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Tomoko Watanabe

Graduate School of Natural Science and Technology, Kanazawa University

Kakuma, Kanazawa, Ishikawa 920-1192, Japan

E-mail: tomoko@hakusan.s.kanazawa-u.ac.jp Phone: +81-76-264-6519

Yoshihiro Hiramatsu

Graduate School of Natural Science and Technology, Kanazawa University

Kakuma, Kanazawa, Ishikawa 920-1192, Japan

E-mail: yoshizo@hakusan.s.kanazawa-u.ac.jp Phone: +81-76-264-6519

Kazushige Obara

National Research Institute for Earth Science and Disaster Prevention

3-1, Tennodai, Tsukuba, Ibaraki 305-0006, Japan

E-mail: obara@bosai.go.jp   Phone: +81-29-863-7626

Abstract

We investigate a duration-amplitude relation of non-volcanic deep low-frequency (DLF) tremors in the Tokai region, southwest Japan, to constrain the source process of the tremors. We apply two models to the distribution, one is an exponential model as a scale bound distribution and the other a power law model as a scale invariant distribution. The exponential model shows a better fit to the duration-amplitude distribution of the tremors than a power law model, implying that the DLF tremors are caused by a scale-bound source process. The source process of the DLF tremors, therefore, differs from those for earthquakes. We suggest that the non-volcanic DLF tremor is possibly caused by a fixed source dimension with variable excess pressure of fluid or variable stress drop.

Introduction

Continuous movement of tectonic plates causes great earthquakes repeating on plate interfaces. Not only coseismic and postseismic phenomena but also interseismic ones are important keys to understand and to construct a physical model of the whole earthquake process.

Recent seismological and geodetic observations from dense networks have revealed characteristic phenomena in the interseismic period in subduction zones, non-volcanic DLF tremors (*Obara*, 2002; *Katsumata and Kamaya*, 2003; *Rogers and Dragert*, 2003), very low-frequency earthquakes (*Obara and Ito*, 2005; *Ito and Obara*, 2006) and slow slip events (SSE) (*Hirose et al*., 1999; *Dragert et al*., 2001; *Ozawa et al*., 2002; *Obara et al*., 2004).

Sources of the tremors, first noted by *Obara* (2002), show a beltlike distribution of about 30-40 km in depth, parallel to the strike of a subduction zone where the transition from unstable to stable slip may occur at the plate interface. One of the interesting features of the tremors is a spatial and temporal correlation with SSE found in Cascadia (*Rogers and Dragert*, 2003; *Kao et al*., 2006) and in the southwest Japan (*Obara et al*., 2004; *Hirose and Obara*, 2005, 2006; *Obara and Hirose*, 2006). This coincidence proves the importance of the tremor as a real-time indicator of the occurrence of slip on the plate interface because a slip event could trigger a large subduction thrust earthquake (*Rogers and Dragert*, 2003).

DLF events in volcanic areas are considered to occur mainly due to the migration of magmatic fluid (*Chouet*, 1996). The cause of non-volcanic DLF tremors is suggested to be associated with fluid (*Obara*, 2002), hydroseismogenic processes (*Kao et al*., 2006), or shearing at the interface (*Rogers and Dragert*, 2003; *Shelly et al*., 2006) or in a deformation zone across the interface (*Kao et al*., 2006). Their source process has, however, remained unknown.

The scaling or frequency of occurrence versus size distribution usually reflects a physical process of phenomena in nature. For example, the frequency-size distribution of earthquakes is well described by a power law (e.g. *Ishimoto and Iida*, 1939; *Gutenberg and Richter*, 1954). On the other hand, the amplitude scaling of volcanic tremor is described by an exponential law rather than a power law (*Aki and*

Koyanagi, 1981; *Benoit et al.*, 2003), indicating that a unique length scale is involved in the source process of volcanic tremors.

In this paper, we examine the duration-amplitude distribution of non-volcanic DLF tremors in the Tokai region, in order to provide an important physical constraint on the source process of the tremors.

