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Frictional property of plate interface east off NE Japan inferred from spatial variation in *b*-value

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Abstract

Simultaneous evolutions of AE activity on a pre-cut fault and frictional properties of the fault with sliding were observed in a laboratory. The evolutions are probably due to brittle evolution of fault surfaces. It is reported in literature that the *b*-value of shallow earthquakes east off NE Japan varies with distance from the trench-axis. Because the distance from the trench-axis is regarded as a displacement of the subducting slab, the *b*-value variation is considered to be a similar phenomenon to the evolution of AE activity in the laboratory. The spatial variation of the *b*-value is examined to estimate the upper limits of the unstable region on the plate interface. The depths of estimated upper limits are 20 km on average, and vary laterally to depict unstable regions estimated from other seismological and geodetic evidence. The present study suggests that detailed analyses of high-quality seismic data provide useful information about the mechanical properties of the plate interface.

Key words: AE activity, *b*-value, frictional property, plate interface

1. Introduction

It is believed that a substantial amount of sliding occurs aseismically on the plate interface east off NE Japan. Pacheco *et al.* (1993), for example, reported that the average seismic slip rates in this subduction zone are as small as 18% of the average convergence rates of relative plate motions estimated for global plate models. Further, Miura *et al.* (1993 a, b) and Kawasaki *et al.* (1995) examined strain data obtained by extensometers in some observation vaults, finding significant postseismic deformations associated with Off-Sanriku earthquakes of 1989 (M7.1) and 1992 (M6.9), which suggest that aseismic sliding followed the respective earthquakes. Nishimura *et al.* (2000) analyzed GPS data for 1 year after the 1994 Far-Off-Sanriku earthquake (M7.5), to show that aseismic sliding on the plate interface may explain postseismic GPS data. The occurrences of aseismic sliding following large earthquakes mean not only low seismic coupling in this region, but also spatio-temporal complexity of sliding behavior. Because the complexity should be caused by inhomogeneity of mechanical properties and stress states on and around the plate interface, it is important to examine spatial variations in frictional properties of the interface.

Spatio-temporal variations in *b*-value in the Gutenberg-Richter's relation are sometimes understood in relation to variations in stress states around a fault (e. g., Wiemer and Wyss, 1997). Laboratory observations, however, show that the frictional properties of a fault also relate to the *b*-value variations (Yabe, 2002). In the present study, spatial variations in frictional properties of the plate interface east off NE Japan are investigated from spatial variations in *b*-value by applying laboratory observations.

2. Data Analyses and Results

2. 1 Experimental Observations

Experiments were carried out to examine evolutions of AE activity and frictional properties associated with abrasive wear of sliding surfaces. Details of the experiments are described by Yabe (2002). I briefly introduce them below. A granite sample with a pre-cut fault was loaded by a direct-shear appara-

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tus to generate stable sliding along the pre-cut fault. The normal stress applied to the fault was about 5

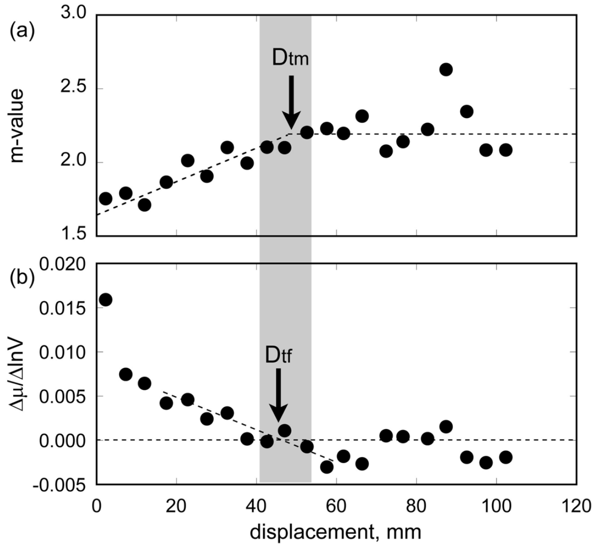

Fig. 1. Evolutions of (a) the *m*-value and (b) the rate-dependence parameter of friction observed in a laboratory experiment. Shaded area indicates displacements within which the *m*-value becomes stable and the rate-dependence parameter of friction transits from positive to negative.

