

Inversion Analysis of Historical Interplate Earthquakes Using Seismic Intensity Data

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Summary

An inversion method has been developed to evaluate short-period seismic wave radiation zones on an earthquake fault plane using seismic intensity data. It is robust and widely applicable even for historical earthquakes without ground motion, tsunami and geodetic data observed by instruments. It is applied to the great interplate earthquakes whose source regions are called Nankai, Tonankai, Tokai, Kanto, Off Miyagi, and Off Tokachi. The earthquakes have occurred off the Pacific coast in Japan and have brought about severe damage repeatedly. The analytical results indicate that short-period seismic wave radiation zones are often adjacent to large slip areas, termed asperities, but don't always overlap them. They are sometimes located where fault rupture has stopped. Furthermore, They don't always repeat at the same location. Some of their fracture process may be attributed to crust structures.

1. Introduction

Huge interplate earthquakes have occurred in the Pacific coast in Japan and have brought about severe damage repeatedly. Fig.1 shows the Japanese map with major source regions to be discussed in this paper.

The source region along the Nankai Trough where the Philippine Sea plate is subducting beneath the Eurasian plate is one of the areas that attract attention most on disaster prevention these days. Three M8 class earthquakes have occurred in the Hoei, Ansei and Showa eras for three hundred years. The occurrence of a next earthquake is predicted in the early of 21st century. The source region of the 1923 Great Kanto earthquake was located in the east. Since there was much population in the vicinity of this area, it was one of the most disastrous earthquakes in the history.

Many interplate earthquakes have also occurred along the Japan and Kuril Trench in northern Japan, where the Pacific plate is subducting beneath the Eurasian plate. The earthquake off Miyagi-ken is predicted to occur in the near future with high probability, because its average occurrence interval is about 37 years and 26 year has passed since the latest event. The Off Tokachi earthquake just occurred last year. Although the danger on disaster prevention in the near future may be low, much data can be taken and it should be an important earthquake on research.

It is important on disaster prevention to investigate these earthquakes. The method on the estimation of strong ground motions using fault model has been developed significantly for ten years. As a method of presuming the focal process of an earthquake in the future, there is no realistic method except investigating the focal process of past earthquakes. Furthermore, it

is necessary to analyze as many earthquakes as possible to answer the question whether or not the same source mechanism of earthquakes in the same source region repeats in the future. However, since there was no ground motion, tsunami and geodetic data measured by instruments before modernization, the number of available earthquakes for the analysis is restricted.

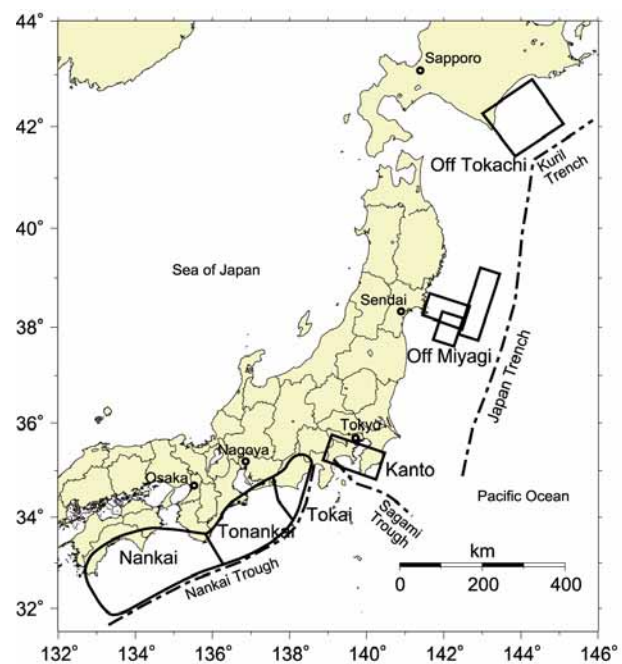


Figure 1. Source regions of the interplate earthquakes for the inversion analysis

An inversion analysis has been developed to

evaluate the distribution of radiation energy from an earthquake fault plane using seismic intensity data in JMA scale (Kanda *et al.*, 2003, 2004). There is much seismic intensity data not only for recent earthquakes but also for historical earthquakes in Japan. Some seismic intensity data were presumed from earthquake damage recorded in historical documents.