Data

We use continuous waveform data recorded by a nationwide high-sensitivity seismograph network (Hi-net) (*Obara et al*., 2005) with an average station interval of 20km across Japanese Islands operated by National Research Institute for Earthquake Science and Disaster Prevention (NIED). We select 40 non-volcanic DLF tremors with large amplitudes and durations larger than one minute that have occurred in the Tokai region from January 2002 to June 2006 (Figure 1). The hypocenters of these events are reported by the Japan Meteorological Agency (JMA) and their magnitudes (M_{JMA}) are greater than 0.7. Most of tremors we analyzed here include several JMA events whose magnitudes are smaller than 0.6. In this case we use the hypocenter location of the largest event. We select five Hi-net stations in the Tokai region, Asahi (ASHH), Asuke (ASUH), Horai (HOUH), Shidara (STRH), Tukude (TDEH) (Figure 1), that provide high S/N waveform data of the tremors.

Estimation of the amplitude-duration distribution

In order to examine the amplitude-duration distribution, we convert the observed tremor amplitudes to reduced displacements. We apply the band-pass filter of 2-10Hz and the moving average with the time window of 6s for root-mean-squared (RMS) ground displacement. The reduced displacement is RMS ground displacement corrected for the geometrical spreading and those units are distance×amplitude (m^2) (*Aki and Koyanagi*, 1981). Because a non-volcanic DLF tremor is mainly composed of S waves (*Obara*, 2002; *Rogers and Dragert*, 2003), we calculate the reduced displacement using the following formula for body waves (*Aki and Koyanagi*, 1981),

$$D_R = \frac{A \cdot r}{2\sqrt{2}}, \quad (1)$$

where A is the RMS ground displacement and r the distance between a source and a receiver.

To determine the frequency-size distribution of discrete events such as earthquakes, we usually count events of a particular size and plot their numbers versus their size. Non-volcanic DLF tremor is, however, a continuous signal, so that we use tremor durations to determine the frequency of occurrence for the tremors. The tremor duration at a particular amplitude or greater is measured using the procedure of *Benoit et al.* (2003) (Figure 2). We count the duration of amplitudes that are greater than 0.2×10^{-4} m^2 in this study.

We fit both the exponential model and the power law model to the duration-amplitude distribution of the tremors. The exponential model is expressed as

$$d(D_R) = d_t e^{-\lambda D_R}, \quad (2)$$

where D_R is the amplitude, d is the total duration of tremor with amplitudes greater than or equal to D_R, λ is the slope of the line or scaling parameter, and d_t is the prefactor. The power law model is expressed as

$$d(D_R) = d_t (D_R)^{-\gamma}, \quad (3)$$

where γ is a modulus and represents the slope of the line, similar to the *b*-value for earthquakes.

Scaling relationship between duration and amplitude of non-volcanic DLF tremors

For the duration-amplitude distribution of non-volcanic DLF tremors, the exponential model seems to be a better fit than the power law model (Figure 2). We compare the correlation coefficients for both models to quantitatively estimate the goodness of fit. For most events, the exponential model shows larger correlation coefficients (Figure 3). This result is independent of whether a tremor corresponds to a single JMA event or multiple JMA events. The average of correlation coefficients (R^2) is 0.953 for the exponential model and 0.851 for the power law model. We calculate *p*-value of *t*-test to examine a significance of the difference between two mean values statistically. The *p*-value of *t*-test is 6.945×10^{-10}, indicating that the difference in correlation coefficients between the exponential model and the power law model is statistically significant. We, therefore, consider that the exponential model is better than the power law model to describe the duration-amplitude of the tremors. The average value of λ, the slope of the line for the exponential model, is $5.7 \pm 3.1 \times 10^4$ m^{-2}. This value is larger than that of volcanic tremors reported by *Benoit et al*. (2003).

