VARIABILITY AMONG TSUNAMI SOURCES IN THE 17TH-21ST CENTURIES ALONG THE SOUTEHRN KURIL TRENCH

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Instrumental, historical, and geological records of tsunamis show that successive plate-boundary ruptures differ in size along the southern Kuril trench off eastern Hokkaido. Tsunami source area of the 2003 Tokachi-oki earthquake (M 8.0), the most recent and the best-measured earthquake, is only about 2/3 of that of the predecessor, the 1952 Tokachi-oki earthquake (M 8.2). This difference is apparent from tsunami waveform inversions of the two events. The inversion of the 1952 event, redone with the clock corrections estimated from comparison of the 1952 and 2003 tsunami waveforms, confirms that the 1952 tsunami source extended about 100 km to the east of the 2003 source. The coastal tsunami runup heights were also different; the maximum height in 1952 was recorded by more than 100 km east of that in 2003. An earthquake in 1843 may have resembled the 1952 event, based on tsunami damage distribution recorded in historic documents. Prehistoric tsunami deposits have shown that larger tsunamis occurred in the eastern Hokkaido in an approximately 500 year interval with the last event in the 17th century. These deposits are best explained by earthquakes that broke not only the area of the 1952 event but also the adjoining Nemuro-oki segment to the east. This evidence for variable rupture mode complicates the task of forecasting future earthquakes and tsunamis in eastern Hokkaido. According to a long-term forecast, issued six months before the 2003 earthquake, probability of an M~8 earthquake, similar to the one in 1952, was 60 % by 2033. The forecast was correct for the timing but overestimated the earthquake size.

Key words: Kuril trench, Tokachi-oki earthquake, earthquake recurrence, paleoseismology.

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1 Introduction

Along the southern Kuril trench, where the Pacific plate subducts beneath Hokkaido at a rate of ~8 cm/yr, great (M~8) earthquakes have recurred since 19th century when the region's written history started (Figure 1). In the region offshore Tokachi coast (Tokachi-oki), the southernmost segment of the Kuril trench, earthquakes have been documented in 1843 (M 8.0) and 1952 (M 8.2). Offshore from Nemuro (Nemuro-oki), to the east, large earthquakes occurred in 1894 (M 7.9) and in 1973 (M 7.4). Besides these interplate earthquakes, slab earthquakes have also generated tsunamis. For example, an M 8.1 earthquake occurred in Shikotan-oki in 1994 and generated the tsunami (Tanioka et al., 1995; Satake and Tanioka, 1999).

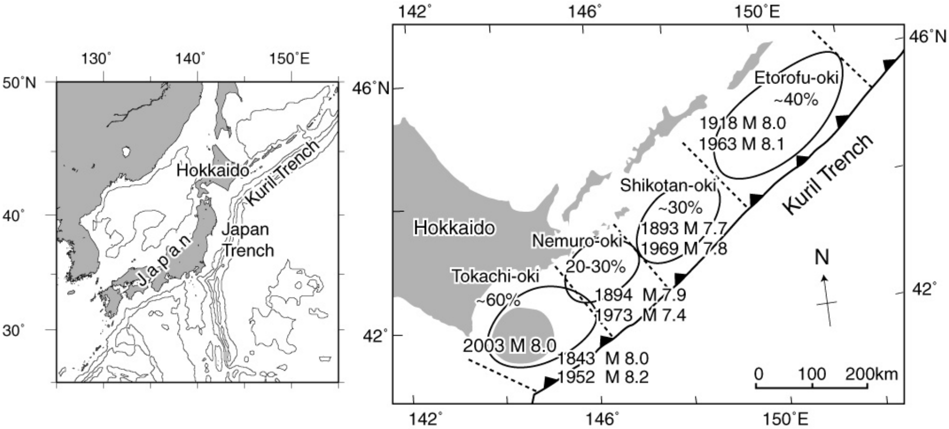

Fig. 1. Location of Kuril trench (left) and the source regions of the great earthquakes along the southern Kuril trench (right). Recurrence of earthquakes in the 19th and 20th centuries in each segment (bordered by dashed lines), as well as the probabilities (in the next 30 years) forecasted before the 2003 Tokachi-oki earthquake are shown (Earthquake Research Committee, 2004). Magnitudes of these events are on the Japanese scale, based on instrumental or historical data (Utsu, 1999).

In March 2003, the Japanese government made long-term forecast for great (M~8) earthquakes along the Kuril trench (Earthquake Research Committee, 2004). The committee estimated that the probability in the next 30 years (starting March 2003) as 60 % in Tokachi-oki and 20-30 % in Nemuro-oki. This forecast was based on the above recurrence of great earthquakes in the 19th and 20th centuries, incorporating key simplifying assumptions: in each of the offshore segments, characteristic earthquakes repeat at regular intervals and the rupture the source area that broke in the 20th century.

