net for regular aftershocks. The linear regression line is used for estimating the magnitude of the VLF earthquakes based on the amplitude in the low-frequency band. Figure 4 shows the magnitude-time plot of the VLF seismic activity. VLF events with magnitudes greater than 3.5 are plotted comparing them with the regular aftershock seismicity determined by the JMA. The VLF seismicity is more active than the regular aftershock sequence.

## 3. Epicentral Distribution

### 3.1 Location method

Because waveforms of the VLF events are quite similar at neighboring stations, epicenters are estimated by using a cross correlation analysis. The Hi-net stations in southwest Japan are divided into 11 groups with a diameter of about 100 km as shown in Fig. 5. The cross correlation for the

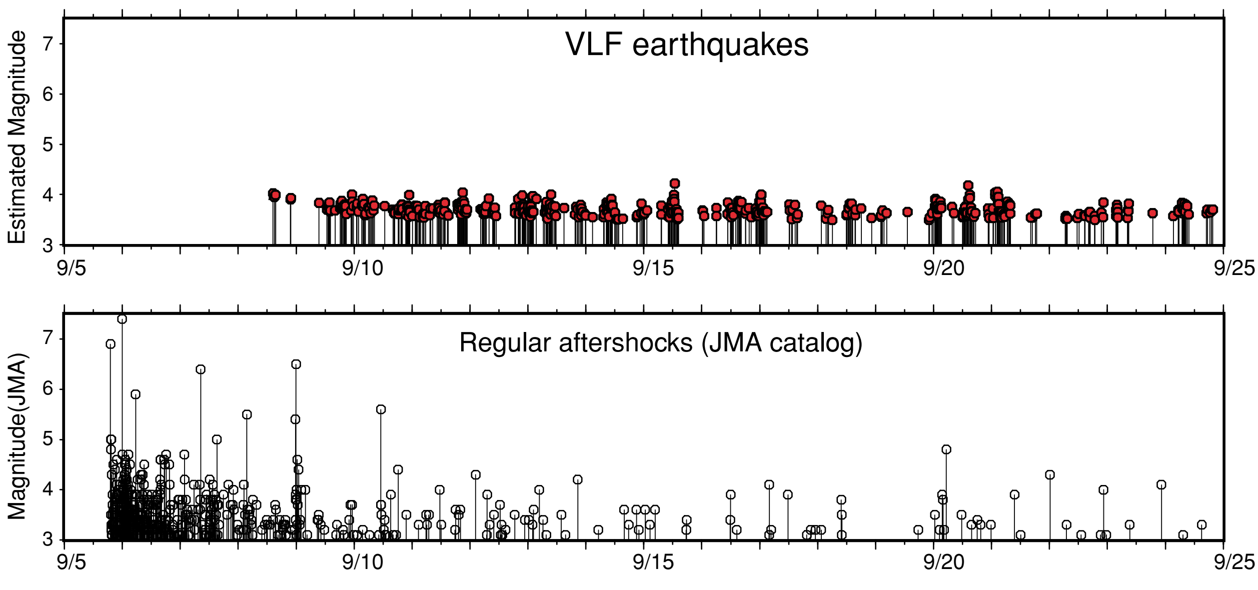


Fig. 4. (Top) Time sequence of VLF earthquakes in the aftershock region southwest of the Kii Peninsula. Only events with an estimated magnitude greater than 3.5 are plotted because the VLF signals of earthquakes smaller than M3.5 is sometimes contaminated by noise as indicated in Fig. 8. (Bottom) Magnitude-Time diagram for the 2004 aftershock sequence southeast of the Kii-Peninsula listed in the JMA catalog.

