Preliminary report of the 2011 off the Pacific coast of Tohoku Earthquake

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1. Introduction

In March 11, 2011, "Off the Pacific coast of Tohoku Earthquake" was generated with magnitude 9.0, which records the largest in the history of seismic observation in Japan. The greatest disaster on record was brought by huge tsunami with nearly 30 thousand killed or missing people. We would like to express our deepest sympathy for the victims of this earthquake.

Associated with this earthquake, nuclear reactors No.1 through 4 at the Fukushima 1st Nuclear Power Plant got into the serious situation by considerable disability of cooling and confining functions. General public felt alarm with this situation and power shortage led many people in disruption by unprecedented planned outage of electricity.

Coincidence of earthquake and nuclear hazards made people partly in panic and civilian life was attacked by unprecedented disasters such as difficulty in commodity procurement of gasoline and foods.

Here, we will present a preliminary report about the outline of the 2011 off the Pacific coast of Tohoku Earthquake.

2. Main shock

Main shock occurred on 14:46 of March 11, 2011 (JST). Seismic intensity of 7 in JMA (Japan Meteorological Agency) scale was recorded at Kurihara City, Miyagi Pref., and intensity of 6+ or 6- were observed in wide area along Pacific region ranging from Iwate Pref. to Ibaraki Pref (**Fig.1**).

Peak ground acceleration of 2,933gal (composite of three components) was observed at Tsukidate, Kurihara City, one of the NIED K-NET station.

It was the third time that intensity of 7 was recorded in Japan following the 1995 Kobe Earthquake (M7.3) and 2004 mid-Niigata Earthquake (M6.8). JMA named this earthquake "2011 off the Pacific coast of Tohoku Earthquake".

Hypocenter locates off Sanriku at 130km ESE of Oshika Peninsula with the focal depth of 24km.

Magnitude of the earthquake was initially announced as M7.9 (Quick) by JMA and was revised to M8.4 (Prelim.) in 16:00 and M8.8 (Prelim.) in 17:30. It was finally determined as M9.0 in March 13,

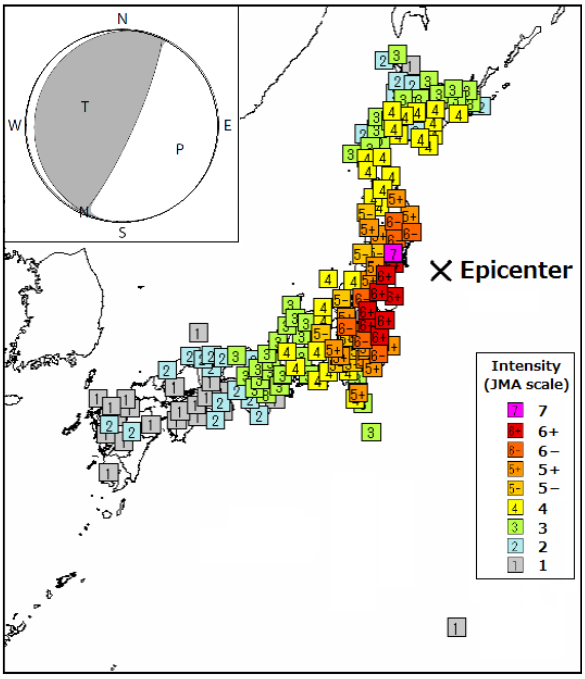

Fig.1 CMT of 2011 off the Pacific coast of Tohoku Earthquake and intensity distribution (JMA)

CMT solution of this earthquake was thrust type with a pressure axis in

WNW-ESE direction as shown in the inset of **Fig.1**. This means that this earthquake was generated as a typical inter-plate earthquake which is caused by the rebound of a continental plate (North American plate) against a subducting oceanic plate (Pacific plate) at Japan trench (**Fig.2**).

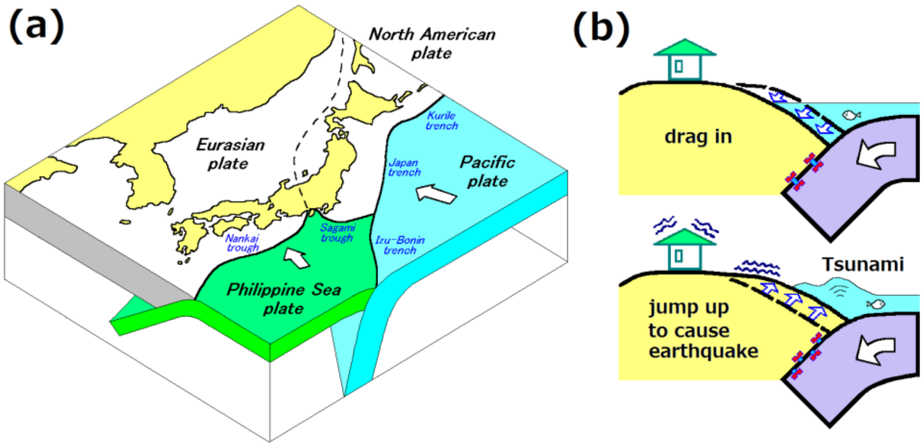

Fig.2 (a) Plate configuration around Japan, **(b)** mechanism of inter-plate earthquake