Fig.2 shows the overview of data processing and analysis pipeline for the inversion analysis using seismic intensity data. The relative intensity as an index for the local soil amplification and the distance attenuation formula of seismic intensity are evaluated using the measured seismic intensity data of moderate recent earthquakes near the source region. The attenuation formula used is expressed as:

$$I = -a \log(X_{eq}) + bM + c + I_{rel} \quad (1)$$

where a , b , c are constants estimated from the regression analysis for each region. A fault plane is modeled along the subducting plate boundary. Once energy E_i radiated from the i th sub-fault is given, the seismic intensity at an arbitrary point k can be calculated using the attenuation formula (1) with equivalent hypocentral distance X_{eq} and the relative intensity I_{rel} . X_{eq} is derived from the following equation (Ohno *et al.*, 1993):

$$X_{eq,k}^{-2} = \sum_i (E_i / X_{i,k}^2) / \sum_i E_i \quad (2)$$

In the inversion analysis, energy distribution on the fault plane is evaluated so as to minimize the estimated error of the seismic intensity using the least square method. The source area of concentrated energy where the radiation energy level is over a twice of the average is hereafter referred to as the short-period radiation zone.

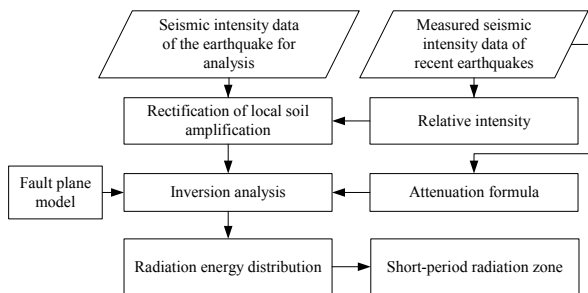


Figure 2. Overview of data processing and analysis pipeline

Fig. 3 shows the attenuation relation (M7.8) of seismic intensity evaluated for every source region. There is a little discrepancy of attenuation between the northern Japan and other regions. Seismic intensity in the northern Japan is somewhat large especially within 100km in hypocentral distance.

In the following sections, we introduce the short-period radiation zone evaluated from the

inversion analysis using seismic intensity data for the four source regions of subduction earthquakes, and discuss their characteristics.

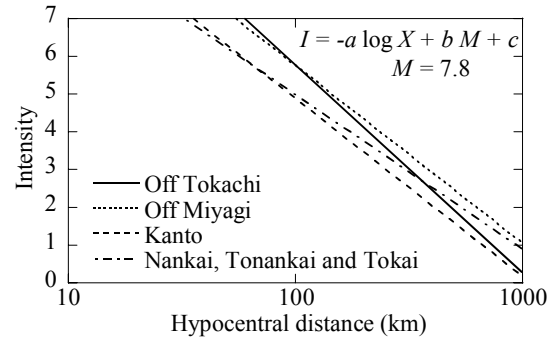


Figure 3. Comparison of the attenuation formula of seismic intensity (Eq.(1)) for every source region.

2. The Nankai, Tonankai and Tokai earthquakes

The earthquake for this source region occurring in the Showa era consisted two events. One occurred at the Tonankai region in 1944 and the other at the Nankai region in 1946. The 1854 Ansei earthquake fractured two regions with an interval of one day. One occurred at the Tonankai + Tokai regions and the other at the Nankai regions. The 1707 Hiei earthquake, however, fractured the whole regions almost simultaneously.

Fig.4 shows the comparison of isoseismal intensity area among the 1707 Hiei, 1854 Ansei, and 1944 & 1946 Showa earthquakes. The seismic intensity data of the Hiei and the Ansei earthquakes was evaluated from earthquake damage records from historical documents (Usami, 2003). As for the Showa earthquake data reported from JMA is used. It indicates that the Showa earthquake was smaller than the others and that the Hiei earthquake was quite larger especially in the west region so that more than intensity 6.0 (6+) area existed.

Fig.5 shows the contour map of relative intensity estimated from recent earthquakes occurring in the vicinity of the source region except shallow earthquakes. It shows the tendency that relative intensity is large in the plain and basin and is small in the mountain area.

Fig. 6 illustrates the short-period radiation zones along the Nankai Trough, compared with (a) slip distribution from waveform inversion and (b) crust structures. These zones are divided into six regions for the following discussion.

