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

Aimin Cao and Stephen S. Gao
Kansas State University, Manhattan, Kansas, USA

Received 13 July 2001; accepted 5 November 2001; published 14 May 2002.

[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 seismotectonics; 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 to be 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 [Wiener 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.,

\[
b = \frac{\log e}{\bar{M} - M_c} \tag{2}
\]

where $M_c$ is the magnitude cut-off, and $\bar{M}$ 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
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.

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 $0.86 \pm 0.01$ for the period of 1984–1990, to $0.73 \pm 0.02$ for the period of 1991–1995.

3. Discussion

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 $0.5^\circ \times 0.5^\circ$, and that of the moving step is $0.25^\circ$. 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].

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
months per year, while during 1991–1995 the value is 2.80 ± 0.97.

period of 1984–1990, on average there are 1.43 ± 0.43 active
number of months with clear volcanic events each year. In the
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volcanos compiled by the
significant change of global seismic activity. We use a database of
and decrease in
low seismic activity (Figure 4). The observed increase in seismicity
improve the moment release, from 2.08 × 1019 to 2.10 × 1020
earthquakes. Between
Mw ≥ 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 × 1019 to 2.10 × 1020
Newton-
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
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

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.

Acknowledgments. We are grateful to the operators of the Tohoku seismic network at Tohoku University. Discussions with K. H. Liu and I. S. Sacks are greatly appreciated. This research was support by NSF grants EAR-0001000 and EPS-9874732 at Kansas State University.

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A. Cao and S. S. Gao, Department of Geology, Kansas State University,
Manhattan, KS 66506, USA. (acao@mars.geol.ksu.edu; sgao@ksu.edu)