The duration-amplitude distribution may be, however, affected by the length of the time window of the moving average. We apply other two time windows, 3s and 12s, for RMS of the reduced amplitude to check the effect of the length of the time window (Figure 4). For the both cases, we confirm that the exponential model is better than the power law model to describe the distribution. We also confirm that the band width has no effect on the result.

Implication of source process of non-volcanic DLF tremors and Conclusions

The duration-amplitude distribution of non-volcanic DLF tremors in the Tokai region is well described by the exponential model, not the power law model as in earthquakes. The exponential model requires the source process to be scale bound rather than scale invariant. The same result was obtained for the duration-amplitude distribution of volcanic tremors (*Aki and Koyanagi*, 1981; *Benoit et al.*, 2003). They interpreted that the source process of volcanic tremor involved a unique scale length such as the average size of conduits or resonators.

The location of non-volcanic DLF tremors in the bottom of continental crust near the inferred locations of slab dehydration suggests that tremor source mechanisms may involve the movement of fluid in conduits or cracks. Furthermore, tremor sources are clustered near regions of high V_P/V_S ratios, thus strengthening the connection to fluids (*Kurashimo and Hirata*, 2004; *Matsubara et al*., 2005; *Shelly et al*., 2006; *Kao et al*., 2006). We, therefore, suggest that the exponential duration-amplitude distribution of the tremors in the Tokai region indicates a characteristic scale in the tremor source process, such as the length of a fluid-filled crack.

We compare amplitude spectrums of the tremors whose magnitudes reported by JMA are from 0.3 to 1.0 to examine relations of the frequency and the event size. We recognize that both the frequency content and the dominant frequency are almost independent of the amplitude or the event size. This supports that the source of the tremors involves a unique length scale.

Shelly et al. (2006) indicated that precise locations of low-frequency earthquakes were on the plate interface by using a combination of waveform cross-correlation and double-difference tomography. They proposed that low-frequency earthquakes might be generated by local slip accelerations at geometric or frictional heterogeneities that accompanied large slow slip events on the plate interface. *Rogers and Dragert* (2003) also suggested that for tremors observed in Cascadia a shearing source seemed most likely. Long-duration tremor may, therefore, be a superposition of many concurrent low-frequency earthquakes or a combined signal of shear slip and fluid flow (*Shelly et al*., 2006; *Kao et al*., 2006).

If a non-volcanic DLF tremor is the superposition of many low-frequency earthquakes, an exponentially decaying waveform such as the coda of a low-frequency earthquake may be a cause of the exponential scaling. *Benoit et al*. (2003) checked this possibility by examining the duration-amplitude distribution using a series of synthetic low-frequency earthquakes with a power law distribution. The duration-amplitude distribution calculated for the synthetic tremor followed a power law scaling. This result showed that an exponential duration-amplitude scaling was never reproduced through the superposition of many low-frequency earthquakes closely spaced in time if the size-distributions of the low-frequency earthquakes obey a power law. A power law scaling of regular earthquakes is the consequence of the constant stress drop and the power law distribution (L^3) of the product of a fault area and a fault slip. A variation in the stress drop with a fixed source dimension might generate the exponential distribution if the continuous tremors are the result of the superposition frequently excited intermittent.

The exponential scaling of non-volcanic DLF tremors concludes that the source process of the tremors is different from that of regular earthquakes that obey the power law distribution. We, therefore, suggest that the non-volcanic DLF tremor is possibly caused by a fixed source dimension with variable excess pressures of fluid or variable stress drops.

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Figure captions

Figure 1.

The distribution of tremor epicenters (solid circles) and the Hi-net stations (solid squares). Open circles are tremors and dots are regular earthquakes shallower than 60km and M2.0 and greater during 2001-2005 reported by JMA.

Figure 2.