No.1 zone is located beneath the interior of Suruga Bay in case of the Hiei and Ansei-Tokai earthquakes, and is consistent with the collision point between the Suruga trough and Izu peninsula. It is suggested that the fault rupture might be rapidly stopped at the zone and strongly radiate short-period seismic waves.

No.2 zone is located off the Enshu Sea where the

Paleo-Zenisu Ridge has subducted. The short-period radiation zone appeared during every earthquake. Baba(2003) suggested, however, that this zone was not ruptured during the Showa-Tonankai earthquake, and that the Paleo-Zenisu Ridge inhibited rupturing. Short-period seismic waves might radiate where the Paleo-Zenisu Ridge acted as a barrier inhibiting the rupture.

No.3 zone is located beneath the Kumano Sea, where the asperity estimated from the tsunami (Baba, 2003) and strong motion waveform inversions (Kikuchi *et al.*, 2003) adjoins for the Showa-Tonankai earthquake. This short-period radiation zone appeared during every earthquake.

No.4 zone is located off Cape Shiono. It appeared during the Showa and Ansei earthquakes, when the area became an edge of fault segment. There is no short-period radiation zone at this area during the Hoi earthquake, when the both segments of Tokai and Nankai zone were ruptured successively.

No.5 zone is located at the entrance of the Kii Channel. It appeared during every earthquake. Cummins *et al.*(2002) suggested a possible tear in the slab beneath the western edge of the Kii peninsula. It

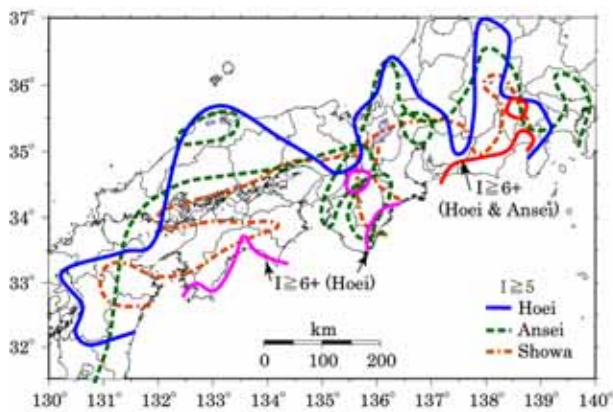


Figure 4. Comparison of isoseismal intensity area among the 1707 Hoi, 1854 Ansei, and 1944 & 1946 Showa earthquakes along the Nankai Trough (data courtesy of Usami).

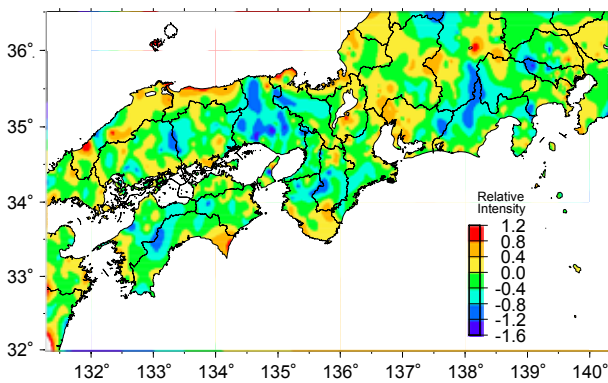


Figure 5. Relative intensity for the Nankai, Tonankai and Tokai earthquakes evaluated from measured seismic intensity data of recent earthquakes.