Two recent findings cast doubt of these assumptions. First, prehistoric tsunami deposits indicate that unusual large tsunamis have occurred along the Kuril trench (Nanayama et al., 2003). These outsized tsunamis are characterized by large inundation area (kilometers inland from the limits of historical tsunamis) and long (about 500 yrs) recurrence interval. These tsunamis are best explained by earthquakes that rupture multiple segments of the Kuril subduction zone. Soon after this finding was published, an earthquake smaller than forecasted ruptured part of the Tokachi-oki segment in September 2003. Waveform inversion of the 2003 tsunami records (Tanioka et al., 2004a) indicates that the slip distribution on fault is different from that of 1952 earthquake (Hirata et al., 2003).

Improved forecasts will require more attention to variability among successive earthquakes along the southern Kuril trench. To this end, we review earthquakes and tsunamis from 17th through 21st centuries along the Kuril trench. We start with the 2003 Tokachi-oki earthquake, and compare its source region with our reanalysis of the 1952 tsunami. We then make further comparisons with tsunamis of the 19th and 17th centuries. We thereby attempt to define some of the variability among source areas of plate-boundary earthquakes and their tsunamis along the southern Kuril trench.

2 2003 Tokachi-oki tsunami

The source region of the 2003 earthquake has been estimated from seismic waves (e.g., Yamanaka and Kikuchi, 2003), aftershocks (Hamada and Suzuki, 2004) and tsunami first arrivals (Hirata et al., 2004). These studies show that the source was located off the Tokachi coast (Tokachi-oki). The slip and aftershocks extended about as far east as the Kushiro submarine canyon (Figure 2).

Inversion of tsunami waveforms recorded at 9 coastal tide gauges and 2 ocean bottom pressure gauges shows slip distribution on subfaults placed on the subduting plate (Tanioka et al., 2004a). The slip is confined on deep subfaults near the Tokachi coast (Figure 2). The slip distribution is similar to the asperity distribution estimated from seismic waves (e.g., Yamanaka and Kikuchi, 2003). The seafloor deformation calculated from this slip distribution predicts the offshore uplift and coastal subsidence.

The 2003 source area estimated from the seismic and tsunami data is smaller than that of the 1952 Tokachi-oki earthquake estimated by Hirata et al. (2003); the 1952 tsunami source extended to the east of the Kushiro submarine canyon.

The coastal tsunami runup heights, measured within a few days of the tsunami (Tanioka et al., 2004b), were 2-4 m on the Tokachi coast between cape Erimo and Kushiro, and less than 2 m to the east of Kushiro, except for one locality (Mabiro) (Figure 3). While it damaged coastal properties and left two persons missing, the tsunami left no deposits likely to be preserved in coastal geology.