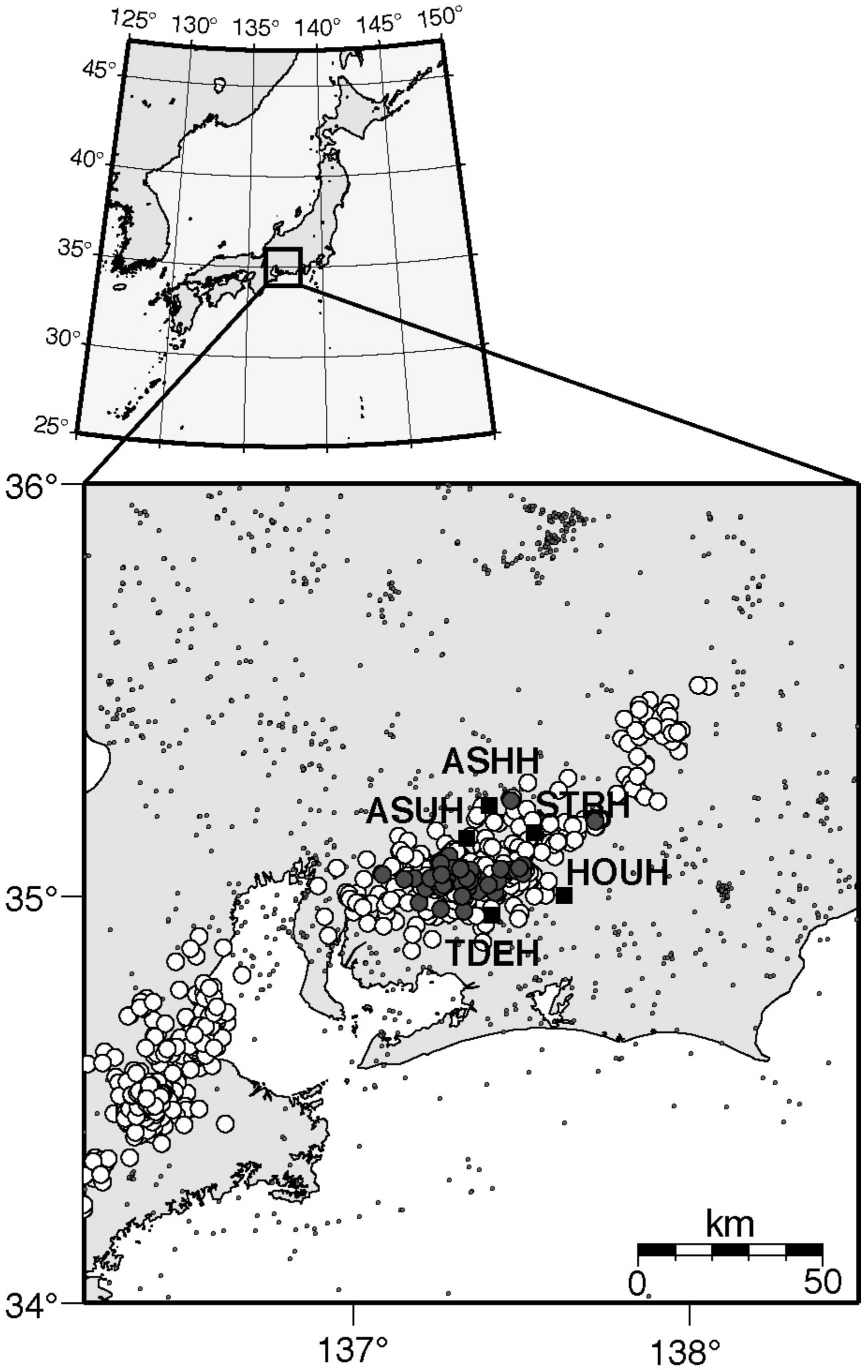
Measurements of the duration-amplitude distribution of non-volcanic DLF tremors using (a) the exponential model and (b) the power law model for each station. The duration at a particular amplitude or greater (open circles) measured in the window between the dashed lines of (c). Gray lines show the best fits to the models. R^2 shows the correlation coefficient. (c) Envelope waveforms of the reduced displacement for each station. The noise level is 0.2×10^{-4} m^2.