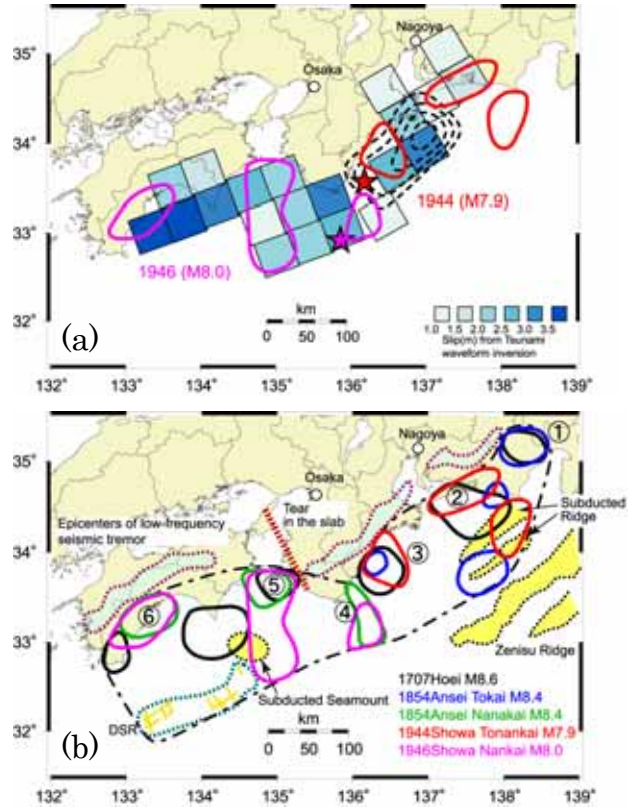


Fig. 6. Short-period radiation zones for the Nakai, Tonankai, and Tokai earthquakes for three hundred years (Kanda *et al.*, 2004). (a) Comparison with slip distribution from the waveform inversion in the case of the Showa earthquake. Stars represent the epicenters. Colored squares show slips more than 1m from tsunami data (Baba, 2003), and Dotted lines show slip contours from ground motions data (Kikuchi *et al.*, 2003). (b) Comparison with crust structures. Epicenter regions of low-frequency seismic tremor (Obara, 2002), a tear in-slab (Cummins *et al.*, 2002), a deep strong reflector (DSR) (Park *et al.*, 2002) and a subducted seamount (Kodaira *et al.*, 2002) are depicted in dotted lines.

seems that the tear was a boundary between Tonankai and Nakai fault rupture plane. It is remarkable that this short-period radiation zone is located so as to avoid the epicenters of deep low-frequency seismic tremors (Obara, 2002). A short-period radiation zone of the Hoi earthquake exists in the west of a subducted seamount. The fault rupture of the Hoi earthquake seemed to extend throughout the subducted seamount, though it might act a barrier to inhibit the propagation of an interplate rupture during the Showa and Ansei earthquakes. The rupture of a subducted seamount induced a large stress drop, increased slip speed, generated short-period seismic waves, and propagated to the deep landward edge. The structural role of the subducted seamount may explain that seismic intensities along the Pacific coast and in Osaka plain were quite larger than those of the Showa and Ansei

earthquakes.

No.6 is located around the west coast of Kochi and corresponds to the northwest end of the asperity from tsunami waveform inversion at the Showa-Nankai earthquake. Park *et al.*(2002) suggested that the deep strong reflector existed near the trench and acted as a possible releaser of the shear stress energy at the plate boundary and generated a steady state slip during the interseismic period. There was no short-period radiation zone near the Nankai Trough.

It is noted that short-period seismic wave radiation zones were often located in the vicinity of large slip areas, termed asperities, and were sometimes located at the area where fault rupture had stopped. Furthermore, They didn't always repeat at the same location. Their mechanism may be attributed to crust structures such as a subducted seamount and ridges.

3. The Kanto earthquake

The 1923 Kanto earthquake M7.9 occurred near metropolitan area and is famous for its huge damage. The casualties exceeded a hundred thousand.

Fig.7 shows seismic intensity distribution estimated from the collapse rate of wooden dwelling houses arranged per cities, wards, towns, and villages (Moroi and Takemura, 2002). The relation between seismic intensity and the collapse rate listed in the table of Fig.7 was determined based on the earthquake resistant performance of houses those days.

Fig.8(a) shows the contour map of relative intensity estimated from recent earthquakes occurring around the Kanto district except shallow earthquakes. Fig.8(b) shows the geologic time of surface soil layer. It is obvious that the relative intensity is closely related to the geology of surface soil layer. For instance, the area of high relative intensity almost corresponds with the lowlands colored in white as the Holocene. On the country, relative intensity is low on an old stratum such as mountains, plateau, and hill.

Wald and Somerville (1995) evaluated the slip distribution of the 1923 Kanto earthquake from the waveform inversion of geodetic data. We assume the same fault model, and implement the inversion analysis using the seismic intensity data shown in Fig.7.

Fig.9 shows the map view of short-period radiation zones obtained from the inversion analysis on the model fault. The distribution of slip from the waveform inversion using geodetic data by Wald and Somerville (1995) are shown by contour of broken lines. Contour interval is 1m. There were two short-period radiation zones. One was located in the east of the hypocenter and the other in the west of the Kazusa hill of Boso Peninsula. It is noted that both of them adjoined the southeast side of concentrated slip, and the east one was near the area where fault rupture had stopped.