In **Fig.1**, the hypocenter was shown as a cross-mark. But gigantic energy of M9.0 earthquake was never radiated only from this point. **Fig.3 (a)** shows a general scheme of earthquake generation. The rupture (offset of rock) initiated from a hypocenter spreads with a speed of 3-4km/s to make a planar cut surface. The area of this surface called as "fault surface" and the amount of offset determines the magnitude of the earthquake. The point just above the hypocenter (point of rupture initiation) is called as epicenter, while the projection of the fault surface to the ground is called as focal region.

Fig.3 (b) was taken from USGS website where is shown the summary of this earthquake. A star at offshore denotes the epicenter and the tetragon of 500km in NS direction and 200km in EW direction corresponds to the focal region. Rupture of the main shock started from the hypocenter shown by star and propagated to off the coast of Iwate Pref. in north and to off the coast of Ibaraki Pref. in south. Fault offset is estimated to reach around 20m. Color codes show the intensity distribution in MM scale.

Associated to the occurrence of main shock, Earthquake Early Warning was issued 8.6 sec later from the detection of P-wave at Ouri, Ishinomaki City. Margin to the time of S-wave arrival was around 15 sec at central Sendai City, and around 65sec at Tokyo.

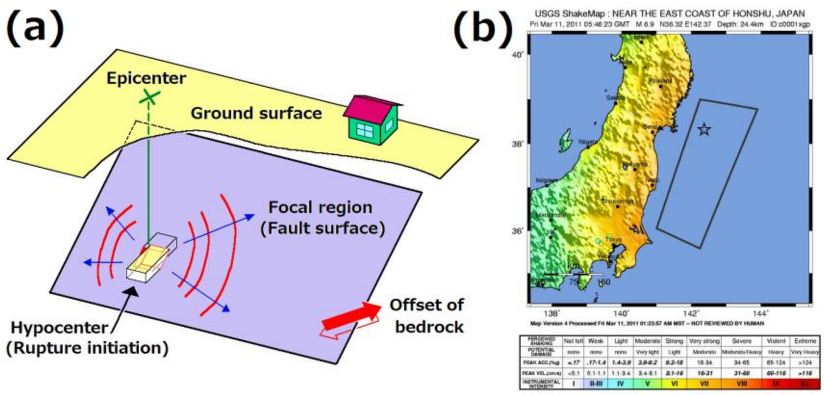

Fig.3 (a) General mechanism of earthquake generation (faulting motion), **(b)** Summary of 2011 off the Pacific coast of Tohoku Earthquake. Color codes show intensity distribution in MM scale (USGS).

3. Tsunami

It is usual that an inter-plate earthquake occurred at trench region accompanies tsunami. Since the magnitude of this earthquake was as large as M9.0, the scale of generated tsunami was also huge one. In Japan, large tsunami attacked the Pacific coast ranging from Hokkaido to Okinawa and the tsunami was also observed at the coast of the Japan Sea, the Okhotsk Sea, and the East China Sea. The tsunami also propagated to the coast of Hawaii, northern and southern America continents, and the Pacific countries.

At Kamaishi, Ishinomaki, and Ofunato, the first arrival of tsunami was at 14:46, which means that the tsunami reached to these coastal cities at the same time of the earthquake occurrence. The tsunami of maximum height attacked these cities around 15:20, i.e. 30 minutes later of the earthquake. **Fig.4** shows the distribution of maximum height of tsunami along the coast of the whole Japan. It was recorded more than 8.5m at Miyako, Iwate Pref., more than 8.0m at Ofunato, Iwate Pref., more than 7.3m at Soma, Fukushima Pref., 4.2m at Oarai, Ibaraki Pref., and so on.

Japan Meteorological Agency issued Tsunami Warning (Major tsunami) at 14:49, i.e. 3 minutes later of the earthquake, to Iwate, Miyagi, and Fukushima Prefectures. It was extended to Aomori, Ibaraki, and Chiba at 15:14, and was followed by Japan Sea side, Bonin Islands, Sagami Bay, Shizuoka and Wakayama Prefectures. They were in series downgraded to Tsunami Warning (tsunami) and Tsunami Advisory for each region, and were completely cleared on 17:58, March 13.

