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Re-estimated fault model of the 17th century great earthquake off Hokkaido using tsunami deposit data

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ABSTRACT

Paleotsunami researches revealed that a great earthquake occurred off eastern Hokkaido, Japan and generated a large tsunami in the 17th century. Tsunami deposits from this event have been found at far inland from the Pacific coast in eastern Hokkaido. Previous study estimated the fault model of the 17th century great earthquake by comparing locations of lowland tsunami deposits and computed tsunami inundation areas. Tsunami deposits were also traced at high cliff near the coast as high as 18 m above the sea level. Recent paleotsunami study also traced tsunami deposits at other high cliffs along the Pacific coast. The fault model estimated from previous study cannot explain the tsunami deposit data at high cliffs near the coast. In this study, we estimated the fault model of the 17th century great earthquake to explain both lowland widespread tsunami deposit areas and tsunami deposit data at high cliffs near the coast. We found that distributions of lowland tsunami deposits were mainly explained by wide rupture area at the plate interface in Tokachi-Oki segment and Nemuro-Oki segment. Tsunami deposits at high cliff near the coast were mainly explained by very large slip of 25 m at the shallow part of the plate interface near the trench in those segments. The total seismic moment of the 17th century great earthquake was calculated to be 1.7×10^{22} N m (M_w 8.8). The 2011 great Tohoku earthquake ruptured large area off Tohoku and very large slip amount was found at the shallow part of the plate interface near the trench. The 17th century great earthquake had the same characteristics as the 2011 great Tohoku earthquake.

1. Introduction

Historically many great underthrust earthquakes occurred off Hokkaido in the Pacific Ocean. In 1843, 1952, and 2003, the Tokachi-Oki earthquakes occurred off eastern Hokkaido (Hatori, 1984; Hirata et al., 2003; Tanioka et al., 2004, respectively). In 1894 and 1973, the Nemuro-Oki earthquakes occurred off eastern Hokkaido at northeast of Tokachi-Oki earthquakes (Tanioka et al., 2007) (Fig. 1). In the southernmost Kuril Trench, large earthquakes have variability in spatial extent in both along-trench direction and trench-normal direction (Hirata et al., 2009).

Tsunami deposits due to prehistoric tsunamis have been found along the coast of eastern Hokkaido (Sawai, 2002; Nanayama et al., 2003, 2007). These tsunami deposits were found at far inland from the coast where tsunamis generated by above historic earthquakes did not reach. The elevations of the locations where tsunami deposits were found at cliffs near the coast were also much higher than estimated tsunami heights by historical earthquakes (Hirakawa et al., 2005). Nanayama et al. (2003) found that the latest event which left those tsunami deposits occurred in early 17th century. Satake et al. (2005) found that the 17th century great earthquake ruptured the plate interface at Tokachi-Oki, Akkeshi-Oki and Nemuro-Oki segments in Fig. 1 from tsunami simulation. Furthermore, Satake et al. (2008) estimated the fault model which reproduce the distribution of lowland tsunami deposits at five areas. However, the elevations of the locations where tsunami deposits were found near the coast as high as 18 m above the sea level (Hirakawa et al., 2005) were not completely explained by this fault model. In this paper, we estimate the fault model of the 17th century great earthquake to explain both locations of lowland tsunami deposits and highland elevations where tsunami deposits were found near the coast.

2. Previous studies of the 17th century tsunami

Several marsh and lakes exist along the coast of eastern Hokkaido, so peat layers are common in those places. Tsunami deposits and volcanic ash layers are also seen within those peat layers. Nanayama et al. (2007) found 9 prehistoric tsunami sand beds in those peat layers among the past about 4000 yrs.

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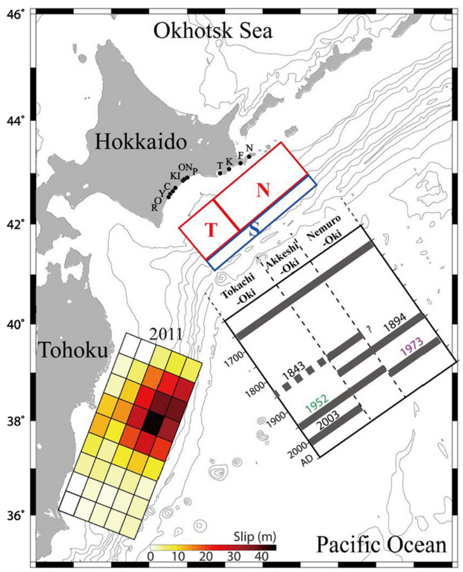

Fig. 1. The fault model of the 17th century great earthquake is shown (T: Tokachi-Oki segment, N: Nemuro-Oki segment, and S: Shallow part of the plate interface). Space–time diagram of great earthquakes along the southern Kurile trench from the 17th through 21st centuries is shown (modified from Satake et al., 2005). Green rectangles show the slip distribution of the 1952 Tokachi-Oki earthquake (Hirata et al., 2003) and purple rectangles show the slip distribution of the 1973 Nemuro-Oki earthquake (Tanioka et al., 2007). Black rectangles show the slip distribution of the 2011 Tohoku earthquake (Gusman et al., 2012). Black dots show locations where tsunami inundation area and tsunami heights were calculated; (R: Rekifune, O: Oikamanai, Y: Yudou, C: Choubushi, K: Kinashibetsu, O: Onbetsu, P: Pashukuru, T: Tokotan, K: Kiritappu, F: Fureshima, N: Nemuro-nambu). The depth contour interval is 1000 m.