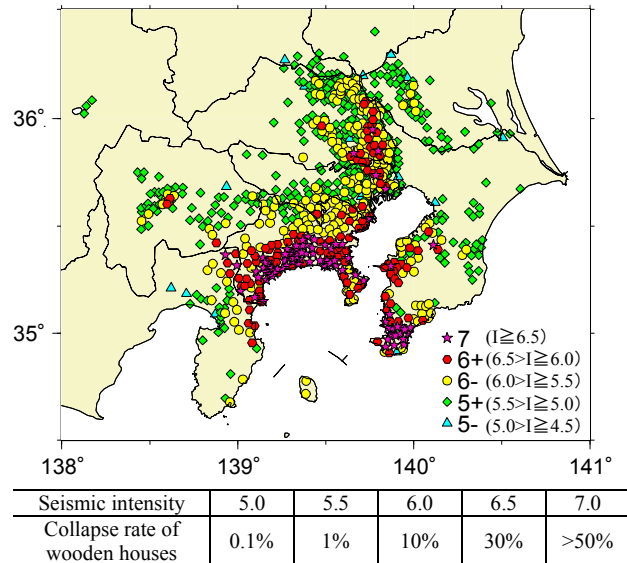


Figure 7. Seismic intensity distribution of the 1923 Kanto earthquake estimated from the collapse rate of dwelling houses (Moroi and Takemura, 2002).

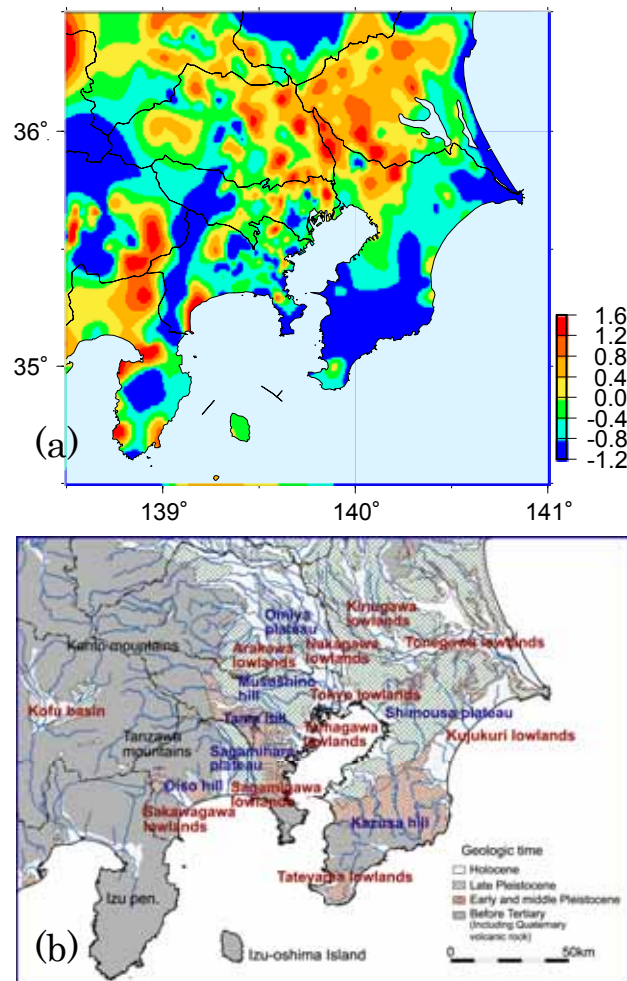


Figure 8. Map view of Kanto district: (a) relative intensity and (b) geologic time of surface soil layer. The relative intensity data are evaluated from measured intensity data of recent earthquakes around the Kanto plain.