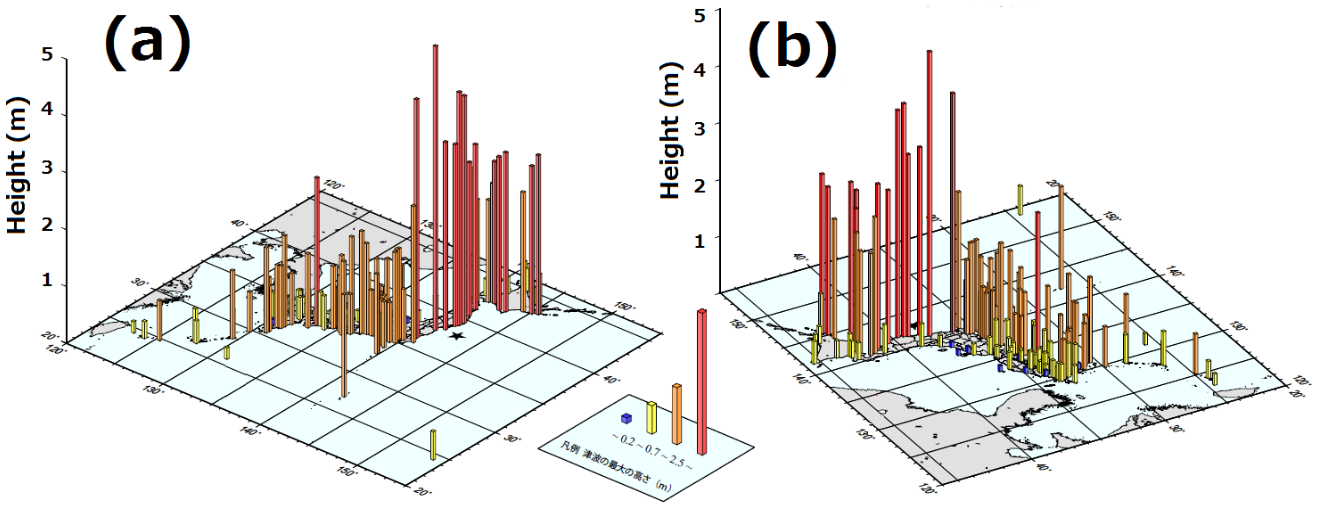

Fig.4 Distribution of maximum height of tsunami viewed from **(a)** Pacific Ocean side and **(b)** Japan Sea side. (JMA). The data of more than 8m at Miyako and Ofunato are not included.

4. Crustal deformation

Huge earthquake of M9.0 brought enormous crustal deformation on eastern Japan. Fig.5 shows displacement field caused by this earthquake detected by GPS network of the Geospatial Information Authority of Japan.

Taking the fixed point at Misumi, Hamada City in Shimane Pref., Pacific side of eastern Japan moved several meters to ESE direction. Displacement of 4.4m was observed at Shizugawa, Minami-Sanriku Town in Miyagi Pref., and the largest displacement of 5.3m was detected at Oshika, Ishinomaki City, while displacement at Japan Sea side was around 1m causing a large extensional field in the eastern Japan.