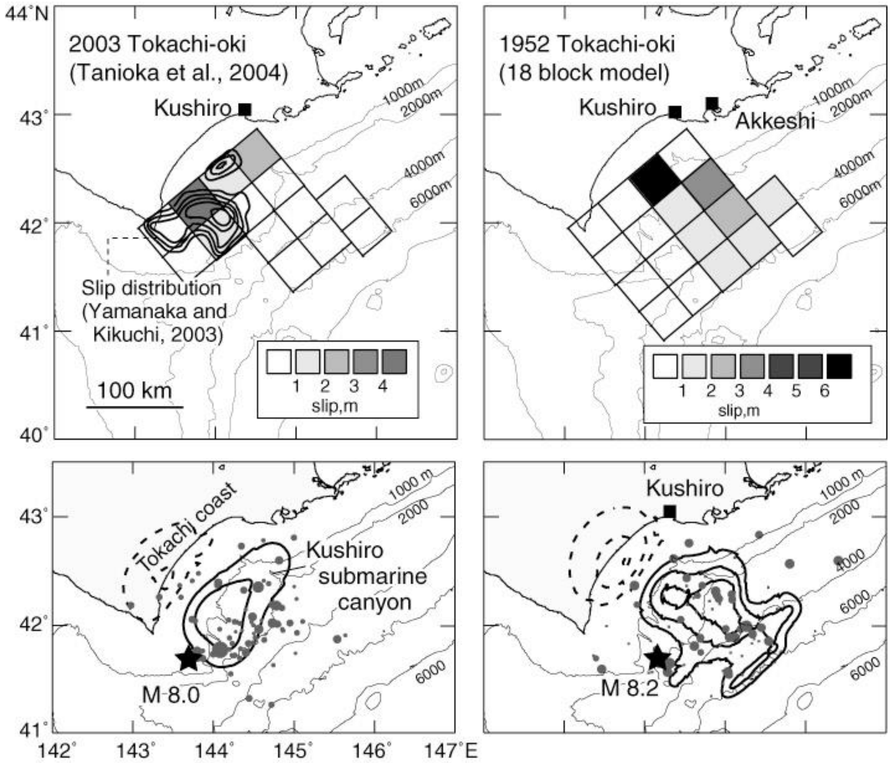

Fig. 2. Slip distribution on subfaults (above) and computed seafloor displacement (below) for the 2003 Tokachi-oki earthquake (left; Tanioka et al., 2004a) and the 1952 Tokachi-oki earthquake (right). The slip distribution estimated from seismic waves (Yamanaka and Kikuchi, 2003) is also shown by contours (interval: 1 m). In the lower map, the mainshock epicenter and the aftershocks within 4 days of the mainshock (Hamada and Suzuki, 2004) are also shown. The contour interval for seafloor displacement is 0.2 m for uplift (solid curves) and 0.1 m for subsidence (dashed curves).

3 Reanalysis of the 1952 tsunami

Distribution of tsunami runup heights from the 1952 Tokachi-oki earthquake is quite different from that of the 2003 event, particularly east of Kushiro (Figure 3). As in 2003, the tsunami heights in 1952 were 2-4 m on the Tokachi coast. To the east of Kushiro, however, the 1952 tsunami heights were 2-7 m, much larger than those in 2003. In fact, the extensive tsunami damage occurred around Akkeshi and Kirittapu, partly because icebergs then floating in the ocean were brought by tsunami to land and caused damage.

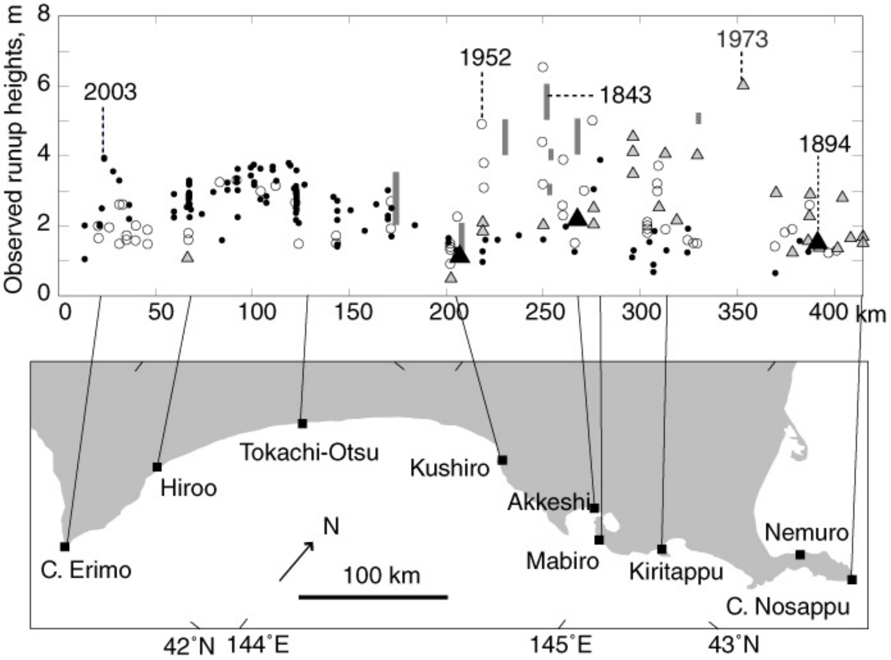

Fig. 3. Measured tsunami heights along the Pacific coast of eastern Hokkaido for the 2003 Tokachi-oki earthquake (Tanioka et al., 2004b), the 1952 Tokachi-oki earthquake (Central Meteorological Agency, 1953; Kusunoki and Asada, 1954), the 1973 Nemuro-oki earthquake (Japan Meteorological Agency, 1974), 1894 Nemuro-oki earthquake (Hatori, 1974), and the 1843 earthquake (ranges estimated from historical documents by Hatori, 1984 and Tsuji, 1994).

We reanalyzed the tsunami waveforms from the 1952 Tokachi-oki earthquake and reestimated the slip distribution by waveform inversion (Satake et al., 2004). We first estimated the clock errors of the 1952 tide gauges, by aligning the 1952 and 2003 waveforms at the first peak. The clock error was as large as 10 min, because the 1952 tide gauges were recorded in paper drums with a typical speed of 2 cm per hour whereas the 2003 tsunami was recorded digitally.