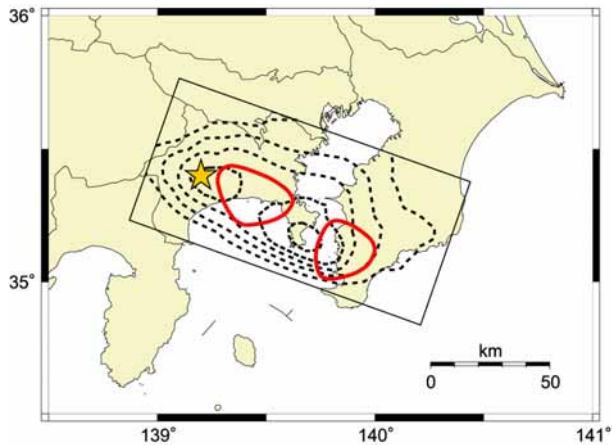


Figure 9. Map view of short-period radiation zone in the 1923 Great Kanto earthquake surrounded with red solid lines. A star shows the epicenter. A rectangle and dotted lines represent the fault plane and slip contour, respectively (Wald and Somerville, 1995).

4. The Off Miyagi earthquakes

M7.5 class interplate earthquakes called the Off Miyagi earthquake have repeatedly occurred with an interval of 30~40 years in the region near the land of the Miyagi offing. Furthermore, other types of earthquakes have occurred in the vicinity of this region. A deep in-slab earthquake (M7.1) occurred in May 2003, and a shallow inland earthquake (M6.4) occurred in July 2003. The occurrence of such kind of earthquakes may have interacted each other even if the source location and mechanism are different. It is important to grasp the pattern of source location and mechanism of past earthquakes in order to estimate ground motions of a future earthquake.

Fig.10 shows the map view of seismic intensity distribution of the Bunkyo earthquake in 1861 (end of Edo era) in the left figure, and relative intensity in the right figure. It is indicated that relative intensity is high along the Pacific Ocean side and is low along the Sea of Japan side of the Tohoku district. It may be related to Q-value crust structure of the Tohoku district. In this case, the relative intensity depends on not only the local site effect but also the wave propagation effect.

Fig.11 shows the map view of the short-period radiation zone for five earthquakes from the inversion analysis using seismic intensity data, and the slip contour of recent two events (Earthquake Research Committee, 2003). The source of the 1897/8/5 earthquake is supposed to be located near the Japan Trench according to the result. It may not be categorized into the Off Miyagi earthquake. The short-period radiation zones don't always overlap among earthquakes. Since the time interval is short compared to other subduction earthquakes, it may be

supposed that different asperities have slipped one after another. The short-period radiation zone of the 1978/6/12 earthquake shifts landward and that of the 1936/11/3 earthquake shifts southward from large slip area obtained from the waveform inversion. The direction of their shift almost corresponds to that of fault rupture. It means that each center of the short-period radiation zone was located at the area where fault rupture had stopped.

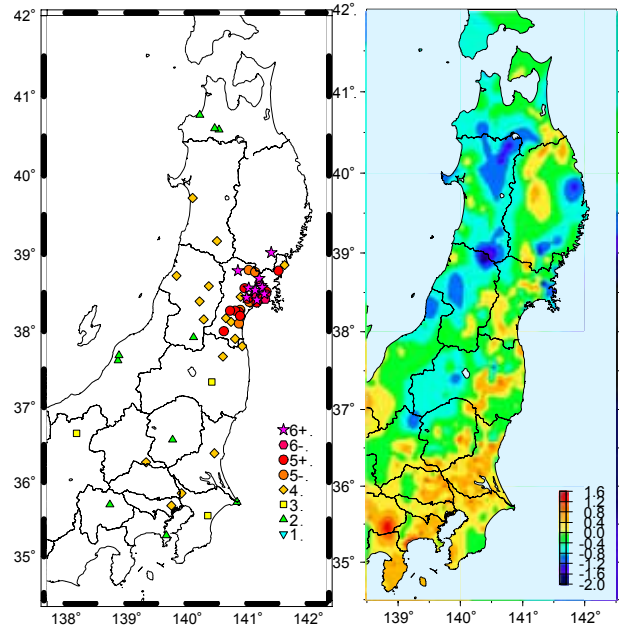


Figure 10. Seismic intensity distribution of the 1861 earthquake (data courtesy of Profs. Koketsu and Tsuji, the University of Tokyo) (left figure) and the contour map of relative intensity evaluated from measured intensity data of recent earthquakes off Miyagi (right figure).

