Deep low-frequency earthquakes near the downward extension of the seismogenic fault of the 2000 Western Tottori earthquake

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Deep low-frequency (DLF) events have often been discussed in association with fluid (magma) activity around volcanoes, in this paper, however, we will show another example of DLF activity beneath active faults. On October 6, 2000, a Mw=6.7 crustal earthquake occurred in the western Tottori, southwest Japan. Beneath the focal region of the earthquake, DLF earthquakes had been observed prior to the mainshock and the activity increased after the mainshock. The events are distributed around 30 km depth and seem to be located around the downward extension of the seismogenic fault. Three types of DLF events have been observed and their seismological features indicate fluid activity around the focal region of the DLF events. If the downward extension of the seismogenic fault in the lower crust exists, fluid activity indicated by the DLF events possibly affect the aseismic slip process of the deep portion of the fault and likely control the occurrence of the earthquakes on the seismogenic portion of the fault.
Key words: Deep low-frequency earthquake, seismogenic faults, fluid.

1. Introduction

Deep low-frequency (DLF) events have been usually observed near active volcanoes or the volcanic front and attributed to magma activity (e.g. Aki and Koyanagi, 1981; Ukawa and Obara, 1993; Hasegawa and Yamamoto, 1994). For low-frequency volcanic earthquakes and volcanic tremor, several types of source models have been proposed (e.g. Aki *et al.*, 1977; Chouet, 1985; Crosson and Bame, 1985). Recently, however, several examples of low-frequency events away from volcanoes were newly detected in Japan. One is the low-frequency tremors along the Nankai trough discovered by Obara (2002). These events are located along the strike of the subducting Philippine Sea Plate over a length of 600 km and attributed to the fluid activity generated by dehydration process from the subducting slab. Another example is the low-frequency earthquakes beneath active faults in the backarc region. Figure 1 shows the distribution of the low-frequency events from June 2000 to April 2004 from the earthquake catalogue compiled by the Japan Meteorological Agency (JMA). DLF events associated with volcanoes, low-frequency tremors, and DLF events beneath active faults are plotted. Larger ordinary earthquakes, with magnitudes are equal to or greater than 6, that occurred from 1983 to 2003 are also plotted by solid stars. It is recognized that the western Tottori area is an unusual example since we have DLF earthquakes associated with a large earthquake and without active volcanoes in the vicinity. In this paper, therefore, we will focus on the DLF activity in the western Tottori district, southwest Japan.

2. DLF Events in the Western Tottori Region
2.1 Hypocenter distribution

On October 6, 2000, a Mw=6.7 crustal earthquake occurred in western Tottori prefecture, southwest Japan (e.g. Ohmi *et al.*, 2002). Figure 2(a) shows the hypocenter distribution of the aftershocks of the Western Tottori earthquake together with DLF earthquakes in the region. Precisely relocated aftershocks within 6 months after the mainshock (Ohmi, 2002) and the DLF events that occurred 1999–2004 from the JMA catalogue are plotted. DLF earthquakes were observed at depths of around 30 km. A fault model derived from the coseismic crustal movements (Sagiya *et al.*, 2002) is also plotted on Fig. 2(a). The strike, dip, and rake angles of the fault model derived by Sagiya *et al.* (2002) is (152°, 86°, −7°). The fault dips slightly westward and the DLF earthquakes are located around the downward extension of the fault. Five DLF earthquakes were detected within 3 years before the mainshock and the activity increased after the mainshock (Fig. 2(b)). Figure 2(b) shows the temporal gaps in the DLF activity. We suppose the gaps are due to detection difficulties during the intense aftershock activity soon after the mainshock and high ground noise level in the winter time caused by the seasonal wind in this region. Since the signals of DLF events are small, they are easily obscured in the background noise.