We then computed tsunami waveforms by using the finite-difference method for a linear long-wave equation and the equation of continuity (e.g., Satake, 2002). The grid size is 30” of the arc (about 925 m along the meridian) for deep ocean, and 6” (about 185 m) near the six tide gauge stations. The grid sizes are similar to those used by Tanioka et al. (2004a) for the 2003 Tokachi-oki earthquake tsunami, but much finer than 60” (about 1850 m) used by Hirata et al. (2003) for the 1952 tsunami.

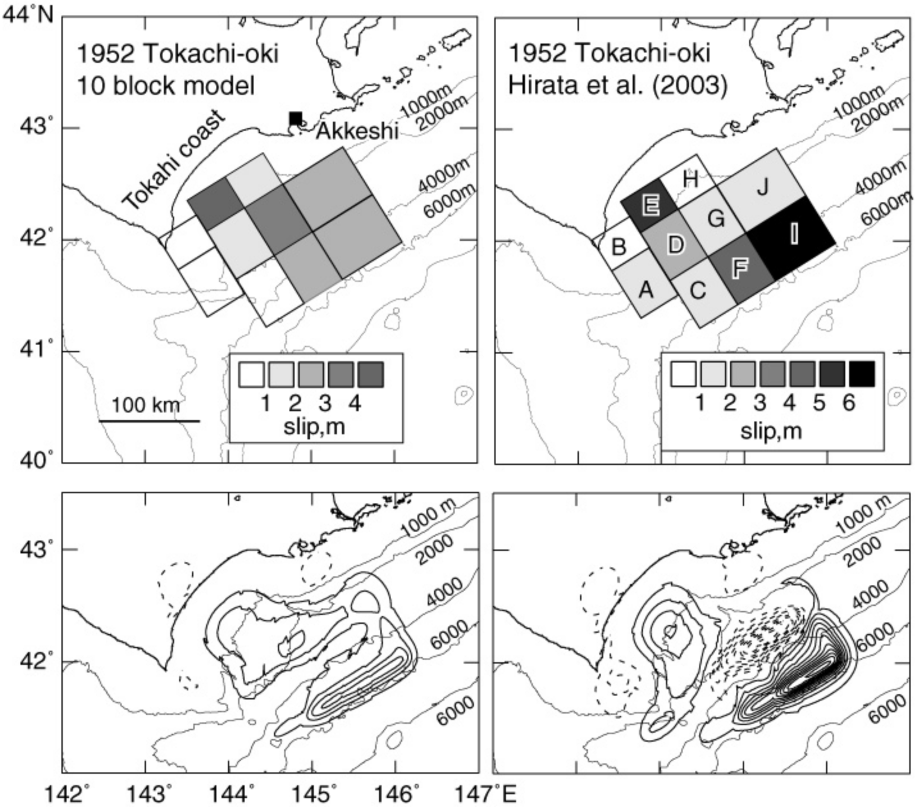

Fig. 4. Slip distribution on faults (above) and computed seafloor displacement (below) for the 1952 Tokachi-oki earthquake. Right panels are those by Hirata et al. (2003) and left panels are those reanalyzed results by Satake et al. (2004). The contour interval for seafloor displacement is 0.2 m for uplift (solid curves) and 0.1 m for subsidence (dashed curves).

To estimate the slip distribution, we divided the source into two kinds of subfaults, 18 blocks and 10 blocks. The 18 block model has the same subfault size (40 km x 40 km) as Tanioka et al. (2004a), except that four additional faults with the same size were added at the southwestern end of the 2003 Tokachi-oki source. The 10 block model has exactly the same configuration as the model of Hirata et al. (2003).

The slip distribution for the 18 block model is quite different from that of 2003 earthquake (Tanioka et al., 2004a) (Figure 2). Seafloor deformation shows two uplift peaks far off Akkeshi and near the Tokachi coast, while there is only one peak near the Tokachi coast in 2003. The slip and seafloor deformation extended to the east of Kushiro submarine canyon in 1952.

The slip distribution for the 10 block model shows that the maximum slip is smaller than that of Hirata et al. (2003) (Figure 4). The largest slip, 4.6 m, is estimated on subfault E, deeper part of Tokachi-oki, where the slip was 5.6 m in Hirata et al. (2003). The slip on subfaults F and I, located off Akkeshi, are less than 3 m, while they were 4.2 m and 7.2 m in Hirata et al. (2003). The seafloor deformation patterns are similar; two peaks near the trench axis off Akkeshi and deeper part of Tokachi-oki, although the amount and the locations are slightly different.