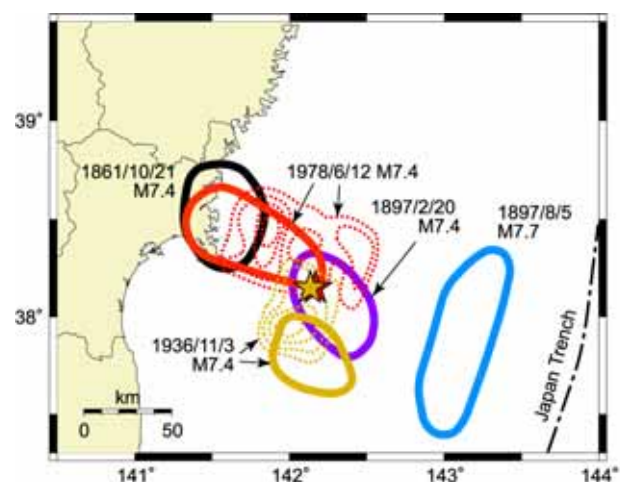


Figure 11. Short-period radiation zones integrated from the inversion analyses for the Off Miyagi earthquakes (solid lines), and slip distribution of the 1978/6/12 and 1936/11/3 earthquakes from waveform inversion represented by dotted lines (Earthquake Research Committee, 2003). Stars represent the

epicenters of the 1978/6/12 and 1936/11/3 earthquakes.

5. The Off Tokachi earthquakes

The Off Tokachi earthquake is also one of major subduction earthquakes in Japan and just occurred on September 26, 2003. It is said that large slip zone of the 2003 Off Tokachi earthquake is similar to that of the 1952 Off Tokachi earthquake based on the waveform inversion analysis (Yamanaka and Kikuchi, 2003). JMA reported some resemblances between these two earthquakes. For instance, a maximum aftershock occurred in the vicinity of a main shock, and aftershock activities moved northeastward from the Urakawa offing to the Kushiro offing. Therefore, It was judged that the same type of earthquake occurred again. We have investigated whether or not short-period radiation zone on the fault plane of the 2003 Off Tokachi earthquake resembled that of the 1952 Off Tokachi earthquake using the inversion analysis of seismic intensity data.

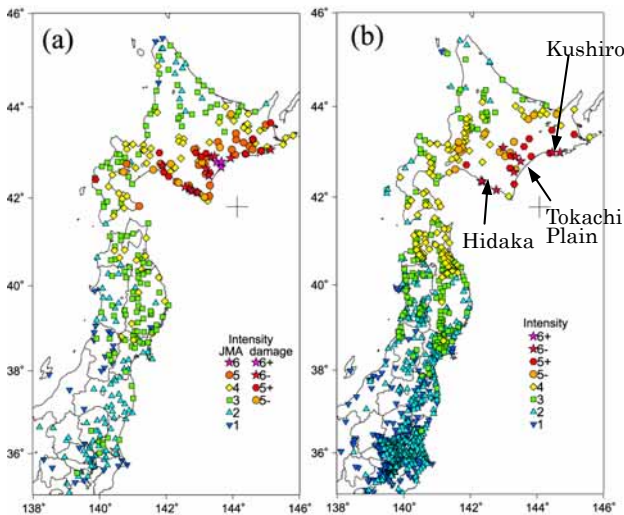


Figure 12. Seismic intensity distribution of the Off Tokachi earthquakes: (a) 1952/3/4, M8.2 (including data reported from JMA and data estimated from the collapse rate of dwelling houses), (b) 2003/9/26, M8.0 (measured intensity data). A cross represents an epicenter for each earthquake.

Based on data from JMA, isoseismal areas for seismic intensity 3 to 5 are quite alike between the 1952 and 2003 Off Tokachi earthquakes. However, though the areas of seismic intensity 6 of the 1952 earthquake are limited in the Tokachi River valley, those of the 2003 earthquake are located not only in the Tokachi River valley but also in Hidaka and Kushiro regions. It may be due to the accuracy of bodily sensed intensity that depends on judgment of an evaluator. In order to improve the accuracy of seismic intensity distribution of the 1952 earthquake, we add seismic intensity data evaluated from the complete collapse rate of wooden dwelling houses (Research

committee of the 1952 Off Tokachi earthquake, 1954). Since the earthquake resistant performance of Japanese dwelling houses at the time of the 1952 Off Tokachi earthquake was almost the same as that at the 1923 Kanto earthquake, we estimate seismic intensity from the collapse rate of wooden dwelling houses like the case of the 1923 Kanto earthquake (Fig.7). In result, towns of intensity 6- also appear in Hidaka and Kushiro regions as shown in Fig.12. It means that an isoseismal area for seismic intensity 6 of the 1952 earthquake becomes similar to that of the 2003 earthquake.

