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Temporal variation of seismic *b*-values beneath northeastern Japan island arc

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[1] Analysis of a high quality seismic catalog reveals that the average of seismic *b*-values in the crust beneath most part of northeastern Japan island arc decreased from 0.86 between 1984 and 1990, to 0.73 between 1991 and 1995. The two areas with the largest decrease are found to be in the same areas where the coupling between the North American and the Pacific plates is the highest, as suggested by a recent geodetic study. In the same time period, the annual seismic moment release increased by 10 times. In addition, there seems to be a corresponding increase in volcanic activities in the same area. One of the most likely interpretations for the observations is an increase in the subduction rate starting from 1991. The timing of this possible increase in subduction rate is consistent with an apparent increase in global seismic activity. *INDEX TERMS:* 7230 Seismology: Seismicity and seismotactonics; 7209 Seismology: Earthquake dynamics and mechanics

1. Introduction

[2] Determination of spatial and temporal variations of plate motion rates along plate boundaries is essential for the understanding of plate dynamics and for practical applications such as earthquake hazard mitigation. During the past two decades, spatial variations in plate motion rates have been well-established for most of the plate boundaries on the Earth through intensive geodetic studies. Temporal variations of tectonic movements, however, have received much less attention, mostly due to the lack of data sets that are suitable for detecting such variations. The variations can either be identified directly through careful analysis of high-quality geodetic data [e.g., *Gao et al.*, 2000], or indirectly by studying their consequences, such as changes in volcanic activities, seismic *b*-values, moment release, and focal mechanisms [*Romanowicz*, 1993; *Press and Allen*, 1995]. Because of the co-existence of a dense regional seismic network, a world-class geodetic network, high seismic and volcanic activities, and numerous seismological, geodetic, and geological studies, NE Japan area is one of the few places on earth to search for temporal variations in tectonic movement. Geological and seismological studies suggest that the lithosphere beneath NE Japan island arc is an area of horizontal compression related to the subduction of the Pacific plate, with the maximum principal axis being horizontal and orthogonal to the trench, and the minimum principal axis being vertical [*Sato*, 1994; *Wesnousky et al.*, 1982]. The subduction rate is estimated at about 10 cm/year [*Hasegawa et al.*, 2000]. In this paper we report a possible tectonic transient occurred beneath NE Japan island arc around 1991. The transient likely caused simultaneous temporal variations in seismic *b*-values, seismic moment release, and possibly volcanic activities.

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[3] The empirical relation between the frequencies and magnitudes of earthquakes proposed by *Gutenberg and Richter* [1954] is that

$$\log N(M) = a - bM \tag{1}$$

where a and b are constants, M is the magnitude, and $N(M)$ is the number of earthquakes in a specific time window in the magnitude range $M \pm \delta M$. The coefficient b is the *b*-value, an important parameter of seismicity. Rock fracture experiments indicate that the *b*-value is primarily a function of applied stress with high stress corresponding to low *b*-values [*Mogi*, 1962; *Scholz*, 1968]. This conclusion is supported by numerous field observations such as those in Taiwan [*Wang*, 1988] and along the Circum-Pacific subduction zones [*Carter and Berg*, 1981]. Measurements of well-pressure, number of triggered earthquakes, and *b*-values in the Denver waste water injection site revealed that high shear stress corresponds to low *b*-values and high seismic moment release [*Evans*, 1966; *Healy et al.*, 1968; *Wyss*, 1973]. This mechanism for the temporal variations of *b*-values has been used to explain *b*-value changes prior to major earthquakes in Japan and elsewhere [*Imoto*, 1991]. Decrease in effective stress due to dehydration is thought to be the cause of the observed high *b*-values in the Alaska and New Zealand subduction zones at the depth of about 95 km [*Wiemer and Benoit*, 1996].