The 10 block and 18 block models have common features that they both have large slip in Tokachi-oki and off Akkeshi. The details of the slip distribution are different, probably reflecting the spatial resolution of the subfaults. Even so, slip distributions for the both models are clearly different from that of the 2003 earthquake.

4 19th century earthquakes and their tsunamis

For the earthquakes in the 19th century, macroseismic data, i.e., distribution of tsunami heights and seismic intensity, are the only available data to estimate the source areas.

The tsunami heights of the 1894 Nemuro-oki earthquake resemble those of the 1973 Nemuro-oki earthquake (Figure 3). The 1894 heights were estimated by Hatori (1974) on the basis of damage report of Omori (1895). The original damage report indicates that the tsunami damage increases from Kushiro towards the east. The eastward increase of tsunami heights seems to be a characteristic feature of Nemuro-oki earthquake.

The 1843 earthquake shows a different pattern more nearly like that of the 1952 tsunami. The tsunami heights were estimated by Hatori (1984) and Tsuji (1994) from damage descriptions. As in 1952, the largest tsunami (4-6 m) was reported from Akkeshi (Figure 2). However, historical documents are limited around Akkeshi, the population center of that time, and no information is available from the Toakchi coast.

Seismic intensity distributions also show different patterns for the Tokachi-oki and Nemuro-oki earthquakes (Figure 5). The isoseismals are elongated along the Pacific coast, because of subducting of Pacific plate, in which seismic waves travel with less attenuation. The largest intensity (6 on JMA scale) was registered around Tokachi coast in 2003 and 1952. The largest intensity was registered at the eastern edge of Hokkaido for the 1973 and 1894 Nemuro-oki earthquakes. The intensity distribution of the 1843 earthquake is limited in eastern Hokkaido and northernmost Honshu, but it seems more similar to Tokachi-oki earthquakes than to the Nemuro-oki events (Hatori, 1984).

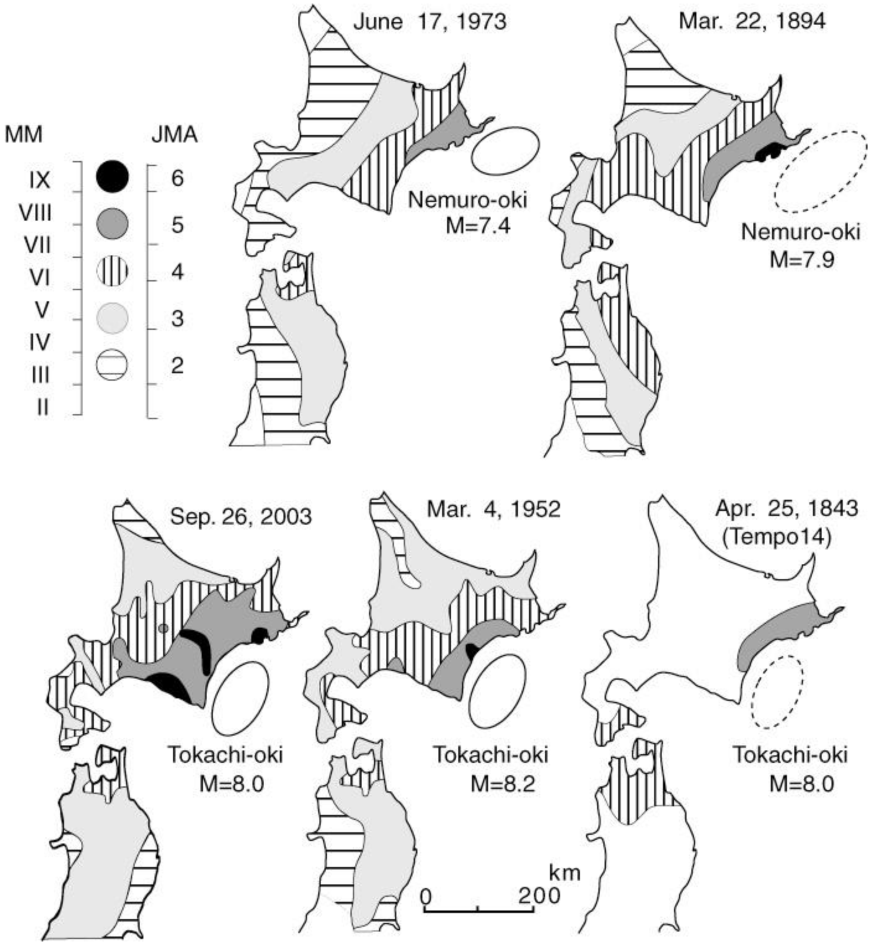

Fig. 5. Seismic intensity distribution of the 1973 and 1894 Nemuro-oki earthquakes (top) and of the 2003, 1952 and 1843 Tokachi-oki earthquakes (bottom). Modified from Hatori (1984); data on the 2003 from Japan Meteorological Agency.