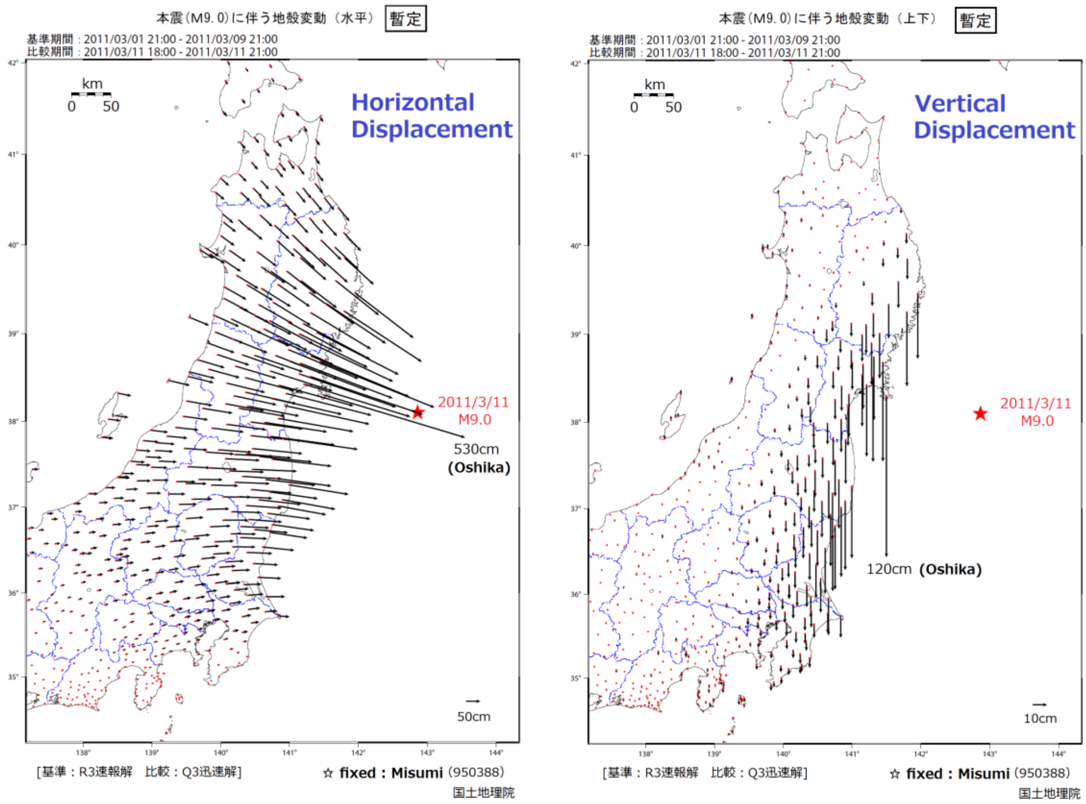

Fig.5 Crustal deformation associated to the 2011 off the Pacific coast of Tohoku Earthquake (GSI)

On the other hand, as to the vertical displacement, subsidence of several tens centimeters was detected in wide area along Pacific coast region. Subsidence of 75cm was observed at Shizugawa, and the largest subsidence of 120cm was detected at Oshika. Such a subsidence makes sea water brought by tsunami difficult to drain back. Also, the descent of breakwater and land itself results reduction of vulnerability to the next tsunami.

According to **Fig.5**, even Tokyo looks to move eastward by around 10cm and subsides around 5cm. As to the aftereffect of this earthquake, GSI reports that eastward after-slips are in progress in wide area in the Tohoku and Kanto districts. As of March 19, total amount of the after-slip is 25cm at Yamada Town, Iwate Pref., and 17cm at Choshi City, Chiba Pref.

The crustal deformation stated above are caused by the formation of a reverse fault in the ground. **Fig.6** displays how the ground surface (or sea bottom) and the inside of the earth theoretically deform associated to a reverse faulting motion.

We can see that the ground are pulled toward the fault surface and the block just above the fault is largely raised to make tsunami, while the inland part shows subsidence.

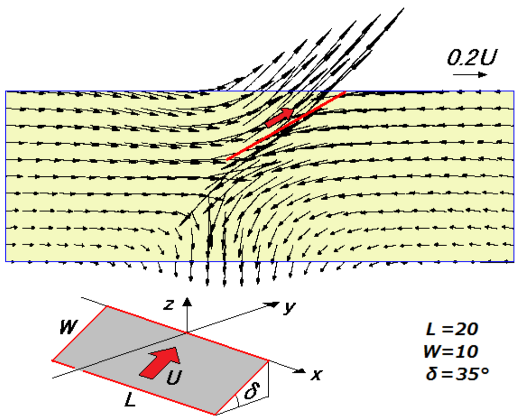

Fig.6 Deformation of ground surface (sea bottom) and the inside of the earth associated to a reverse faulting.

5. Aftershock activity

Fig.7 (a) shows the seismic activity of the main shock and aftershocks of magnitude 5 or larger which occurred in a week since March 11, the occurrence date of the 2011 off the Pacific coast of Tohoku Earthquake. A red circle at off Miyagi Pref. denotes the hypocenter of the main shock, while orange and yellow circles show M7-class and M6-class aftershocks, respectively.

Aftershocks are concentrated within a region of 500km in NS and 200km in EW ranging from offshore of Iwate Pref. to offshore of Ibaraki Pref. This region corresponds to the tetragon area in **Fig.3 (b)**. The main shock of M9.0 started rupturing (offset of the bedrock) from the point of red circle and propagated northward to reach offshore of the Iwate Pref., and southward to reach offshore of the Ibaraki Pref. to form a great cut surface, the fault. Zillions of aftershocks are generated as if the piercing pain along the cut surface.