Figure 3.

The distribution of correlation coefficient R^2 for the exponential and power law models.

Figure 4.

Envelope of waveforms and duration-amplitude distributions for non-volcanic DLF tremors with the moving time window of 3s, 6s and 12s, respectively. The duration-amplitude distribution is not affected by the length of the time window of the moving average.



125°
130°
135°
140°
145°
150°
45°
40°
35°
30°
25°
36°
35°
34°
137°
138°
ASHH
ASUH
STBH
HOUH
TDEH
km
0
50

Figure 1

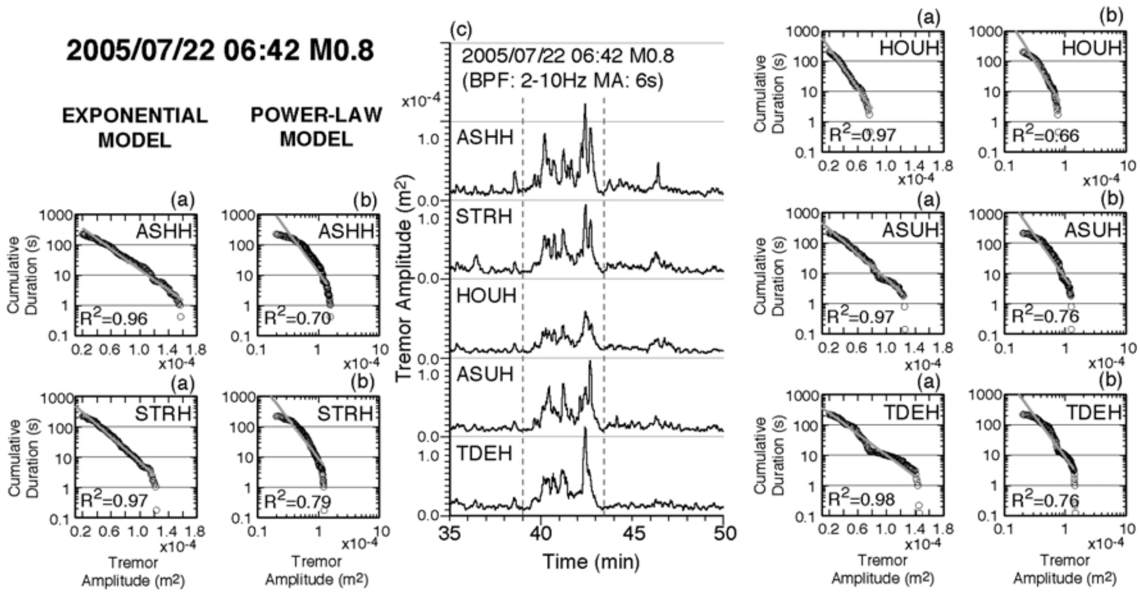

2005/07/22 06:42 M0.8
EXPONENTIAL MODEL
POWER-LAW MODEL
(a)
(b)
(c)
ASHH
STRH
HOUH
ASUH
TDEH
R^2=0.96
R^2=0.70
R^2=0.97
R^2=0.79
R^2=0.66
R^2=0.76
R^2=0.98
Cumulative Duration (s)
Tremor Amplitude (m^2)
2005/07/22 06:42 M0.8
(BPF: 2-10Hz MA: 6s)
Time (min)