5 17th-century tsunami

Tsunami deposits from the past 7000 years in eastern Hokkaido show that the southern Kuril trench repeatedly produced earthquakes and tsunamis larger than those recorded in the region’s 200 years of written history. Deposits of prehistoric tsunamis underlie lowlands and lagoons along 200 km of eastern Hokkaido’s Pacific coast (Nanayama et al, 2003).

In Kiritappu, prehistoric sand sheets extend as much as 3 km inland across a beach-ridge plain. The 1952 tsunami, by contrast, penetrated about 1 km from the coast

(Central Meteorological Agency, 1953). Diatom analysis indicates that the prehistoric sand sheets are of marine origin.

At Kiritappu and elsewhere, the time intervals between the extensive sand sheets average about 500 years (Nanayama et al., 2003). Volcanic ash layers aid in this correlation and dating. The youngest of the prehistoric sand sheets shortly predates ash layers from 1663 (Usu volcano) and 1667 (Tarumai). A second, earlier sand sheet postdates a 10th century ash that erupted from Baitoushan on the border of China and North Korea. Three to five sand sheets are commonly found between the 10th century ash and a Tarumai ash about 2500 years old.

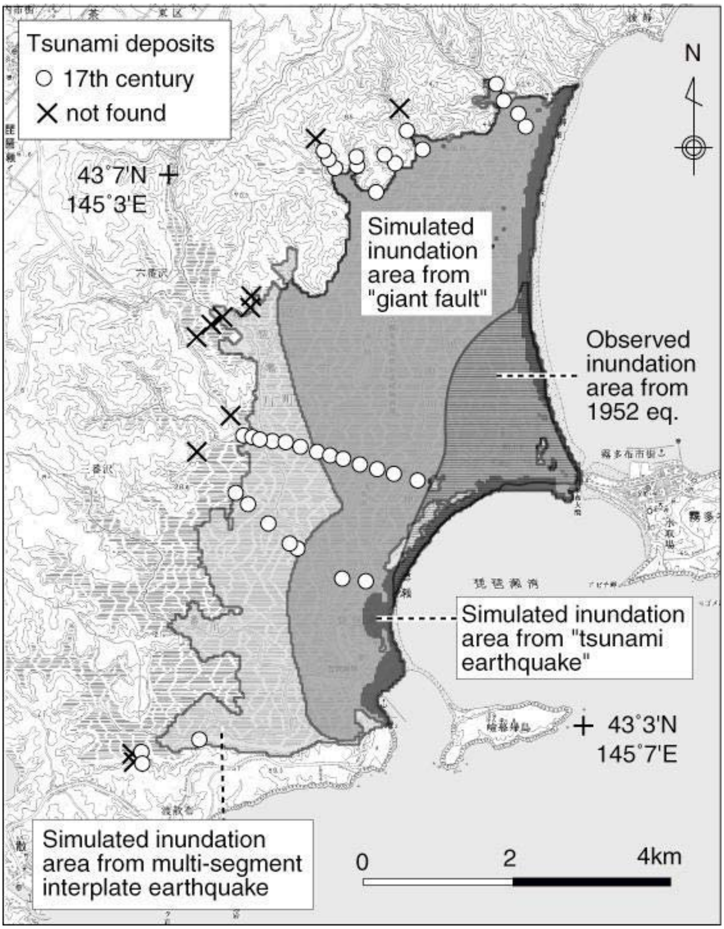

Fig. 6. Distribution of 17th century tsunami deposits in the Kiritappu marsh (Nanayama et al., 2003). Measured inundation area from the 1952 Tokachi-oki tsunami (Central Meteorological Agency, 1953) and computed inundation areas from three different fault models are also shown.

To explain the prehistoric tsunamis we considered three different fault models: giant fault, interplate earthquake, and tsunami earthquake (Figure 7). In all three models, the fault extends 300 km along the trench to include both the Tokachi-oki and Nemuro-oki segments. The giant fault extends 250 km down the plate boundary from the trench to 85 km depth, beneath the Pacific coast. The interplate earthquake fault is 100 km wide, and its depth range is between 17 and 51 km, corresponding to ordinary seismogenic region of subduction zones (Tichelaar and Ruff, 1993). The fault model for the tsunami earthquake is 50 km wide and located near the trench axis, similar to recent tsunami earthquakes (Satake and Tanioka, 1999). The wider the fault, the wider the area of seafloor displacement (Figure 7). For the giant fault, the coast is uplifted at the time of earthquake. For the interplate fault, the coast subsides during the earthquake.