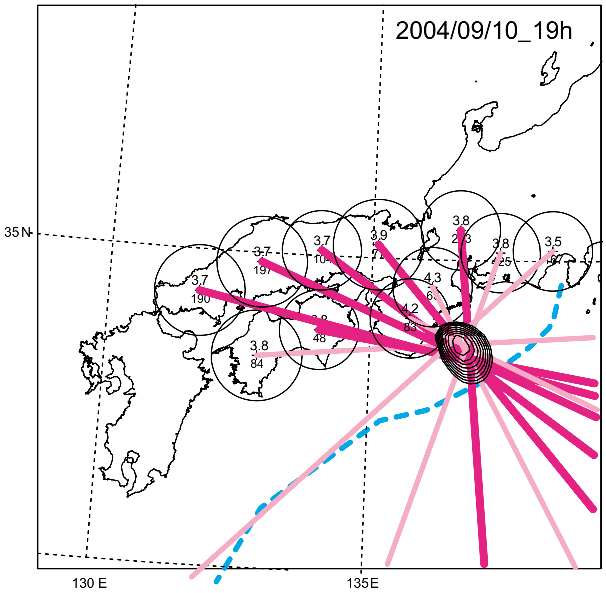


Fig. 5. Distribution of groups of seismic stations for the array analysis and an example of the estimated geometry of the ray propagation. In the upper-left corner, station pairs for the cross-correlation analysis in a group located in the middle part of Chugoku district is plotted. The width of the plotted ray path is inversely proportional to the error in the estimation of the azimuth of the ray propagation. The estimated propagation velocity and the number of pairs with the cross correlation coefficient of greater than 0.9 are plotted above and below the center of each circle, respectively. Contours indicate the distribution of residual in the grid search method to estimate the epicenter location. The blue dashed line indicates the Nankai trough.

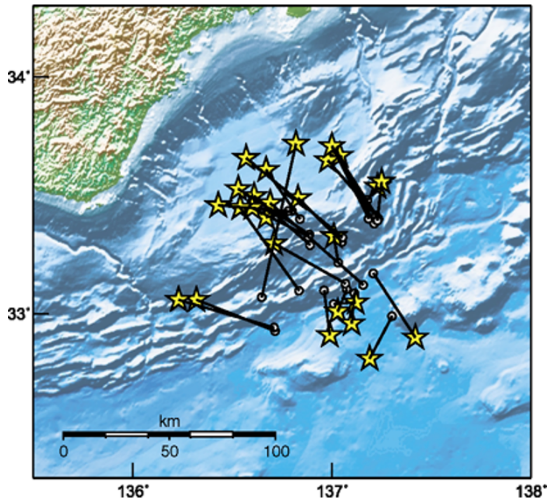


Fig. 6. Comparison between epicenters of regular aftershocks determined by the array analysis in this paper using the waveforms of surface waves (yellow stars) and those determined by JMA based on the ordinal hypocentral determination method using onset time of *P* and *S* wave (small gray circles).

target wave train is calculated with every pair of stations in each group in order to measure the time lag which gives the highest cross correlation coefficient. Then, the set of time lags obtained in each group are used to estimate the propagation direction and the apparent velocity. Finally, the epicenter of the VLF event is estimated as a focus of the ray paths calculated with good resolution in each group based on a grid search method. Well-determined apparent velocities indicated by thick red lines are ranging from 3.7 to 3.9 km/s, which correspond to the propagation velocity of the surface wave. We assume that the ray geometry of the surface wave is straight with a homogeneous velocity structure. The residual contour indicates a kind of error ellipse which has the major axis extending towards land.

VLF events and regular aftershocks shared the same source area. The surface waves of the major aftershocks are adequate to evaluate the epicentral determination method based on the array analysis used in this paper. Figure 6 shows the comparison of epicentral location of regular aftershocks estimated by the array analysis to that determined by JMA based on the ordinary hypocentral determination method using onset times of *P* and *S* waves. The epicenters estimated by this array processing method are systematically offset landward by several tens of kilometers for events located on the land side of the trough axis. This might be due to curving of the ray geometry affected by the inhomogeneous distribution of the velocity structure for the surface wave.

### 3.2 Result

The estimated epicentral distribution of VLF events including other time periods from January 2003 (Obara and Ito, 2004) is plotted in Fig. 7. In 2003, there were two active clusters near the Nankai trough; Hyuga-nada and the region off Cape Muroto. The VLF seismic activity lasted for about a month in each cluster. Just after the occurrence of the 2003 Tokachi Earthquake (M8.0) in northeast Japan on September 26, 2003, the VLF seismic activity in the eastern part of Hyuga-nada region became very active.

In May 2004, VLF events occurred south of the Kii peninsula for a several days. On September 8, three days after the major intraslab earthquakes (Mw 7.2 and Mw 7.5), the VLF seismic activity started in the same source area of regular aftershocks. During the seismic activity, another VLF cluster appeared in the southern part of the Kii channel. All VLF activity is located on the land side of the trough axis. Considering the systematic error in the epicentral estimation as shown in Fig. 6, each cluster of VLF events could be more concentrated towards the trough axis.