MPa. Sliding rate was 1–100 μm/s, which was changed stepwise by a factor of 2–10 every 0.5–1 mm of sliding. Cumulative displacement applied to the fault was several to 10 cm. An example of the experimental observations relating to the present objects is shown in Figure 1 and is summarized as follows: (1) The *m*-value of Ishimoto-Iida's relation was determined from the amplitude distribution of AE events for steady sliding, finding that it linearly increases with sliding until the cumulative displacement reaches a transition displacement, D_{tm} (Figure 1 a). After D_{tm}, the linear relation breaks down. (2) The rate-dependence parameter of the friction coefficient for steady sliding, which is equivalent to (*a*-*b*)-value in rate-and state-dependent friction laws, takes a positive value (velocity hardening) at initial sliding and decreases with sliding to become negative (velocity weakening) at a transition displacement, D_{tf} (Figure 1 b). (3) Two transition displacements, D_{tm} and D_{tf}, are almost equal to each other.

2. 2 Application to Seismic Data

Figure 2 (a) shows the *b*-value distribution of

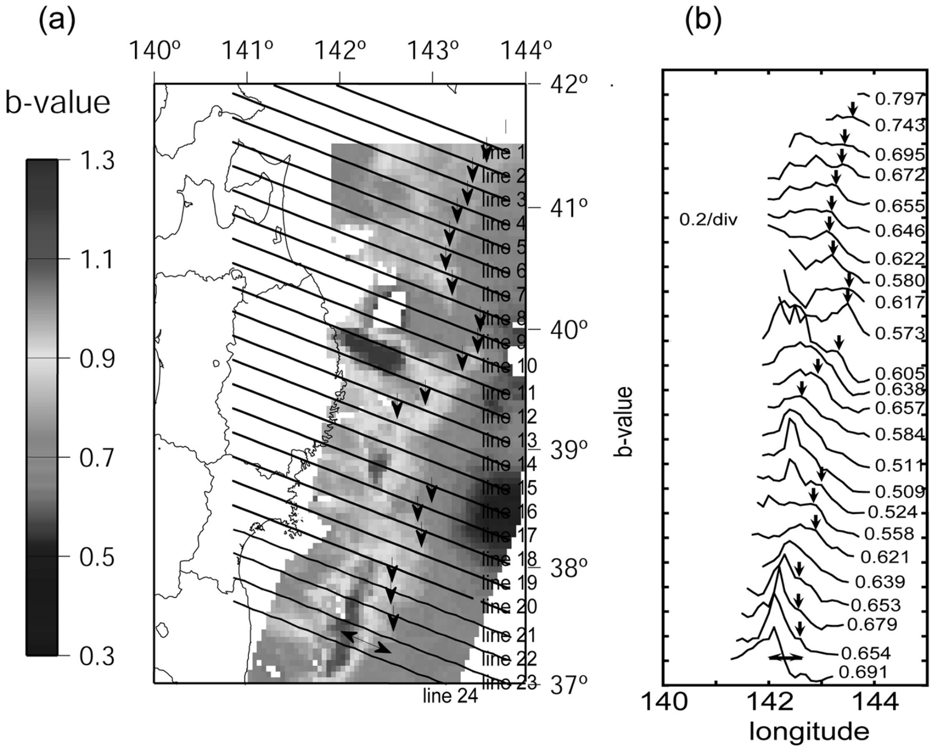

Fig. 2. (a) Spatial variations in *b*-value on the plate interface east off NE Japan determined by Hirose *et al.* (2002) for earthquakes with a magnitude larger or equal to 2.8 from 1981/1/1 to 2001/10/31. (b) Variations in *b*-value along profile lines in (a). The profile lines are taken parallel to the relative plate motion direction. Numerals attached are the *b*-values at the eastern ends of the respective profile lines. Arrows denote transition points.

shallow earthquakes east off NE Japan determined by Hirose *et al.* (2002) using seismic data for the past 20 years. Asperities determined by Yamanaka and Kikuchi (2002, in preparation) and Okada *et al.* (2001) were found to exist in regions with a locally small b-value. They claimed that the locally small b-value region is a representation of highly stressed asperity. It is pointed out, however, that the b-values near the trench-axis are small relative to those near the east coast of NE Japan. Stress acting on the plate interface near the trench-axis should be low due to low confining pressure and probably unconsolidated fault gauge. That is, a small b-value does not always indicate a highly stressed asperity.

Figure 2(b) shows the b-value variations along profile lines in Figure 2(a) taken along the relative plate motion direction. Because distance from the trench axis measured along the plate interface in the relative plate motion direction can be regarded as a cumulative displacement of subducting slab, the figure shows the evolution of the b-value with sliding. The evolution of b-value is similar to that of the m-value observed in the laboratory presented in Figure 1. A linear increase in the b-value with distance from the trench-axis is clearly observed, for instance, along lines 3–10 and it breaks down at the point indicated by the arrow. It is proposed that the transition points of b-value behavior correspond to the upper limits of the unstable region on the plate interface. That is, the eastern side of the transition points is velocity-hardening (aseismic or stable) region, while the western side is velocity-weakening (seismic or unstable). The ambiguity of the transition point location should be 30–50 km, because it is a typical value of spatial resolution of b-value, except for regions quite close to the trench-axis.