Sawai et al. (2009) also found sandy deposits by 15 tsunamis in about 6000 yrs in those places.

The recurrence interval of those events is about 400∼600 yrs (Hirakawa et al., 2000a). The latest event occurred early 17th century because the latest tsunami deposits can be seen just under the volcanic ash caused by the 1667 Tarumae eruption (Nanayama et al., 2007).

Those tsunami deposits are found about 1∼4 km inland from the coast of eastern Hokkaido. At Kiritappu marsh, tsunami deposits can be seen far inland from observed tsunami inundation area by the 1952 Tokachi-Oki earthquake (Satake et al., 2005). On the other hand, tsunami deposits were also observed at high cliffs near the coast (Hirakawa et al., 2000b, 2005; Hirakawa, 2006). The elevations of the locations where tsunami deposits were found are more than 10 m. At Oikamanai pond in Taiki town, the elevation was 18 m at high cliff near the coast (Hirakawa et al., 2005). At Fureshima marsh, the elevation of the locations where tsunami deposit was found was 15 m (Nakamura et al., 2011). Observed tsunami heights by historical earthquakes that occurred off Hokkaido were less than 4 m from Erimo Cape to Kushiro and less than 7 m from Kushiro to Nosappu Cape along the coast of eastern Hokkaido. The prehistoric tsunami of the 17th century were much larger than those historical tsunamis.

Satake et al. (2008) estimated the fault model of the 17th century great earthquake by comparing locations of lowland tsunami deposits and computed tsunami inundations at five areas. The estimated slip amounts were 10 m in Tokachi-Oki segment and 5 m in Nemuro-Oki segment which includes Akkeshi-Oki segment in Fig. 1. The total seismic moment was calculated to be 0.8×10^{22} N m (M_w 8.5) with the rigidity of 4×10^{10} N/m^2. However, the tsunami heights along the coast of eastern Hokkaido calculated by this fault model (Satake et al., 2008) are smaller than the elevations of the locations where tsunami deposits were found near the coast in Tokachi (Hirakawa et al., 2005).

3. Data

3.1. Tsunami deposit data

Lowland tsunami deposit data used by Satake et al. (2008) at Oikamanai pond in Taiki town, Pashukuru pond in Kushiro city, Tokotan pond in Akkeshi town, Kiritappu marsh in Hamanaka town, and Nambu pond in Nemuro city are used in this study. New lowland tsunami deposit data found by Nakamura et al. (2011, 2012) at Kinashibetsu marsh and Onbetsu in Kushiro city, and at Fureshima marsh in Nemuro city are also used in this study. Lowland tsunami deposit data found by Hirakawa et al. (2000b) at Rekifune river in Taiki town, Yudou pond and Choubushi lake in Toyokoro town are also used in this study. The locations of those ponds and marsh are shown in Fig. 1. The eight elevations of tsunami deposits surveyed at highland cliffs near the coast by Hirakawa et al. (2005) are also used as data.

3.2. Fault model parameter

As we have already discussed before, the fault models of Tokachi-Oki segment and Nemuro-Oki segment are not enough to explain the elevations of the locations where tsunami deposits were found at high cliffs near the coast by Hirakawa et al. (2005). We need to find the fault model that can explain both lowland tsunami deposit data and the elevations of the locations where tsunami deposits were found near the coast.

Satake et al. (2008) tested tsunami earthquake model which rupture the shallow part of the plate interface. The tsunami earthquake model yielded locally variable coastal heights on the coast of eastern Hokkaido and yielded little tsunami inundation to lowland marshes where tsunami deposits were found. Therefore, we hypothesize that both widespread inland tsunami inundations and locally large tsunami heights near the coast are potentially explained by the fault model which rupture not only the plate interface at Tokachi-Oki segment and Nemuro-Oki segment but also the shallow part of the plate interface near the trench.

This hypothesis is come from the similarity of the 2011 great Tohoku earthquake (M_w 9.1) occurred along the Japan Trench and the 17th century great earthquake. Both tsunamis of the 17th century great earthquake and 2011 great Tohoku earthquake have characteristics that high tsunami heights were observed along the coast and large inundation areas were spread over wide areas. Slip distributions of the 2011 great Tohoku earthquake were estimated by several previous studies using seismic waves (Hayes, 2011), GPS data (Pollitz et al., 2011) and tsunami waveform data (Fujii et al., 2011). Gusman et al. (2012) also estimated the slip distribution of the earthquake using tsunami waveforms, GPS data, and seafloor crustal deformation data. The result shows that the largest slip amount of about 44 m ruptured the plate interface near the trench (Fig. 1). Satake et al. (2013) also estimated the slip distribution of the earthquake shown the huge slip on the shallow part of the plate interface near the trench. The characteristics of very large slip at the plate interface near the trench is common in all of the above previous studies. The largest slip near the trench was one of reasons to generate devastating tsunami along the coast in Tohoku. Before the 2011 great Tohoku earthquake occurred, it was believed that the shallow part of the plate interface near the trench is aseismic or rupture with a slow velocity. However, the 2011 great Tohoku earthquake indicates the plate interface can be ruptured with very large slip amount. Therefore, the fault model of the 17th century great earthquake can be similar to that of the 2011 great Tohoku earthquake.

We assumed that the 17th century great earthquake ruptured the shallow part of the plate interface near the Kurile trench with a large slip amount, similar to the 2011 great Tohoku earthquake.