### 3.3 CMT analysis

The centroid moment tensor (CMT) analysis can be done for larger VLF events by using not only Hi-net tiltmeters but also F-net broad-band seismograph data. A preliminary result for the focal mechanism of a VLF event estimated with the grid search method (Ito *et al*., 2005), which is modified from the routine analysis of F-net (Fukuyama *et al*., 1998), is plotted in Fig. 7. The mechanism is a reverse fault type with a steep dip angle and an estimated depth of 2 km. The reverse faulting mechanism and the very shallow depth is very similar to the CMT results for the Hyuga-nada VLF events (Obara and Ito, 2004). Because the estimated depth of 2 km is the shallowest grid in depth, the true depth might be shallower than 2 km. On the land side of the trough axis, there exists thick accretionary sediment layer (e.g. Davis *et al*., 1983; Kimura, 2002). Based on the marine profiling, a reverse fault system is well developed in the accretionary

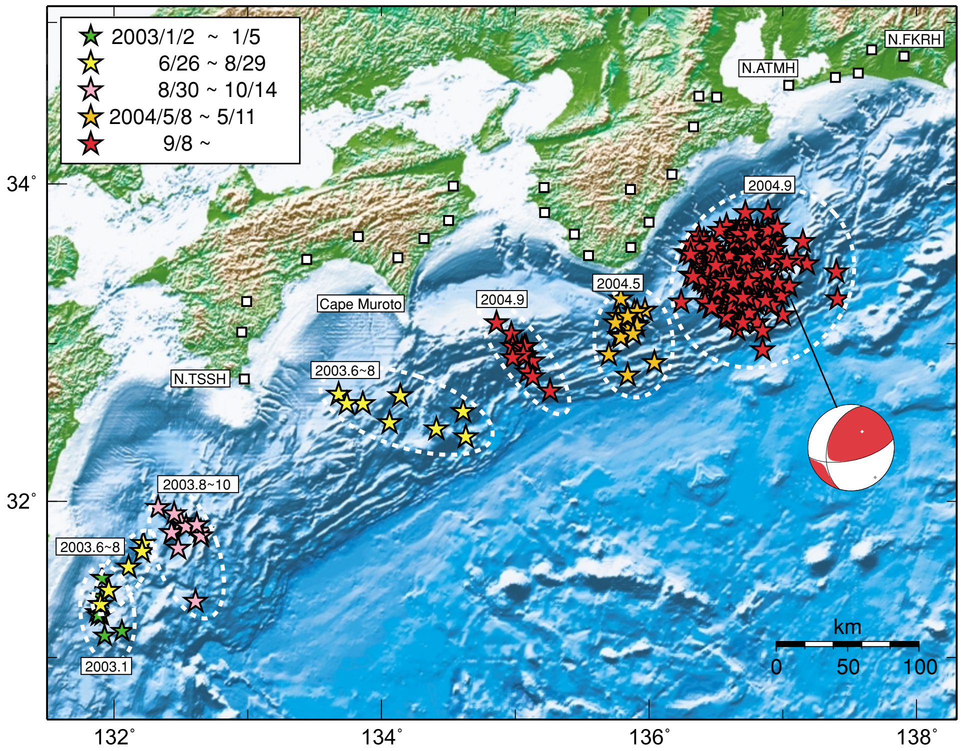


Fig. 7. Epicentral distribution of VLF events and the result from one CMT analysis. Green, yellow and purple stars indicate epicenters of VLF events in 2003. Orange and red stars are VLF seismic activity in 2004. Each cluster is enclosed by white dashed ellipse with year and month. The estimated depth, moment magnitude, and variance reduction in the CMT analysis for the VLF event shown (2004/09/12 21:38) is 2 km, Mw 3.6, and 55, respectively.

