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The 869 Jōgan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan

K. MINOURA
Institute of Geology and Paleontology, Graduate School of Science,
Tohoku University, Sendai 980-0845, Japan
F. IMAMURA
Disaster Control Research Center, Graduate School of Engineering,
Tohoku University, Sendai 980-8579, Japan
D. SUGAWARA
Institute of Geology and Paleontology, Graduate School of Science,
Tohoku University, Sendai 980-0845, Japan
Y. KONO
Department of Civil Engineering, Tohoku-Gakuin University,
Tagajō 985-8537, Japan
T. IWASHITA
Institute of Geology and Paleontology, Graduate School of Science,
Tohoku University, Sendai 980-0845, Japan

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ABSTRACT

The fore-arc region of northeast Japan is an area of extensive seismic activity and tsunami generation. On July 13, 869 a tsunami triggered by a large-scale earthquake invaded its coastal zones, causing extensive deposition of well-sorted fine sand over the coastal plains of Sendai and Sōma. Sediment analysis and hydrodynamic simulation indicate that the tsunami inferred to be triggered by a magnitude 8.3 earthquake spread more than 4 km inland then coast. We postulate that the sand layer was developed by the tsunami's first wave. Traces of large-scale invasion by old tsunami as recorded in the coastal sequences of the Sendai plain show about a 1000-year reoccurrence interval. We suggest that the Jōgan tsunami was much larger than tsunami generated by normal earthquakes in the subduction interface.

INTRODUCTION

An earthquake offshore of northeast Japan on July 13, 869 (Usami, 1987) produced a large-scale tsunami that damaged the low-lying coastal zones of northeast Japan. This 869 tsunami, named the Jōgan tsunami after the reign of then emperor, is unusual because of its widespread flooding.

The historical document Sandai-jitsuroku, which gives a detailed history of all of Japan for 1200 years, describes the Jōgan earthquake and subsequent tsunami as follows: "The large earthquake was accompanied by a luminous phenomenon, and coastal areas were illuminated in the dark. Some time after severe seismic shocks, a gigantic tsunami reached the coast and invaded entire Sendai plain. Rising seawater flooded an old castle town (Tagajō; Fig. 1A), causing the loss of 1000 lives." There is no historical evidence of co-seismic subsidence of the plain (Usami, 1987), therefore the prolonged period of flooding indicates that waves from the Jōgan tsunami sequentially invaded the coastal areas. Destroyed structural foundations that date from the 8th and 9th centuries, discovered in the ruins of Tagajō, are overlain by sediment layers containing artifacts from the middle 10th century. The committee studying the remains considers that exposed structures in the castle town collapsed owing to erosion by the Jōgan tsunami (Board of Education, Tagajō City, 2000).

More than a century has passed since scientific observations were begun in northeast Japan. During that time no tsunami has penetrated more than 2 km inland (Watanabe, 1998). On the basis of the Tagajō findings remains, seawater inundation by the Jōgan tsunami is thought to have reached 4 km or more inland. Is this deep penetration of seawater evidence of the occurrence of an unprecedented large-scale tsunami?

The Pacific coast of northeast Japan is known for repeated tsunami invasions (Fig. 1B; Watanabe, 2000). The Sendai plain, however, has not been struck by such a large tsunami since the Jōgan event. Urbanization has rapidly advanced to the coastal area, and most of the land inundated by the Jōgan tsunami is now developed. An understanding of the cause and effect of the region's extensive invasion by the Jōgan tsunami is important, not only for disaster prevention, but to gain an understanding of fore arc tectonic processes. We studied Jōgan tsunami deposits by sediment analyses and numerical hydrodynamic model to clarify the origin of that tsunami.

KEY WORDS: Jōgan earthquake, Historical tsunami, tsunami deposits, northeast Japan arc, numerical simulation