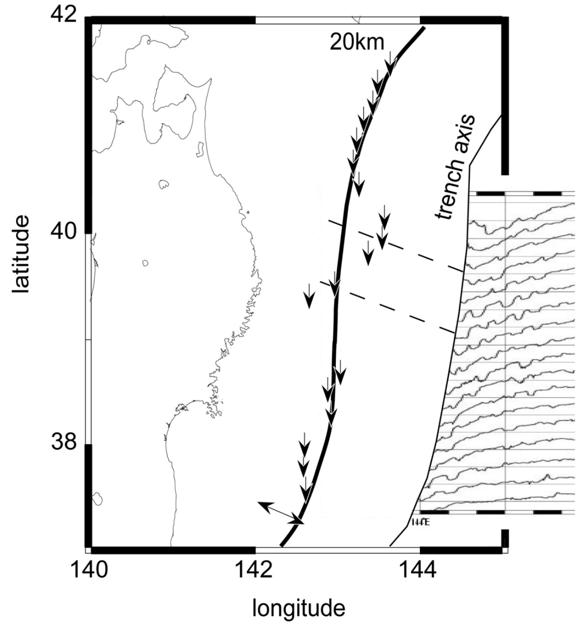

Fig. 3. Comparison between the distribution of transition points (arrows) and sea bottom topography of pre-subducting slab (eastern side of the trench-axis) measured by Hydrographic and Oceanographic Department, Japan Coast Guard. The thick solid line indicates the 20 km isodepth line of the plate interface. Dashed lines indicate the direction of relative plate motion.

3. Discussions

3.1 Depths of transition points

The thick solid line in Figure 3 represents the 20 km isodepth line of the plate interface. Many of the transition points are on this line. It is known in this region that the dip angle of the subducting slab becomes steeper at this depth (Unimo *et al.*, 1995). Further, Moho of the overriding plate is about 20 km in depth near the interface (Takahashi *et al.*, 2000; Ito, 2000; Miura *et al.*, 2000). The b-value behavior on the interface may be partly affected by these structural inhomogeneities, in addition to depth variations in pressure and thermal conditions. However, variations in transition point depth cannot be explained by them.

Marone (1998) compiled previous studies on the evolution of frictional properties, and pointed out that D_{tf} is scaled by a characteristic length of fault surfaces or gouge thickness. Spatial variations in the surface topography of the subducting slab along the trench-axis are a possible cause of depth variations in transition points. Sea bottom topography (SBT) near the trench-axis is shown in Figure 3. It seems that the SBT of the pre-subducting slab in 39 N-39.5 N is richer in short wavelength components than the remaining parts. When we assume that the surface topography of the subducting slab is similar to the SBT of the pre-subducting slab, it is understood as the roughness dependence of D_{tf} that the transition points around 39.5 N-40 N, to which the SBT in 39 N-39.5 N is subducting as indicated by the dashed lines, are shallower than the other parts. It is suggested from these considerations that a possible mechanism of the transition is topographical evolution of fault surfaces.

3. 2 Comparison with other evidence

Figure 4 represents asperities of large earthquakes ($M>7$) for the past 70 years determined by Yamanaka and Kikuchi (2002, in preparation) from strong ground motions. No asperity is determined along the 39N line where the stable region seems to extend to a greater depth than the other parts. Persistent asperity is found around (40 N, 143 E). The transition point depth is decreased to trace the upper edge of the asperity. Further, it can be stated by considering the ambiguity of the transition point location that the asperities generally exist at the western side of the transition points. Because the asperities are considered to be strongly unstable regions, the correlation between asperity distribution and variations in transition point depth may *a posteriori* justify the application of laboratory observation to seismic data.

Figure 5 shows the back-slip distribution on the plate interface determined by Nishimura *et al.* (2002) from GPS observations. The back-slip occurs inhomogeneously and is concentrated in two regions around (40.5 N, 143.5 E) and (38.0 N, 142.5 E). Note that a peak around (42.0 N, 144.5 E) is an artifact due to an edge effect of the model fault. The spatial resolution of the back-slip estimation is ~70 km. Although it is difficult to reach a clear conclusion due to the relatively low resolution of both estimations of back-slip distribution and transition points, the transition points seem to delineate eastern margin of regions with a large back-slip.