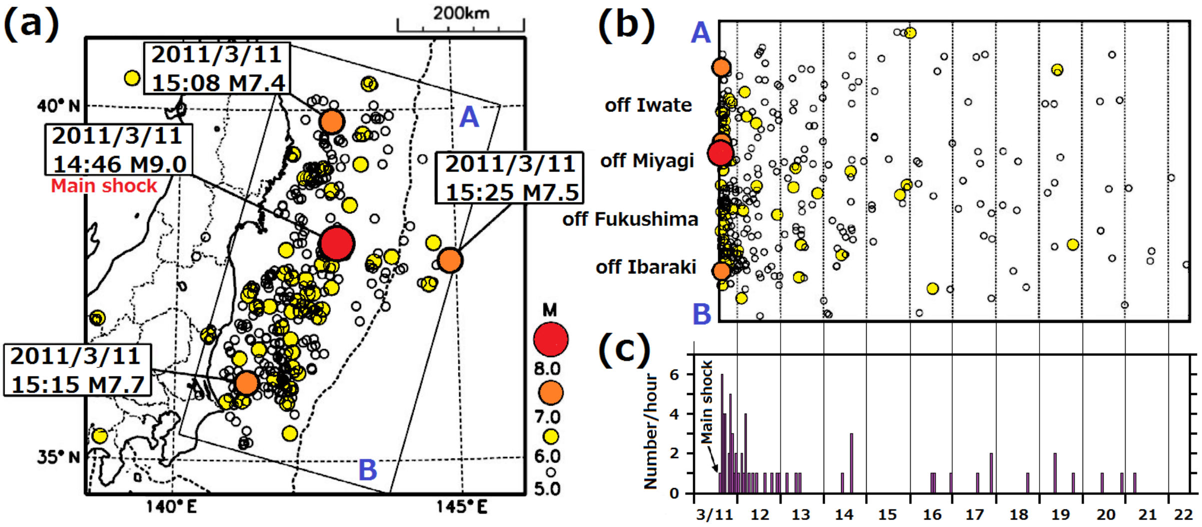

Fig.7 (a) Distribution of main shock and the aftershocks of M5 or larger which occurred in the period, Mar.11 to 09:00 Mar.18, **(b)** Temporal-spatial distribution of the aftershocks occurred in the rectangle shown in (a), **(c)** Hourly number of the earthquakes which recorded intensity 4 or larger (JMA)

While the aftershocks generated around the fault surface of the main shock are called “aftershock in the narrow sense”, there exists “aftershock in the wide sense” which occurred in the region far apart from the focal region of the main shock. These events are assumed to be triggered by the main shock. Strong inland earthquakes were generated next to the next, such as northern Nagano (M6.7) on 03:59, Mar.12, off Akita (M6.4) on 14:47, Mar.12, and eastern Shizuoka (M6.4) on 22:31, Mar.15.

Maximum intensity of 6+ was recorded at Sakae Village associated to the northern Nagano earthquake. Severe shaking of intensity 6+ was also observed at Fujinomiya City associated to the eastern Shizuoka earthquake, whose hypocenter locates just beneath the Mt. Fuji with a focal depth of 14km, and its relation to the forthcoming Tokai earthquake brought an issue of concern. When we compare the whole distribution of the earthquakes in **Fig.7 (a)** to the plate configuration in **Fig.2 (a)**, it looks that the aftershocks are generated as if they are tracing the rim of the North American plate.

Fig.7 (b) shows temporal-spatial distribution of the aftershocks which occurred in the rectangle shown in (a), while **Fig.7 (c)** shows the change in hourly number of the earthquakes which recorded intensity 4 or larger. A series of M7-class events, M7.4, M7.7, and M7.5 were successively generated within 20 to 40 minutes after the main shock, but no M7-class event occurred thereafter. The number of M6-class earthquakes was 52 and the number of the events with intensity 4 or larger was 64 in the period of 11 days after the main shock.

By comparison, the Sumatra earthquake (M9.1) of December, 2004 accompanied the largest aftershock of M7.1 on 3.5 hours after the main shock and the number of aftershocks of M6 or larger was 65.

Fig.8 shows the cumulative number of the aftershocks of M5 or larger within 10 days after the main shock compared to the inter-plate earthquakes in the past. Since the 2011 off the Pacific coast of Tohoku Earthquake was huge one and has very wide focal region, numerous number of aftershocks are following than ever before. However, as a general trend, the aftershock activity is becoming weak with gradual elongation of the interval, although it sometimes contain large sized one.