2. Data, Method, and Results

[4] The earthquake catalog that we used is from the Tohoku University (TU) seismic network for the period of January 1, 1984 to March 31, 1995. A total of 243,458 events were detected for the area between 35°N and 46°N, and 137°E and 147°E. During this time period the number of stations was stabilized at about 50 and no significant changes were made in the operating parameters [*Umino and Sacks*, 1993]. We remove the aftershocks by replacing each earthquake cluster by an equivalent event using the declustering procedure proposed by *Reasenberg* [1985]. The declustered catalog contains 201,160 events, which is a 17% reduction in the number of events.

[5] The maximum likelihood method [*Aki*, 1965] is used to calculate the *b*-value, i.e.,

$$b = \frac{\log e}{\overline{M} - M_c} \tag{2}$$

where M_c is the magnitude cut-off, and $\overline{M}$ is the average magnitude of a group of earthquakes with $M \geq M_c$.

[6] Figure 1 indicates that the completeness magnitude of the shallow (0–30 km) events for both the land and ocean areas is about 2.3–2.5, which is similar to that from several previous studies using the same catalog [e.g., *Umino and Sacks*, 1993; *Huang et al.*, 1997; *Wyss et al.*, 2001].

[7] We calculate *b*-values in successive time windows. For each time window, we choose $M_c = 2.5$ as the starting cut-off magnitude and obtain the *b*-value and its standard deviation. Then we increase M_c in steps of 0.05 and calculate the *b*-value again. The final result

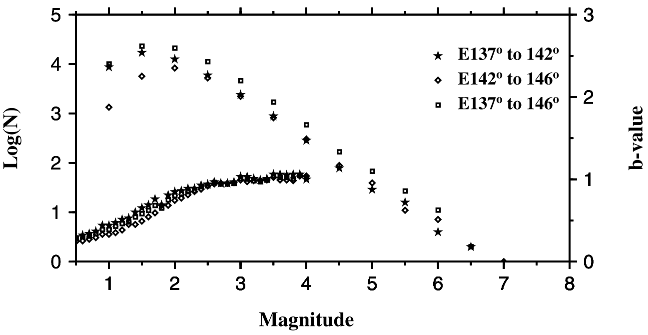

Figure 1. Plots of magnitude-frequency relation and *b*-values as a function of cut-off magnitude for shallow earthquakes. Stars are for events occurred in land area; diamonds are for the ocean area; and squares are for the entire area. Note that above magnitude 2.3–2.5, the *b*- values for both the land and ocean areas are stabilized, implying that the completeness magnitude is 2.3–2.5.

is taken as the one when the difference between the *b*-values in two neighboring steps is less than 0.03. For most of the time windows, the resulting M_c is equal to or slightly larger than 2.5.

[8] Figure 2a shows temporal variations of *b*-values calculated in successive 1-year time windows. The length of the steps between adjacent time windows is 30 days. The mean *b*-value decreases from 0.86 ± 0.01 for the period of 1984–1990, to 0.73 ± 0.02 for the period of 1991–1995.