2.2 Observed features in the waveforms

The DLF events in the western Tottori region exhibit several types of features in the waveforms. Figure 3 shows typical examples of the waveforms. Type-1, shown in Fig. 3(a), is most commonly observed. Ohmi and Obara (2002) summarized the observed feature of the waveforms of the Type-1 events as follows; (1) Predominant frequency is 2 Hz–4 Hz, although they are not monochromatic events, (2) Both P- and S-waves are observed with S-waves having larger
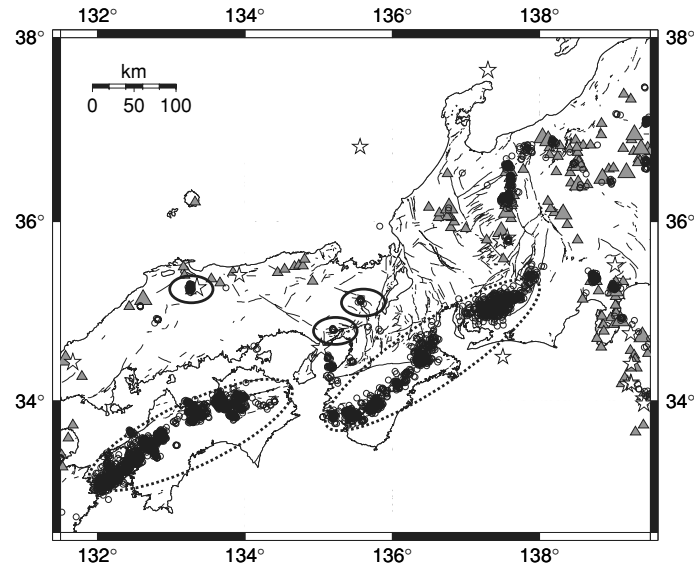
Fig. 1. Hypocenter distribution of low-frequency events in southwest Japan from the catalogue of the Japan Meteorological Agency (JMA) from January 1999 to July 2004. Large and small triangles represent active and Quaternary volcanoes while solid lines represent active faults. Low-frequency tremors along the Nankai trough (dotted ovals) and examples of deep low-frequency events associated with active faults (solid ovals) are shown. Stars represent large earthquakes (M≥6.0) that occurred from 1983 to 2003.
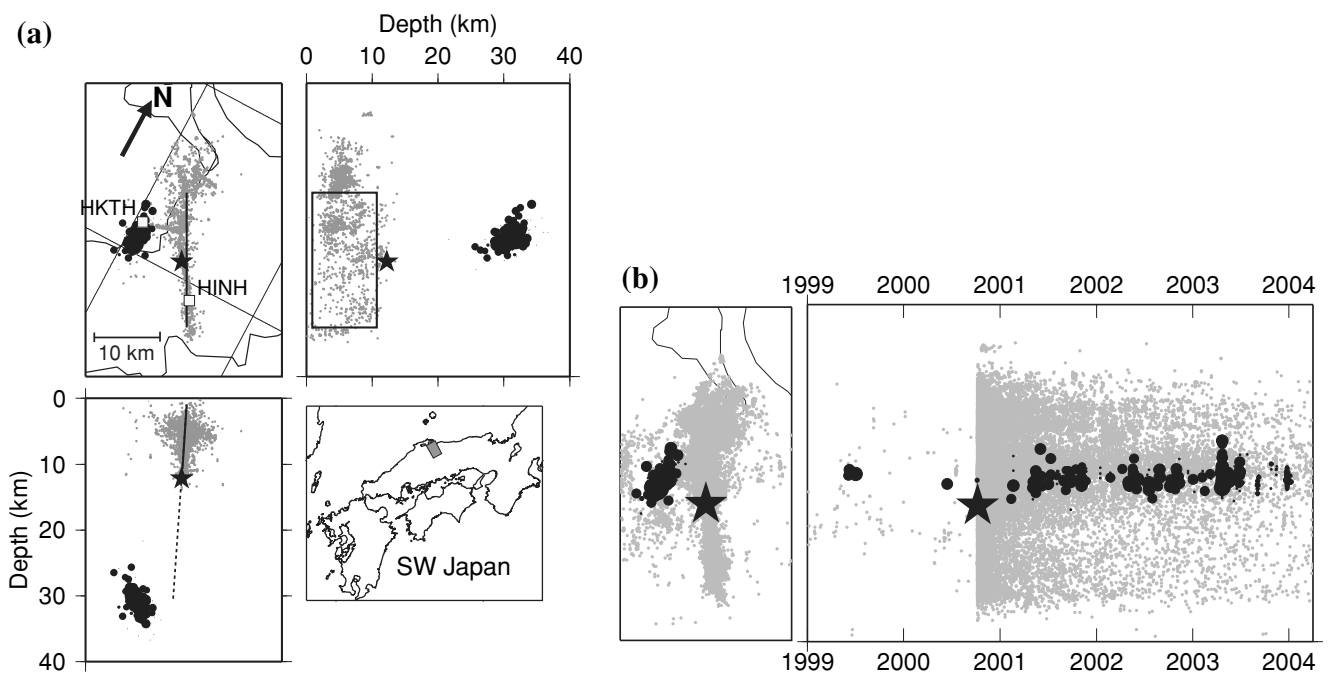