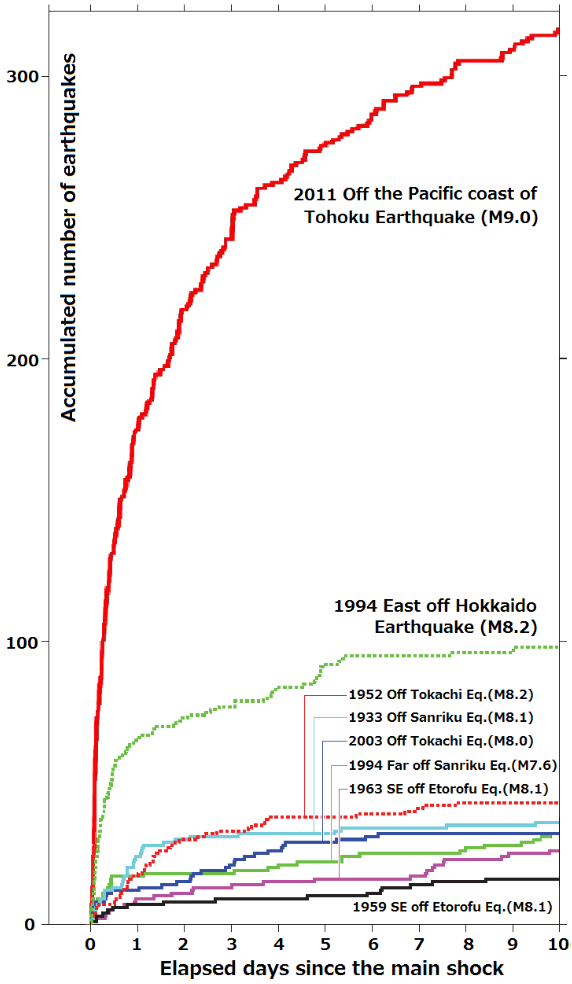

Fig.8 Cumulative number of the aftershocks of M5 or larger within 10 days after the main shock compared to the inter-plate earthquakes in the past (JMA)

6. Foreshock activity

Two days before the main shock, an earthquake of M7.3 took place off the Sanriku coast on 11:45, March 9. It accompanied active aftershocks including a M6.8 event of the next day (**Fig.9**). These events were located just north of the 2011 off Pacific coast of Tohoku Earthquake implying the foreshock of this huge event as a result. However, since the earthquake of M7.3 is sufficiently large one by itself, no one could imagine that this event links to the coming huge earthquake.

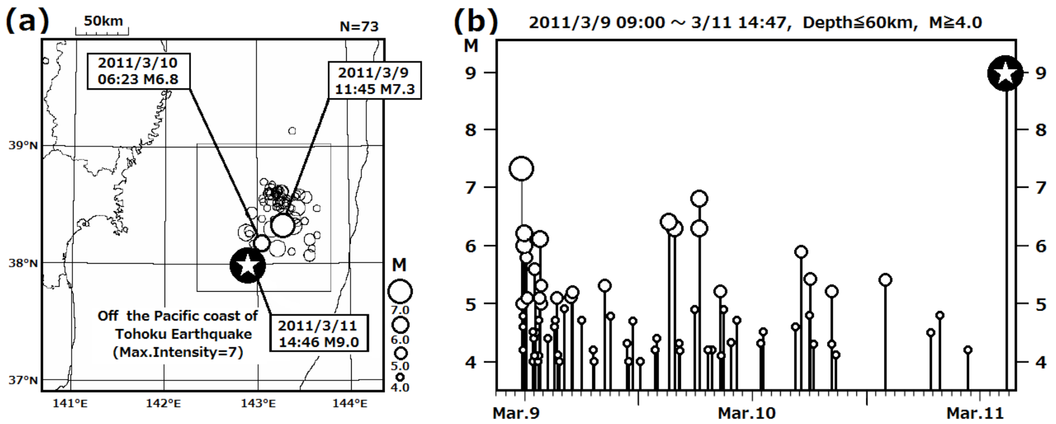

Fig.9 (a) Epicentral map and **(b)** M-T diagram for the off Sanriku earthquake (M7.3) of Mar.9 and its aftershocks. A star denotes the epicenter of the 2011 off the Pacific coast of Tohoku Earthquake (JMA)

7. Long-term forecast

The Earthquake Committee of HERP (the Headquarters for Earthquake Research Promotion) has announced the Long-term Forecast about the occurrence potentials of subduction-zone earthquakes off the Pacific coast of the eastern Japan including the focal region of this M9.0 event.

The target area has been divided into the regions shown in **Fig.10** and the estimated magnitude, occurrence probability within coming 30 years, and average recurrence interval have been estimated as in **Table 1**.