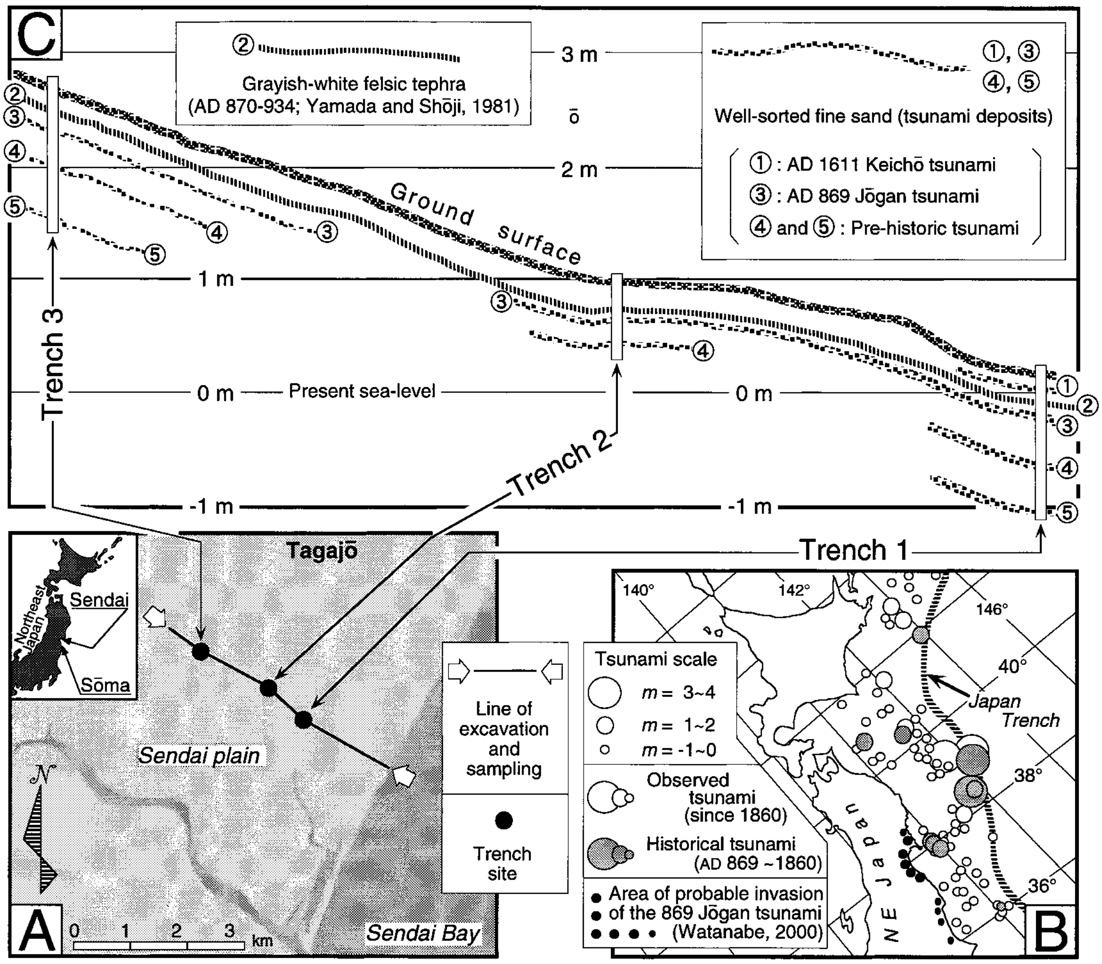

Fig. 1 Stratigraphic section of coastal sequences (C) on the Sendai plain (A). Well-sorted fine sand layers are intercalated in marsh deposits at three horizons. Layer 2 is interpreted as having been developed by the AD 869 Jōgan tsunami. Layer ②. Overlying felsic tephra are traceable inland 4.5 km or more from the shore. Historical and observed tsunami (B), which struck the Sendai plain, mostly originated in the region offshore Sendai Bay (Watanabe, 1989).

SEDIMENT LAYERS LEFT BY THE JŌGAN TSUNAMI

Historical documents record that the Jōgan tsunami invasion turned the flood plain into a broad expanse of water (Watanabe, 1998). We used trenching and coring to obtain traces of tsunami invasion on the coastal plains of Sendai and Sōma (Fig. 1A). Results of sediment facies analysis and a stratigraphic correlation of the deposits are shown in Figures 1C and 2 as sectional views of subsurface sequences. Sediment layers consisting of well-sorted, fine arkosic sand are intercalated with nonmarine black organic mud that includes fossil plant roots. A grayish-white felsic tephra underlies the Sendai plain. Below this tephra, we found three 2- to 15–cm-thick layers of well-sorted sand exposed at approximately 40cm intervals on our trench walls (Fig. 1C). The sand layer just beneath the tephra (layer 3 in Figure 1C) was traceable inland more than 4.5 km and showed evidence of landward tapering and fining. In the coastal sequences of Sōma a 1-cm-thick felsic tephra and underlying 2-cm-thick sand layer are intercalated in organic mud at the highest horizon. The absence of sediment grading within the sand layers of Sendai and Sōma suggests rapid sediment deposition.

We examined fossil diatoms in order to determine the source of the sediments. Dominant species in the sand layers are marine or brackish-water diatoms, or both, whereas the underlying or overlying organic mud has abundant fresh-water diatoms (Fig. 2). In the sand layer of the Sōma section, more than 60 % of the floral assemblage is marine. Because of the abundance of saltwater diatoms in the flora assemblages and excellent grain sorting, the arkosic sand must have originated in a shoreface or foreshore environment. The organic mud contains an abundance of deciduous pollen and fossil grass roots, indicative of deposition in a flood plain environment.