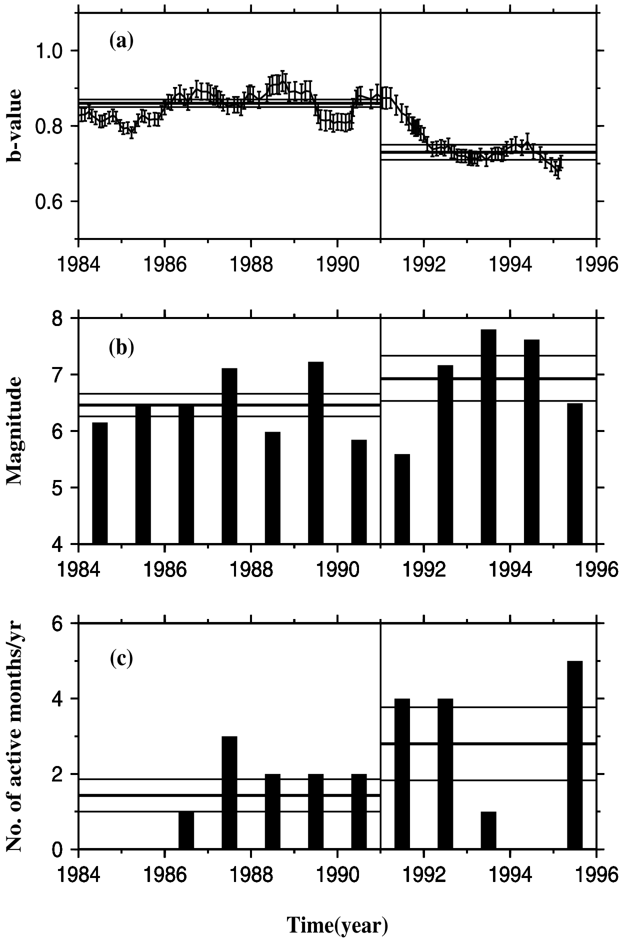

Figure 2. Temporal variations of (a) *b*-values, (b) equivalent magnitude per year, and (c) volcanic activities in the study area. The thick horizontal bars in each plot represent annual mean values, and the upper and lower thin horizontal bars represent mean + σ and mean-σ, respectively, where σ is the standard deviation of the mean.

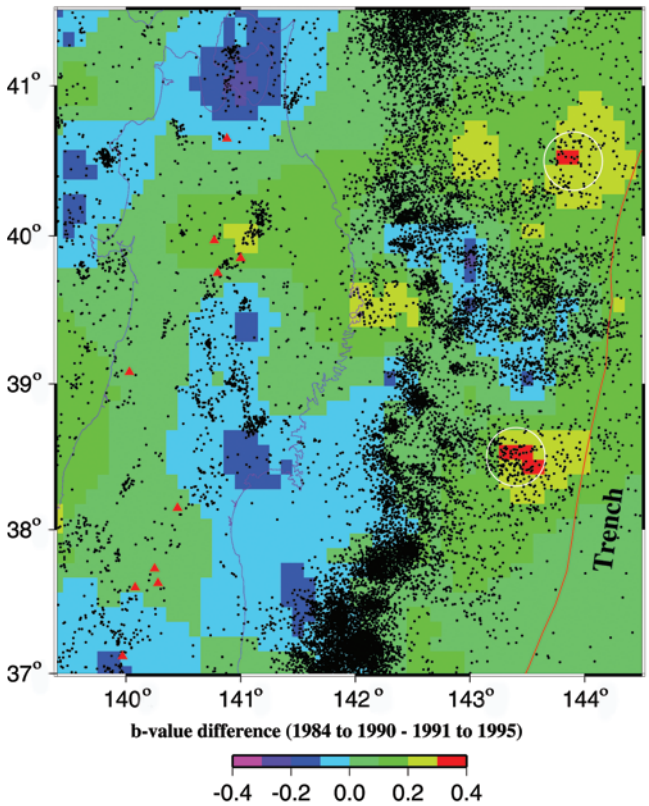

Figure 3. Spatial distribution of *b*-value variations between 1984–1990 and 1991–1995 in NE Japan and adjacent areas. Black dots are epicenters of shallow earthquakes used in the study, and red triangles are active volcanos.

3. Discussion

[9] Many factors can cause temporal variations in observed *b*-values. One of the most common factors is the change in network operating parameters and station density. Previous studies using the same catalog [*Huang et al.*, 1997] and personal communications with those who are responsible for the operation of the TU network found no evidence for such a change. Figure 3 shows the spatial distribution of *b*-value variations between the pre- and post-1991 periods. The size of the spatial windows is 0.5° × 0.5°, and that of the moving step is 0.25°. It is clear from Figure 3 that most of the study area contributed to the post-1991 decrease in *b*-values (Figure 2a). The two areas with the largest decrease are located at about 38.5°N and 40.5°N, respectively, and are about 50 km west of the trench. The two areas almost exactly co-site with the two areas where the coupling between the Pacific and the North American plates is the strongest, as suggested by a recent geodetic study [*El-Fiky and Kato*, 1999]. In those areas it is estimated that about 1/3 to 1/2 of the plate convergence rate along the Japan trench is accomplished by aseismic slip [*El-Fiky and Kato*, 1999], while in adjacent areas the value is about 2/3 [*Peterson and Seno*, 1984; *Pacheco et al.*, 1993].