Table 1 Long-term forecast of subduction-zone earthquakes off the Pacific coast of Japan (HERP)

<table>
<tr><th>Region</th><th colspan="2">Estimated magnitude</th><th>Occurrence probability within coming 30 years</th><th>Average interval</th></tr>
<tr><td>off northern Sanriku</td><td colspan="2">～M8.0</td><td>0.5%～10%</td><td>～97 yrs</td></tr>
<tr><td>off central Sanriku</td><td colspan="4">(cannot evaluate due to the lack of records)</td></tr>
<tr><td>off southern Sanriku</td><td>～M7.7</td><td rowspan="2">～M8.0 if coupled</td><td>80%～90%</td><td>～105 yrs</td></tr>
<tr><td>off Miyagi</td><td>～M7.5</td><td>99%</td><td>37 yrs</td></tr>
<tr><td>off Fukushima</td><td colspan="2">～M7.4 (multiple)</td><td>less than ～7%</td><td>＞ 400 yrs</td></tr>
<tr><td>off Ibaraki</td><td colspan="2">M6.7～M7.2</td><td>more than ～90%</td><td>～21 yrs</td></tr>
<tr><td>off Boso</td><td colspan="4">(cannot evaluate due to the lack of records)</td></tr>
<tr><td rowspan="2">Trench zone</td><td colspan="2">～M8.2(Tsunami Eq.)</td><td>～20%</td><td>～133 yrs</td></tr>
<tr><td colspan="2">～M8.2(Normal F. Eq.)</td><td>4%～7%</td><td>400～750 yrs</td></tr>
</table>

In "off Miyagi" region, six events were repeated in the past 200 years with average interval of 37.1 years. They occurred in 1793(M8.2; coupled), 1835(M7.3), 1861(M7.4), 1897(M7.4), 1936(M7.4), and 1978(M7.4), which results the occurrence probability of 99%, the highest value in Japan.

In this region, an earthquake of M7.2 has occurred in August, 2005. Since the M was less than estimated level of M7.5, it was evaluated that we cannot ease up our attention to this region.

Next, an earthquake of M7.3 occurred in the region of "off southern Sanriku" on March 9, two days before the M9.0 event. This time, there was an opinion that the occurrence probability of the coupled event of "off Miyagi" and "off southern Sanriku" may be lowered.

However this was a foreshock of the M9.0 event and the main shock involved five regions from "off central Sanriku" to "off Ibaraki" as well as "trench zone".

Historically, it was known that a great earthquake associated with huge tsunami occurred in 869 (Jogan) in Heian Era and killed more than 1,000 people at Tagajo, Miyagi Prefecture. But one could hardly imagine that such a event would recur nor the greater event would happen in the land of the living.

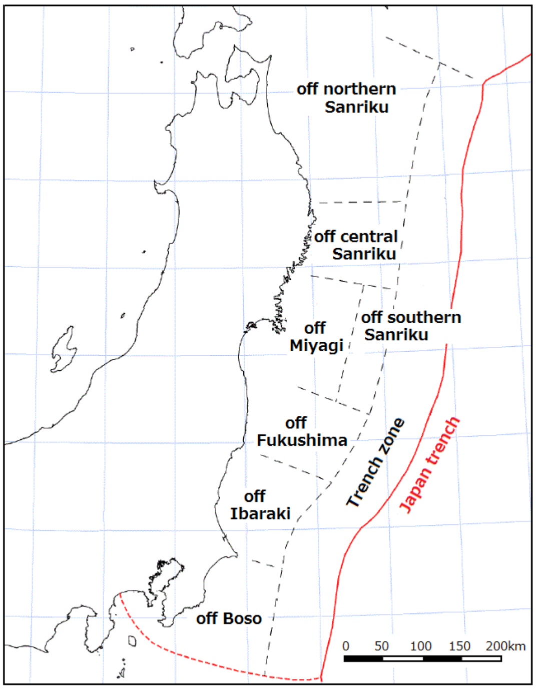

Fig.10 Division of the region off the Pacific coast of the eastern Japan (HERP)

8. Problems of the triggering

Since the 2011 off the Pacific coast of Tohoku Earthquake of M9.0 was so huge event, it is anxious that various geo-phenomena will be triggered by big strain change in the wide surrounding region due to the large crustal deformation.

(1) Triggering of inter-plate earthquake

It is well known that big earthquake often induces another earthquake at the extended portion of the fault surface of the main shock. For example, 1854 (Ansei) Tokai earthquake (M8.4) was followed by 1854 (Ansei) Nankai earthquake (M8.4) which was generated 32 hours later of the former event at the region of western neighbor. Similar example was recurred between the pair of 1944 Tonankai earthquake (M7.9) and 1946 Nankai earthquake.

Also, the 2004 Sumatra earthquake (M9.1) was followed 3 months later by 2005 Nias Island earthquake (M8.4) at the region of eastern neighbor. Most recently, 2010 Canterbury earthquake (M7.3) in New Zealand was followed 6 months later by 2011 Christchurch earthquake (M6.3) at the eastern extension of the aftershock area.