Figure 2

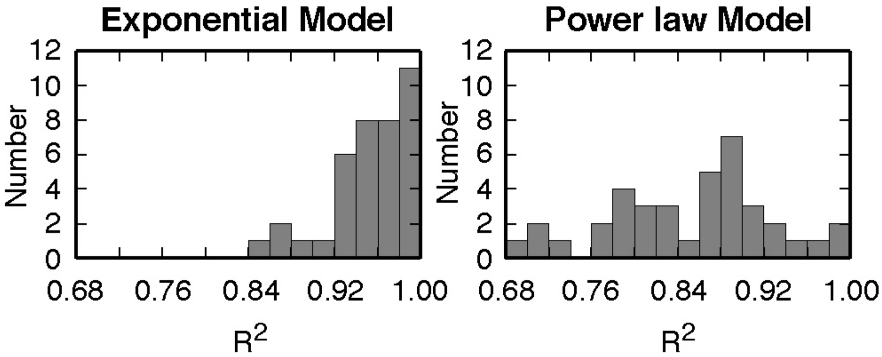

Exponential Model
Power law Model
Number
0
2
4
6
8
10
12
0.68
0.76
0.84
0.92
1.00
R^2

Figure 3

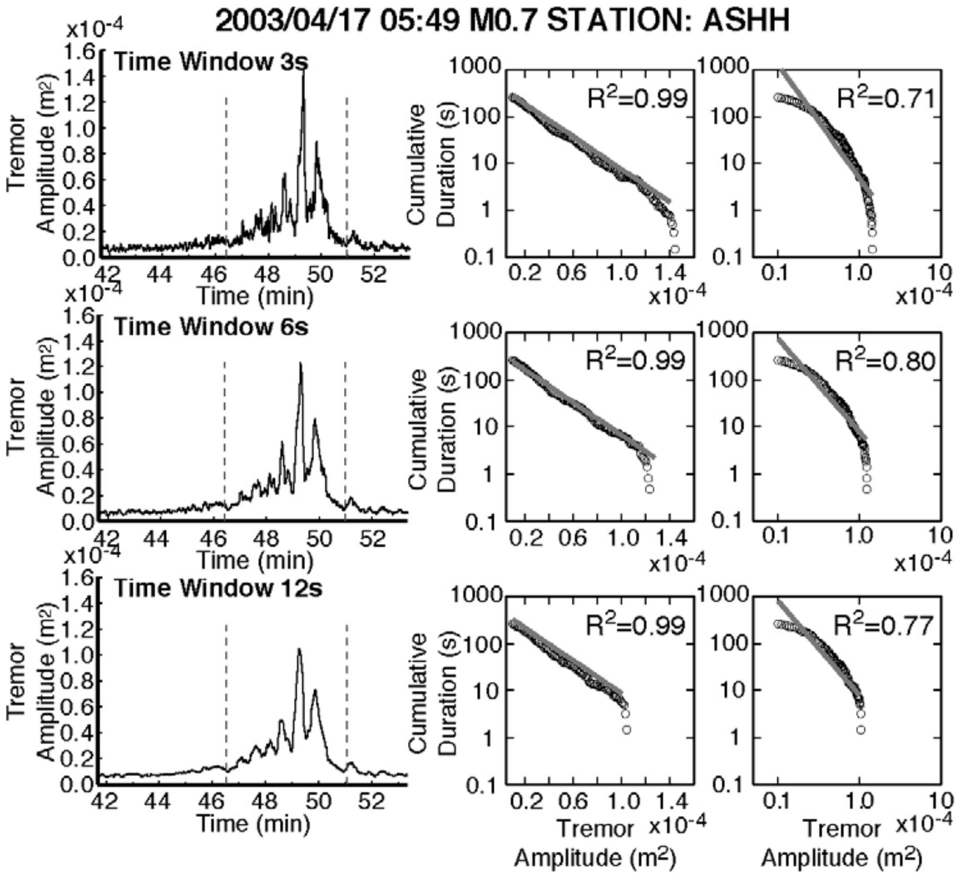

2003/04/17 05:49 M0.7 STATION: ASHH
Time Window 3s
Time Window 6s
Time Window 12s
Tremor Amplitude (m2)
Time (min)
Cumulative Duration (s)
Tremor Amplitude (m2)
R2=0.99
R2=0.71
R2=0.99
R2=0.80
R2=0.99
R2=0.77

Figure 4