Fig. 2. (a) Hypocenter distribution of the deep low-frequency earthquakes (solid) together with ordinary shallow earthquakes (grey). Hypocenters of shallow earthquakes (grey dots) precisely relocated by Ohmi (2002) from October 2000 to March 2001 are plotted. DLF earthquakes (solid circles) are from the JMA catalogue from Jan 1999 to July 2004. Star denotes the hypocenter of the 2000 Western Tottori earthquake. Open squares denote the seismic stations. Solid line and square represent the fault model of the mainshock obtained by Sagiya *et al.* (2002). (b) Space-time plot of the DLF earthquakes (solid circles) together with ordinary earthquakes (grey dots) from January 1999 to March 2004. Hypocenters from the JMA catalogue are plotted.

amplitudes, and (3) Duration are one minute or longer, and in some cases they exhibit durations of several minutes. The magnitude of the Type-1 events is usually less than 1.5. Figure 3(b) shows an example of Type-2 events, which has larger P-wave onsets compared to those of Type-1 events. The magnitude of Type-2 events is between 1.9 and 2.5, slightly larger than that of Type-1 events. We will discuss

this feature in the next section. Figure 3(c) shows an example of a tremor type event observed in April 2003. This is a continuous record for 1 hour, that exhibits a continuous tremor-like feature for several tens of minutes. Figure 3(d) is a magnitude-time diagram of the DLF events showing the time sequence of the three types of events. Type-1 events have been observed throughout the period, whereas Type-2

events are observed only after mid-2002. The only Type-3, or tremor-like, event was observed in April 2003.

2.3 Preliminary investigation of the source

Ohmi and Obara (2002) analyzed the focal mechanism of one of the Type-1 events that occurred 9 hours before the mainshock. They concluded that a single-force source mechanism is more preferable than ordinary double-couple source model, which suggests transports of fluid such as water or magma.

Type-2 events have been observed since mid 2002 and have large amplitudes and long durations in the P-wave on-set portion (compare Figs. 3(a) and 3(b)). First we tried to estimate the source time function of the Type-2 events using a deconvolution method (e.g. Mori and Frankel, 1990; Mueller, 1985). In this analysis, we assumed that they are caused by shear faulting. We chose a smaller ordinary earthquake as an empirical Green function and deconvolved its seismogram from the seismogram of the target events. This procedure removes the path and site effects from the recording of the target events and the result represents the apparent source time function. The small earthquake is usually chosen close to the target event so that they share nearly common ray paths. However, in the case of the western Tottori, it is difficult to choose a small event near the DLF events since no ordinary earthquakes occur in the focal region of the DLF events. Therefore, we assumed that the heterogeneity of the medium is localized in the upper crust, and chose a small earthquake in the upper crust so that they share the ray paths between the focus of the small event and the seismic station. Figure 4 show the original waveform of the Type-2 events analyzed (Fig. 4(a)) and the corresponding deconvolved displacement waveforms (Fig. 4(b)). Once the source time function is obtained, we can calculate the seismic moment from the area of the source pulse and the fault radius from the rise time of the source pulse (e.g. Boatwright, 1980). Figure 4(c) plots the moment against the source dimension with lines of constant stress drop. The lines of constant stress drop are calculated following Kanamori and Anderson (1975). Since the stress drop of ordinary earthquakes are between 0.1 MPa and 100 MPa (e.g. Abercrombie and Leary, 1993), it is obvious that the stress drop of the DLF events are extremely low. This suggests the existence of weak materials, such as a fluid saturated gauge zone, which cannot sustain the stress at the fault interface. This is another indication of fluid activity at the focal zone of the DLF events.