In the present case, we should be cautious to the areas of northern and southern extensions of the fault of 500km length. At the northern neighbor, "off northern Sanriku", 1968 off Tokachi earthquake (M7.9) and 1994 far off Sanriku earthquake (M7.5) were already generated recently. On the contrary, at the southern neighbor, "off Boso", we have not experienced large earthquakes for a long time. In the history, it is known that 1677 (Enpo) Boso earthquake (M8.0) occurred 334 years before, which generated large tsunami at coastal region of Chiba and Ibaraki Prefectures killing around 200 people. We should pay attention to such a kind of earthquake at least half to several years.

(2) Triggering of inland earthquake

As stated in the section 5, after the occurrence of the main shock, "aftershock in the wide sense" frequently occurred in the inland area. M6-class events were also succeeded including northern Nagano (M6.7) on 03:59, Mar.12, off Akita (M6.4) on 04:47, Mar.12, and eastern Shizuoka (M6.4) on 22:31, Mar.15.

Fig.11 shows the distribution of hypocenters in the eastern Japan which were generated in the period of 1 week starting from the next day of the main shock. In this figure, clusters A, B, and C correspond to the above M6-class events and their aftershocks.

As a remarkable activity among the other inland events, there exists a cluster D at Pacific side near the border of Fukushima and Ibaraki Prefectures.

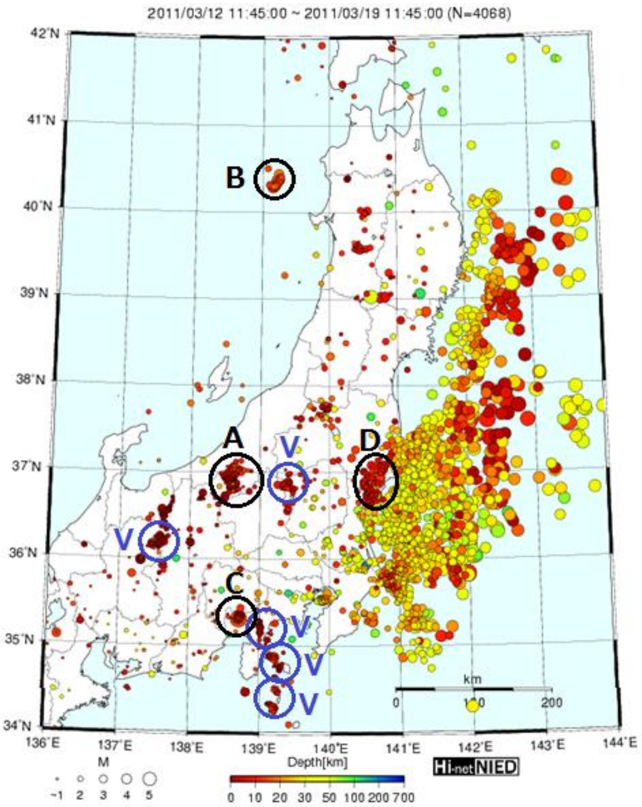

Fig.11 Seismic activity in the eastern Japan in the period of 1 week from the next day of the main shock (after automatic processing of Hi-net). A,B,C,D are shallow inland activities including M6 events, while V are related to volcanic activities.

At this region, noticeable seismic activity was not seen in usual. But this time, extensive earthquakes including M6-class events were induced and sometimes resulted in the shaking of intensity 5+. Since observed focal mechanisms of these events were typically normal fault type with EW tension axis, it can be considered that EW extensional field stated in the section 4 caused the seismic activity in the cluster D.

As a famous example of the coupling of inter-plate earthquake and inland earthquake, the Riku-u earthquake (M7.2) of August, 1896 occurred at the border of Akita and Iwate Prefectures 2 months later the Sanriku earthquake (M8.2) of June, 1896.

(3) Triggering of volcanic activities

In **Fig.11**, besides the clusters A to D, activation of seismicity was seen at the regions denoted as V. All of these are related to the volcanoes in the central Japan, concretely speaking, Nikko-Shirane, Yakedake, Norikuradake, Hakone, Izu-Oshima, Niijima, and Kohzushima. Also, the cluster C is just related to Mt. Fuji.

Originally, volcanic region has mechanically weak structure and is said to be sensitive to the external stress. Adding to the volcanoes in the central Japan, it is reported that activity of volcanic earthquakes has escalated at some volcanoes in Kyushu, although no signs of surface phenomena related to volcanic eruption are observed.

Regarding to the coupling of inter-plate earthquake and volcanic eruption, it is famous that 1707 (Hoei) eruption of Mt. Fuji was induced 49 days later the 1707 (Hoei) Tokai-Nankai earthquake (M8.4).

There is no predicting what will happen in the surrounding region of such a huge earthquake. We must continue careful watch hereafter.