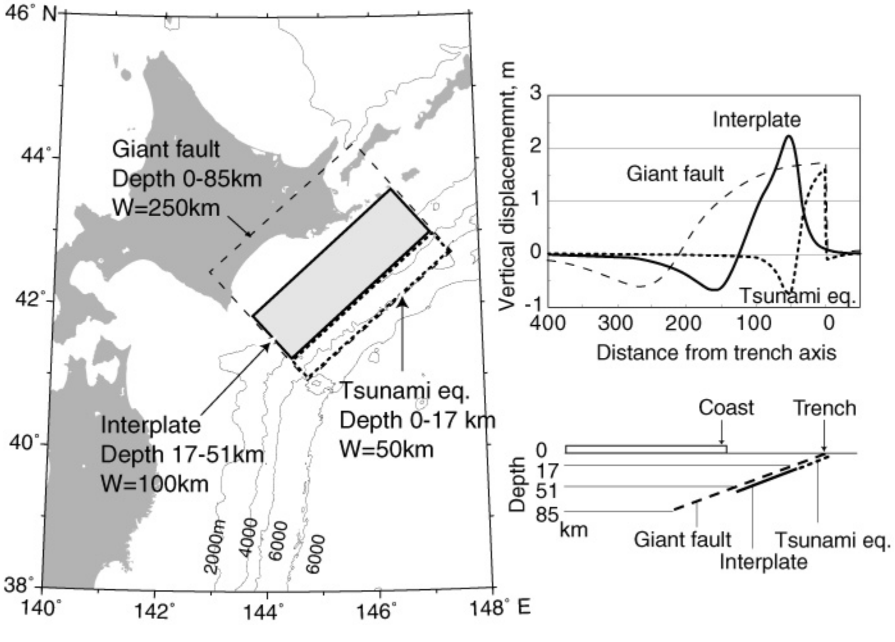

Fig. 7. Three fault models tested for tsunami coastal heights and inundation to Kiritappu marsh. Giant fault is 250 km wide, extending 0-85 km in depth. Interplate fault is 100 km wide and the depth range is 17-51 km. The tsunami earthquake model is 50 km wide, between the depth range of 0-17 km. The average slip is fixed at 5 m.

For inundation modeling, we use the grid size as small as 25 m and include inundation on land, or moving boundary condition, into the computation. For the computations of coastal tsunami heights, we use the finest grid size of 225 m, but without considering inundation or runup on land.

The computed inundation area is largest for the interplate earthquake fault, and the inundation is somewhat less for the giant fault. The tsunami earthquake model yields little inundation. The interplate fault model most nearly matches the mapped distribution of tsunami deposits (Figure 6).

The interplate fault model also yields the largest tsunami heights along the coast, while the giant fault yields the smallest coastal heights (Figure 8). For the giant fault, the coast, as well as the seafloor, is uplifted, hence the vertical displacement effective to tsunami generation is smaller than with the interplate fault, which lowers the coast. The interplate fault model yields larger tsunami heights than the tsunami earthquake on the Tokachi coast, while the heights are similar on the coast east of Kushiro.