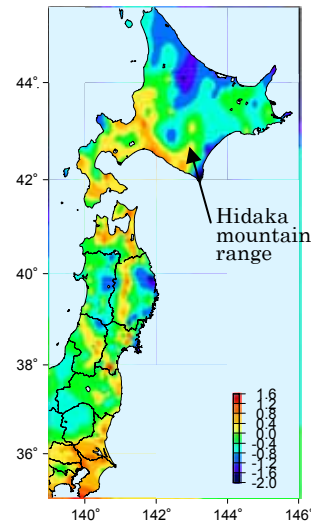


Figure 13. Contour map of relative intensity evaluated from measured intensity data of aftershocks of the 2003 Off Tokachi earthquakes.

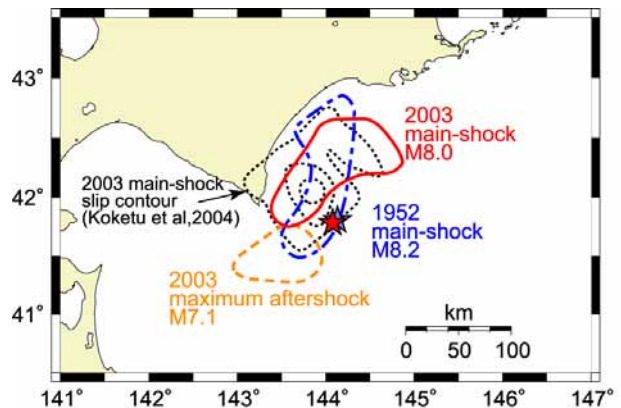


Figure 14 Short-period radiation zones from the inversion analyses for the 1952 and 2003 Off-shore of Tokachi earthquakes. A solid line and a broken line represent the 2003 main-shock and the maximum aftershock, respectively, and a chain line shows the 1952 main-shock. Dotted lines show slip contour from the joint inversion using strong motion and geodetic data for the 2003 main-shock (Koketsu *et al.*, 2004). The contour interval is 2m.

The seismic intensity attenuation formula Eq. (1) and relative intensities shown in Fig.13 are evaluated

from seismic intensity data of six aftershocks ($M > 6.0$) of the 2003 earthquake. It is indicated that the relative intensity is quite high in the west of the Hidaka mountain range compared to that in the east side, the Tokachi plain. It may be due to the influence of wave propagation effect rather than local site effect.

Fig. 14 shows the short-period radiation zones of the 1952 and 2003 earthquake. The result of the 2003 earthquake includes a main-shock and a maximum aftershock. Most of short period radiation zones of the main-shock of 1952 and 2003 earthquakes overlapped with each other. It may be inferred that similar type of earthquakes occurred repeatedly regarding short period seismic waves. The short-period radiation zone of the 2003 maximum aftershock didn't overlap with that of the 2003 main-shock completely. It is considered that the area which was ruptured in the aftershock hadn't been ruptured in the main-shock. Furthermore, it is noted that the short-period radiation zone relatively resembles the large slip areas for the 2003 earthquake (Koketsu *et al.*, 2004). The only difference is the east end of the fault plane, where fault rupture was supposed to stop.

6. Conclusions

An inversion method has been developed to evaluate the short-period radiation zones on an earthquake fault plane using seismic intensity data. It is robust and efficient especially for historical earthquakes without strong motions, tsunami and geodetic data recorded by instruments. It is applied to the four major source regions of subduction earthquakes in Japan.

It is noted that short-period radiation zones were often located in the vicinity of large slip areas, termed asperities (Nankai, Tonankai, Kanto, and Off Miyagi), and were sometimes located at the area where fault rupture had stopped (Nankai, Tonankai, Tokai, Kanto, Off-Miyagi and Off-Tokachi). The location discrepancy between the short-period radiation zone and large slip area (asperity) may be attributed to not only the difference of frequency contents of analyzed seismic waves but also the evaluation error due to the directivity effect of fault rupture. Furthermore, The short-period radiation zones haven't necessarily been repeated at the same location (Nankai, Tonankai, Tokai, Off-Miyagi). Their mechanism may be sometimes controlled by crust structures such as a subducted seamount (Nankai) and ridges (Tokai).

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