The Type-3 event is a tremor-like event observed in April 2003 that continues for several tens of minutes. This activity lasted for about three days. In the Nankai and the Cascadia subduction zones, episodic slip at the plate interface is observed associated with tremor activity. In both areas, the cause of the tremor is attributed to the fluid activity (Obara and Hirose, 2004; Rogers and Dragert, 2003). Thus it is again possible evidence of fluid activity near the deeper portion of the fault in the western Tottori. We examined the tilt data in the region if the associated slip of the fault is observed. We applied the BAYTAP-G program (Tamura *et al.*, 1991) to the original tilt data in order to remove the tidal effects and the response of atmospheric pressure. Figure 5(a) shows the tilt changes around the fo-
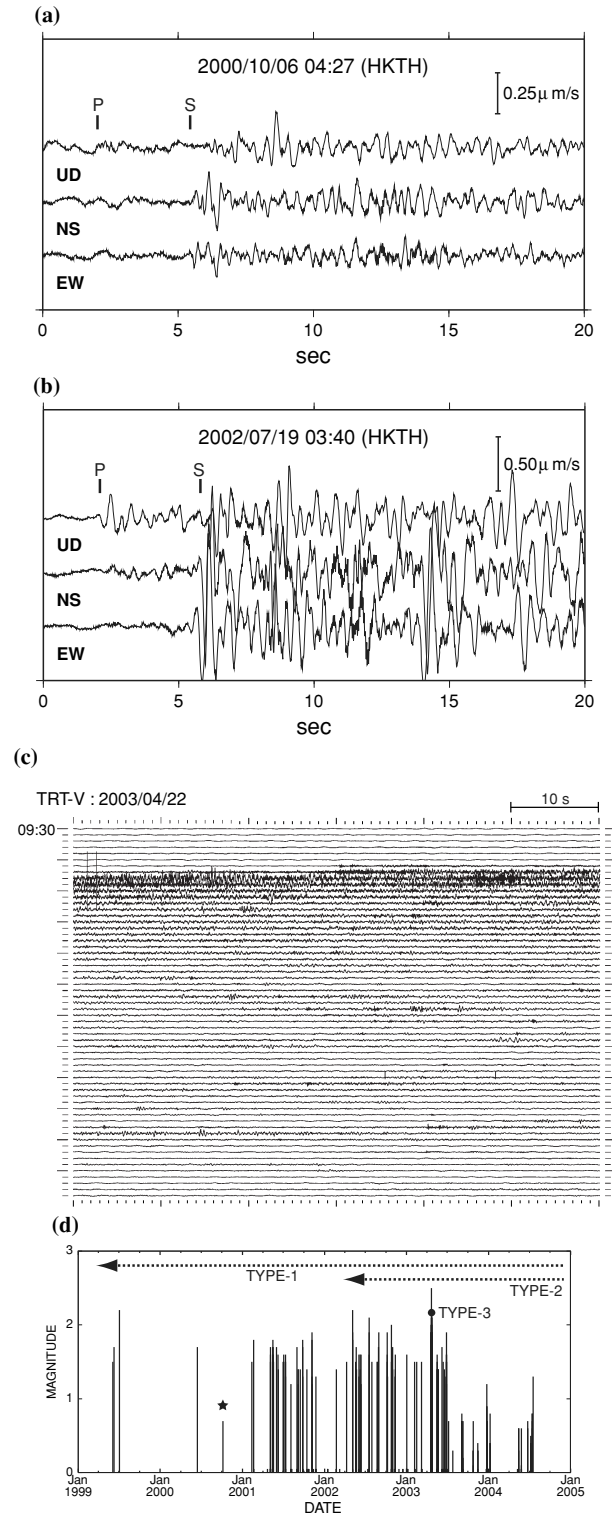