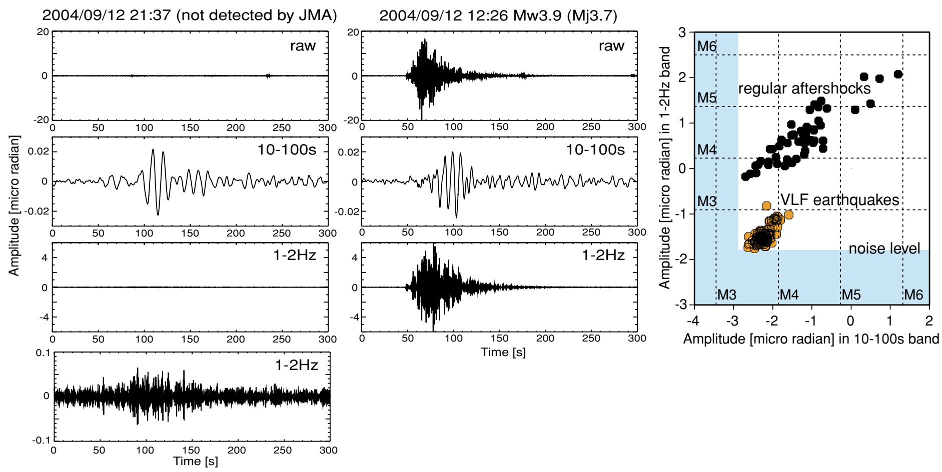


Fig. 8. Left and middle panels show seismograms of a VLF event and a regular aftershock, respectively. Both events have almost the same amplitude in the low-frequency component of 10–100 seconds. From the top panel, raw (no filter) data, seismograms with the pass band of 10–100 seconds, and seismograms with the pass band of 1–2 Hz are plotted. At the bottom on the left panel, the third trace is plotted again with expansion in the vertical axis. Right panel shows the amplitude relationship between the low-frequency component (10–100 seconds) and high-frequency component (1–2 Hz) for regular aftershocks indicated by solid circles and VLF earthquakes indicated by orange circles. The blue area indicates the approximate noise level. Dashed lines indicate the corresponding magnitude estimated from regular aftershocks based on the comparison between the moment magnitude and the amplitude of each frequency range.

sediments (Kuramoto *et al.*, 2000). Considering the fault mechanism and the shallow depth, the VLF earthquakes probably occur in the accretionary prism.

## 4. Discussions

VLF earthquakes share the same epicentral area with regular aftershocks of the 2004 off the Kii peninsula earthquakes. However, the frequency content of these events is totally different from each other. The left and middle panels of Fig. 8 show seismograms of a VLF event and a regular aftershock, respectively. Both events have almost the same amplitude in the low frequency range of 10–100 seconds; however the amplitude of the signal is quite different in the raw (unfiltered) seismograms. The difference comes from higher-frequency components as shown in the band-pass filtered seismogram with the pass band of 1–2 Hz. However, a spindle-shaped wave train with very small amplitude is seen in the higher frequency components of the VLF events in the left bottom panel in Fig. 8. The right panel indicates the amplitude relationship between the low-frequency content (10–100 seconds) and relatively high-frequency content (1–2 Hz) of regular aftershocks and VLF earthquakes. The amplitude of the high-frequency content of the VLF event is 100–200 times smaller than that of regular earthquakes if we compare events with the same amplitude of low-frequency energy. It might reflect the source process or the strong attenuation in the sediment layer. The stress drop is expected to be very low for slip on a reverse fault in the accretionary prism because of the enriched existence fluids and unconsolidated materials on the fault plane surrounded by sedimentary material. Such VLF earthquakes have only been detected in southwest Japan in the region of Philippine Sea plate subduction (Ishihara, 2003; Obara and Ito, 2004) and there have been no reports in the northern Japan. The difference is probably due to the existence of the large accretionary prism. Along the Japan Trench in the northern part of Japan, tectonic erosion is predominant and the accretionary prism is not well developed (Kimura, 2002). Obara *et al*. (2004b) reported the occurrence of a low-frequency earthquake near the aftershock area of the 2003 Tokachi Earthquake and discussed the cause of the earthquake as a slip event at the subducted seamount on the plate boundary. The earthquake has the clear $P$ initial phase with low-frequency contents, which is different from VLF event in the Nankai Trough. The source spectra, especially relative amplitude of higher-frequency content of VLF event might indicate the inhomogeneity on the fault plane in the accretionary prism. Therefore, it is important to investigate the space and time dependence of the spectra property of the VLF event.

VLF earthquakes in southeast of the Kii peninsula might be a triggered phenomenon. Reverse faults in the accretionary prism take the role of a drain for fluids generated by dehydrating the subducting oceanic plate. If the intraslab earthquakes are caused by the embrittlement due to the dehydration process (Yamasaki and Seno, 2003), the 2004 off the Kii peninsula earthquakes might have affected the dehydration process and the fluid flow. On the other hand, the strong shaking by these Mw 7.2 and Mw 7.5 earthquakes might have increased instability of the fold-and-thrust structures in the accretionary wedge and caused a chain-like occurrence of slip events, which are the VLF earthquakes.

## 5. Conclusions

A sequence of VLF earthquakes which are characterized by a frequency content of about 10 seconds occurred just after the 2004 off the Kii peninsula earthquakes. The region of the major VLF activity is almost the same as the aftershock area. Minor activity also occurred in the southern part of the Kii channel area, which is about 150 km west of the main VLF activity. Between these two source regions, there is a cluster of VLF earthquakes which was active in May 2004. As the result of the monitoring for the VLF events during the 2 years of 2003 and 2004, 5 clusters were found on the landward side of the Nankai trough around the up-dip portion of the seismogenic zone of the plate boundary.

The VLF signal is dominated by low-frequency surface waves, however sometimes higher-frequency phases with much small amplitudes accompany the VLF signal. The depth of these events is very shallow and the focal mechanism is the reverse faulting derived from CMT analysis. The VLF earthquakes probably occur on the reverse fault system in the large accretionary prism.

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