[10] The decrease in *b*-values within the crust of the overriding plate implies an increase in the stress level during the post-1991 period. The fact that the areas with the largest *b*-value decrease are consistent with the areas with the strongest plate coupling, may suggest that the subduction rate between the Pacific and the North American plates in the study area increased during the time period

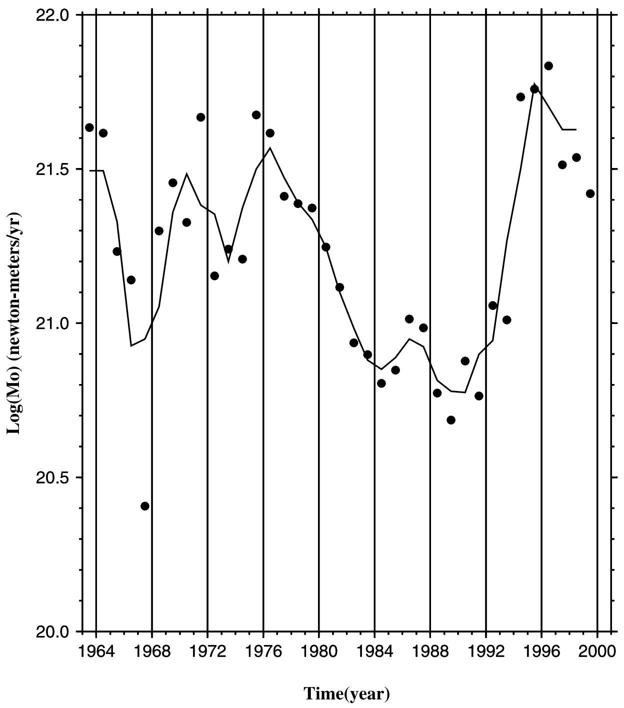

Figure 4. Temporal variation of global annual seismic moment release for the period of 1963 to 1999. The solid curve was obtained by smoothing the data using a 2-year time window. Note significant increase since 1991. Only earthquakes with magnitude $\geq$5.0 are used.

of 1991–1995. Due to the lack of direct geodetic measurements on the Pacific plate in the NW Pacific ocean, indirect measurements such as temporal variations in seismic moment release and volcanic activities can be used to test the hypothesis of an increase in subduction rate in 1991–95. Because both seismic and volcanic activities in the vicinity of subduction zones are the consequences of subduction, it is reasonable to assume that an increase in plate subduction rate may lead to increase in seismic moment release and volcanic activities. Figure 2b shows temporal variations of equivalent moment magnitude per year, which is calculated by summing the annual moment release of $M_w \geq 4.0$ earthquakes. Between 1984 and 1990, the mean magnitude is 6.46 ± 0.20, and between 1991 and 1995 it is 6.93 ± 0.40, which represent a 10-fold increase in moment release, from 2.08×10^{19} to 2.10×10^{20} Newton-meters. It is interesting to note that on a global scale, the seismic moment release began to increase in 1991, after a 10 year period of low seismic activity (Figure 4). The observed increase in seismicity and decrease in *b*-values in the study area could be a part of the significant change of global seismic activity. We use a database of volcanos compiled by the *Smithsonian Institution* [2000] to estimate the level of activity for the 10 volcanos in the study area (Figure 3). The database lists the time of volcanic events such as eruptions, steaming, and earthquake swarms. Figure 2c shows the number of months with clear volcanic events each year. In the period of 1984–1990, on average there are 1.43 ± 0.43 active months per year, while during 1991–1995 the value is 2.80 ± 0.97.

4. Conclusion

[11] We have detected a significant decrease of seismic *b*-values between 1991 and 1995 relative to those between 1984 and 1990 in the crust beneath NE Japan island arc. The change in *b*-values is accompanied by increases in seismic moment release and volcanic activity. The two areas with the largest decrease are consistent with areas with the strongest coupling between the Pacific and North American plates. One of the possible causes for the changes is an increase in subduction rate along the subduction zone.

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