Fig. 3. (a) Example of three component seismograms of the TYPE-1 DLF earthquakes observed at station HKTH on 2000/10/06. Magnitude of the DLF earthquake is 0.8. (b) Example of three component seismograms of the TYPE-2 DLF earthquakes observed at station HKTH on 2002/07/19. Magnitude of the event is 2.1. (c) Vertical component seismogram of the continuous tremor-like events (TYPE-3) observed at station TRT. TRT is located about 20 km south of the epicentral area of the DLF events (see Fig. 5(b)). Continuous seismogram from 2003/4/22 09:30 to 10:30 JST is shown. (d) Magnitude-time diagram of the DLF earthquakes from January 1999 to July 2004. TYPE-1 events have been observed throughout the period, while TYPE-2 events have been observed since mid 2002 and TYPE-3 events (tremor) were observed only once. The mainshock of the 2000 Western Tottori earthquake is denoted by a solid star.
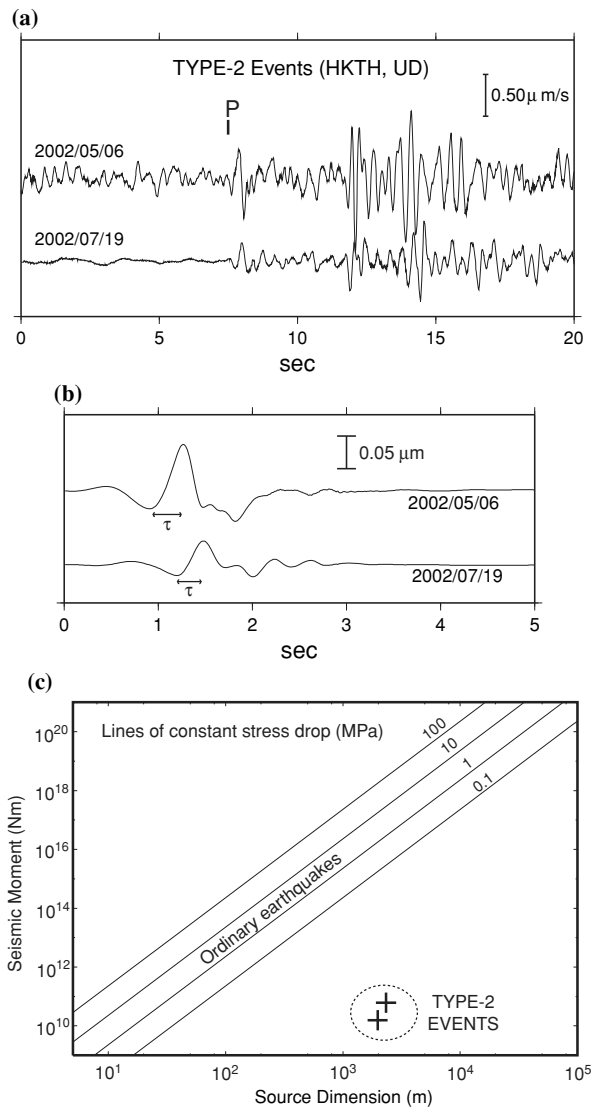
(a)

(b)

(c)

Fig. 4. (a) Examples of observed waveform of the TYPE-2 events. Vertical component seismograms observed at station HKTH are shown. (b) Corresponding deconvolved displacement waveforms. Small ordinary earthquake was chosen as an empirical Green function and deconvolved from the seismograms shown in Fig. 4(a). τ is the rise time for calculating the source dimension. (c) Relation between source dimension and seismic moment of the TYPE-2 events with lines of constant stress drop. The lines of constant stress drop are calculated following Kanamori and Anderson (1975).

cal region of the Western Tottori earthquake. However, it is difficult to detect tilt changes of more than 1.0×10^{-7} radian associated with the intense tremor-like DLF activity. Additionally, we estimated the upper limit of the slip that may cause tilt changes. We assumed the geometry of the fault model of Sagiya *et al.* (2002) with various amount of slip and calculated the associated tilt change by the formula of Okada (1992). Figure 5(b) shows the tilt pattern due to 1.3 cm slip on the whole fault plane (this slip is equivalent to Mw=5.2), which causes a tilt change of 1.0×10^{-7} radian at station HKTH. We conclude that no slip larger than this magnitude occurred associated with the tremor activity in April 2003.
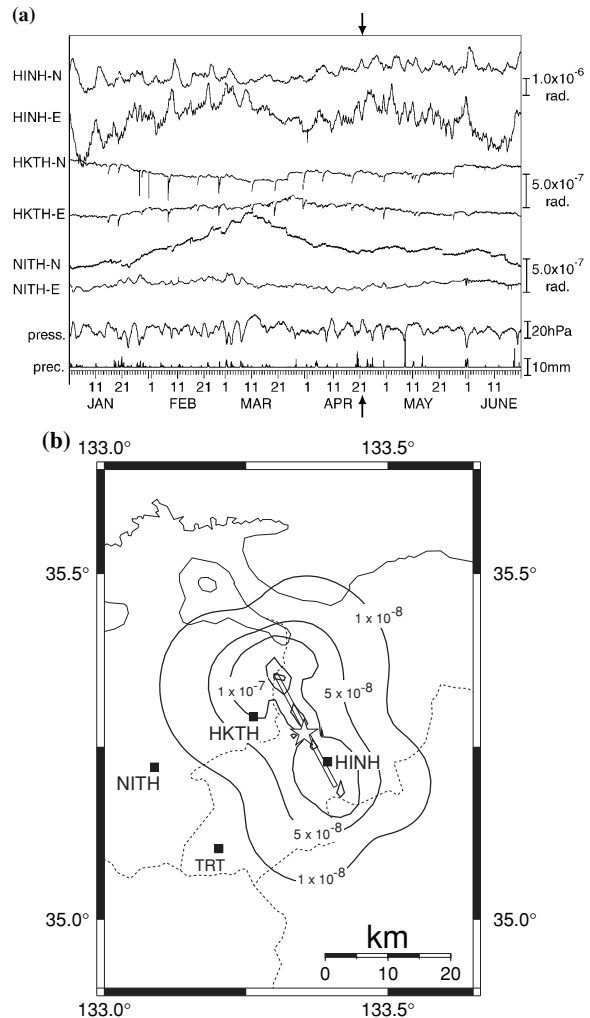
(a)