The transition point distribution is generally consistent with the seismological and geodetic evidence, suggesting that the microscopic process of frictional sliding on the plate interface is similar, at least phnomenologically, to those on laboratory fault.

4. Summary

It was found that the *b*-value of shallow earthquakes east off NE Japan linearly increases with distance from trench-axis, and that the linear rela-

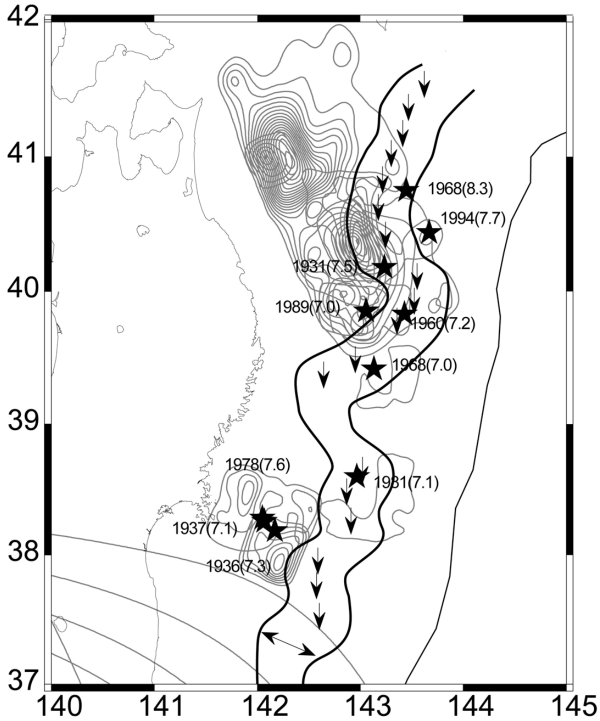

Fig. 4. Comparison between distributions of transition points (arrows) and asperities (contour) determined by Yamanaka and Kikuchi (2002, in preparation). Thick lines represent error of transition point location. Stars indicate epicenters of large earthquakes for the past 70 years.

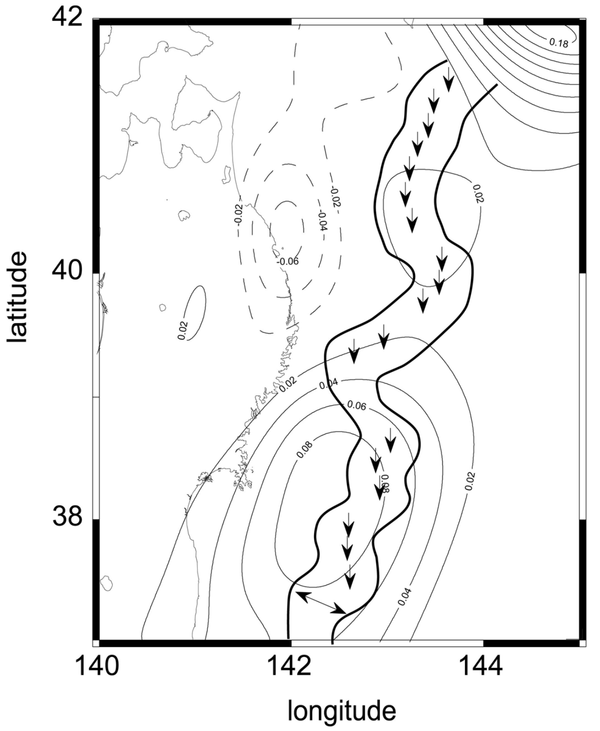

Fig. 5. Comparison between distributions of transition points (arrows) and back-slip for an interseismic period (1996/4–1999/3) estimated from GPS observations (Nishimura *et al.*, 2002). Contour interval is 2 cm/yr. Dashed contours represent forward-slip. Thick lines represent error of transition point location.

tion breaks down at a transition point. The average depth of transition points is about 20 km, suggesting structural inhomogeneity in addition to depth variations in pressure and thermal conditions may be partly responsible for the transition. The lateral variation of the depths, however, cannot be explained by them. A laboratory experiment on simultaneous evolutions of AE activity and frictional properties shows that the transition takes place at the upper limit of the unstable region on the interface. If this can be applied to the plate interface, the variation in transition point depth can be understood as an effect of surface roughness on transition displacement. It is then proposed that the transition of *b*-value behavior indicates the transition of frictional property from velocity hardening to velocity weakening. The estimated distribution of transition points seems to be consistent with other seismological and geodetic evidence. This may *a posteriori* justify the interpretation of the transition.

The present study suggests that detailed analyses of spatio-temporal variations in seismicity using high quality seismic data may provide useful information about mechanical properties of plate interface.

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