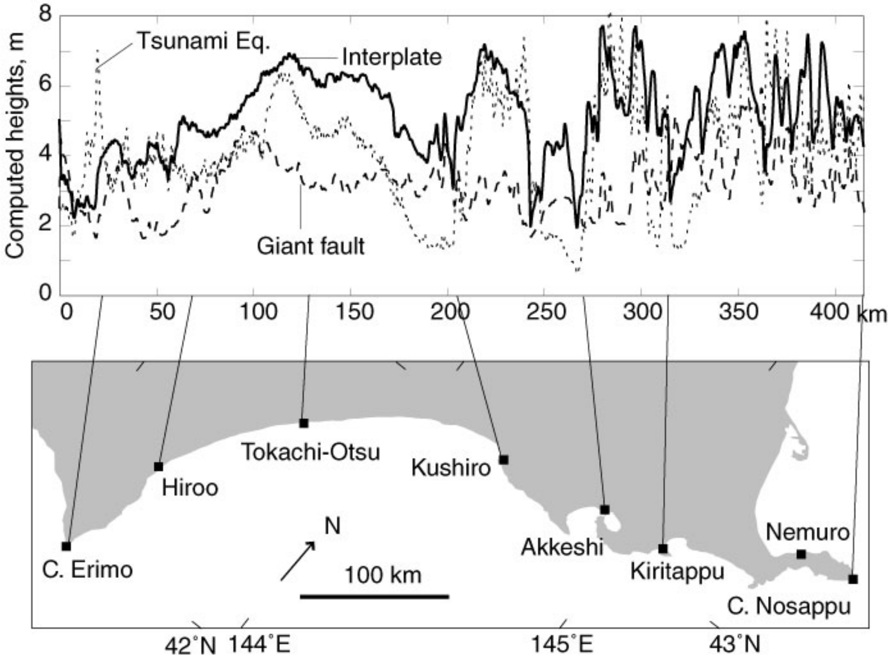

Fig. 8. Coastal tsunami heights computed from the three fault models. For the computation, the smallest grid size along the coast is 225 m.

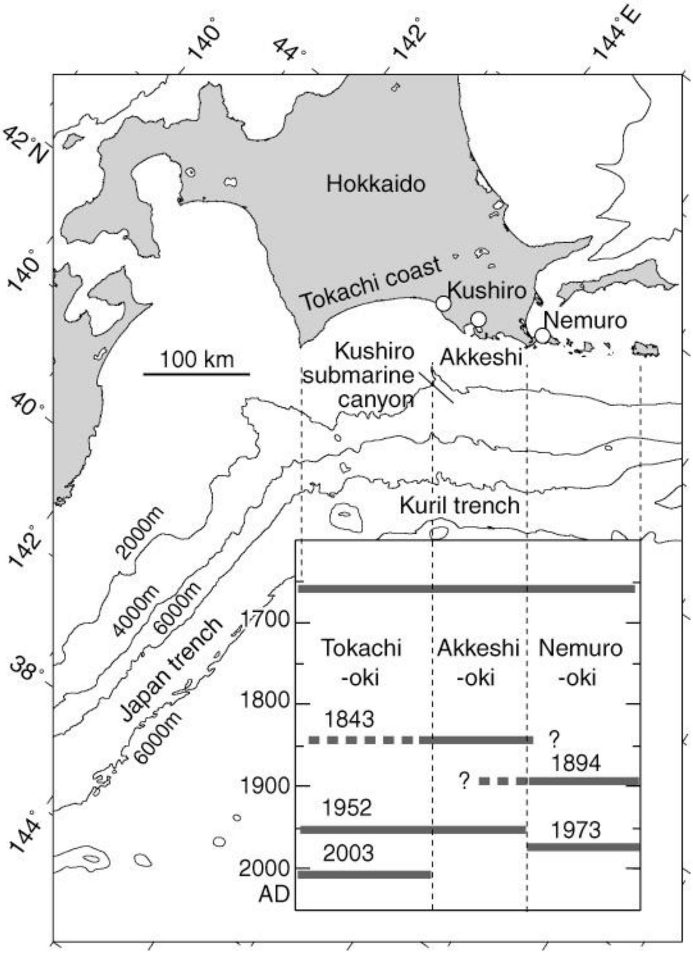

Fig. 9. Space-time diagram of the 17th through 21st century great earthquakes along the Kuril trench. On the basis of Hatori (1984), the 17th century earthquake (Nanayama et al., 2003) and the 2003 earthquake were added.

6 Summary

The source regions probably varied among earthquakes of the 17th through 21st centuries along the southern Kuril trench (Figure 9). Seismic waves and tsunamis indicate that the 2003 Tokachi-oki earthquake (M 8.0) source was limited in Tokachi-oki region, only the western half of Tokachi-oki segment in Figure 1. The tsunami waveforms and coastal runup height distribution of the 1952 Tokachi-oki earthquake (M 8.2) indicate that at least the tsunami source includes both Tokachi-oki and Akkeshi-oki regions, extending to the east of Kushiro submarine canyon (the Tokachi-oki segment in Figure 1). The 1973 Nemuro-oki earthquake (M 7.4) occurred in the Nemuro-oki segment, as shown by the aftershock distributions and tsunami heights. The 1894 Nemuro-oki earthquake (M 7.9) showed similar tsunami height distribution, but the source may be larger than that of 1973 event (Hatori, 1974). The tsunami height from the 1843 earthquake was largest around Akkeshi, suggesting that the source was located at least in Akkeshi-oki, but lack of historical data cannot constrain the eastern and western ends. A 17th-century earthquake generated unusually large tsunamis along the Pacific coast, and tsunami modeling shows that multi-segment (the Tokachi-oki and Nemuro-oki segments) interplate earthquake best explains such unusual tsunamis.

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