(b)

Fig. 5. (a) Tilt change in the western Tottori region from January 2003 to June 2003. High sensitivity accelerometer (tiltmeter) records obtained at stations HINH, HKTH, and NITH were analyzed. For the distribution of the stations, see Fig. 5(b). Tidal effect and response of the atmospheric pressure were removed using the BAYTAP-G program. Arrows indicate the period when the continuous tremor-like seismic signal was observed. (b) Calculated tilt change due to a 1.3 cm slip on the fault plane model of the Western Tottori earthquake (Sagiya *et al.*, 2002), which causes the tilt change of 1.0×10^{-7} radian at station HKTH. The contours represent the tilt change in units of radians.

3. Discussion and Conclusion

As we described, observed features of DLF events in the western Tottori suggest fluid activity in the focal region of the events. One of the Type-1 events exhibits a single-force type source mechanism that indicates transports of fluid. Since they are isolated events, they are likely episodic movement of fluids. Type-3 events exhibit long durations which likely indicate the continuous transport of fluid in the focal region. On the other hand, Type-2 events may be shear faulting with partially fluid saturated materials at the fault plane, that causes low stress drops compared to the ordinary earthquakes.

There are several other geophysical observations that support this idea. Seismic tomography analysis (Zhao *et al.*, 2004) indicates the existence of a low-velocity body at depths from the lower-crust to the upper-mantle in the focal region of the DLF events in the western Tottori region.
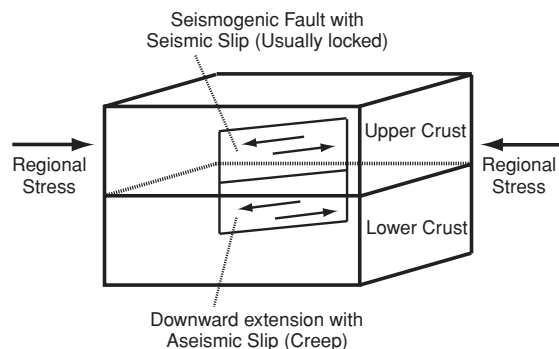
Fig. 6. Schematic cartoon of the downward extension of the seismogenic fault proposed by Iio and Kobayashi (2002). Downward extension of the fault in the lower crust plays an important role to accumulate stress on the seismogenic fault in the upper crust.

The electrical resistivity structure (Oshiman *et al.*, 2003) exhibits low resistivity regions that also may indicate the fluid activity in the focal region.

Doi *et al.* (2003) obtained the three dimensional distribution of the S-wave reflectors beneath the focal region of the Western Tottori earthquake. They detected four reflective layers at different depths, located at (a) 8–13 km, (b) 16–23 km, (c) 28–37 km, and (d) 50–60 km. Reflective layers are attributed to fluid reservoir in some cases. Umino *et al.* (2002) detected a reflective layer beneath the Nagamachi-Rifu fault, northeastern Japan, concluding that the layer is partially filled with fluids. Doi *et al.* (2003) shows the existence of an area of high reflectivity as a part of layer (c), that corresponds to the focal region of the DLF events. Although Doi *et al.* (2003) did not obtain the internal structure of the reflective layer (c), it is likely the reservoir of fluids that is indicated by the DLF activity.

Recent studies (e.g. Iio and Kobayashi, 2002) proposed that seismogenic faults have downward extension in the lower crust, where aseismic slip accumulates stress on the seismogenic faults in the upper crust and controls the occurrence of the earthquake. Figure 6 is a schematic cartoon of the model. Hypocenters of the DLF earthquakes discussed in this paper are distributed around the deeper extension of the shallow aftershock distribution and probably located on the downward extension of the seismogenic fault of the Western Tottori earthquake. It is important to understand the nature of DLF events beneath active faults, in relation to the behavior of fluids in the lower crust that might affect the aseismic slip of the downward extension of the seismogenic faults and control the occurrence of the shallow crustal earthquakes.

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