Landward tapering and sediment fining indicates that arkosic grains were transported inland from the coast. We conclude that the tsunami waves that penetrated the coastal zone of Sendai formed fast-flowing currents associated with rapid lateral translation of water and the suspension of sediments of marine origin. Storm surges along the coast of northeast Japan generally are agents of erosion and do not produce regionally extensive deposits of marine sand on the flood plain (Minoura et al., 1987; Minoura et al., 1993). The transport of marine materials therefore is best explained by in the sand layer having been produced by a tsunami

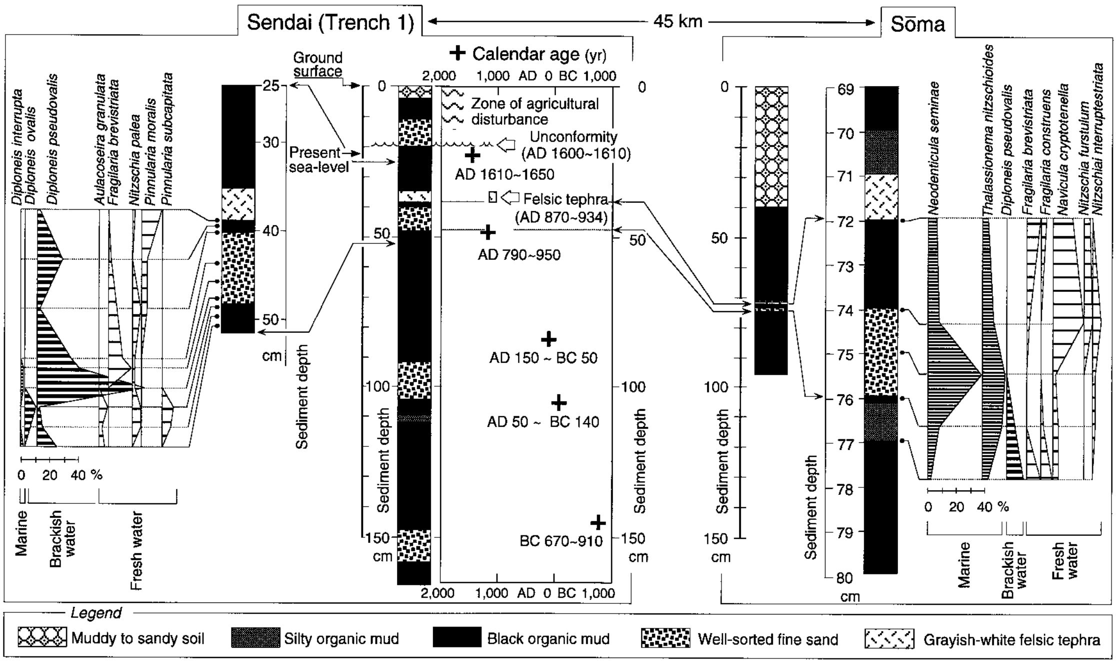

Fig. 2 Stratigraphic and paleontological correlation of the sedimentary sequences of Sendai (Trench 1) and Sōma. Fossil diatoms in the sediments indicate that sand layers of marine to brackish water origin were deposited in a back marsh environment. The thin layer of grayish-white felsic tephra at Sōma corresponds mineralogically and chemically (Fig. 1C) to that of Sendai. It follows that the sand layer just beneath the tephra is a trace of the invasion of the Jōgan tsunami. The Sendai plain was opened to agriculture about 400 years before by a feudal load. Agricultural disturbance of the subsurface layers reaches a depth of 10 to 20 cm at Trench 1, resulting in the formation of an unconformity just below the uppermost sand layer. Some historical documents report that cultivation was interrupted by invasion of the 1611 Keichō tsunami. The calendar periods of the sand layers are estimated by the 14C ages of wood fragments and indicate that the largest-scale tsunami struck the Sendai plain at intervals of about 1000 years.

(Bourgeois and Minoura, 1997; Minoura and Nakaya, 1991). Although we do not have definite stratigraphic evidence that the sand layer of Sōma has extensive distribution regionally, the deposition of marine materials in fluvial environments shows that that sand has characteristics similar to the Sendai samples. Taking into account the landward thinning of the layer in the limited distribution found at the trench site, we conclude the sand is tsunami derived, as is the sand layer in Sendai.

Table 1. EPMA chemistry and refractive index (RI) values of glass shards in felsic volcanic products from geological sections at Sendai (Trench 1) and Sōma.

Constituent	Sōma	Sendai (Trench 1)
SiO_2	79.057	79.390
TiO_2	0.145	0.134
Al_2O_3	12.179	13.605
$FeO+Fe_2O_3$	1.269	0.633
MgO	0.183	0.392
MnO	0.051	0.081
CaO	1.283	1.398
Na_2O	3.686	3.620
K_2O	2.147	0.748
Total (wt. %)	100.000	100.001

Locality	Sōma	Sendai (Trench 1)
RI value of glass shards	1.497 - 1.502	1.500 - 1.504

TSUNAMI DEPOSIT AGE

Felsic volcanic activity to the north of Sendai about 1100 years ago resulted in the deposition of an extensive tephra layer over northeast Japan (Jōgan tephra; Akojima and Danbara, 1991). Yamada and Shōji (1981) performed radiocarbon dating on wood chips from this tephra, which indicated an age range corresponding to the years 870-934 A.D. The reflective–index values of the glass shards from this tephra range from 1.494 to 1.503 (Yamada and Shōji, 1981; Akojima and Danbara, 1991). Refractive-index measurements and EPMA geochemistry results for glass shards in the tephra from Sendai and Sōma are consistent with published data (Table 1). The chemical constituents of the glass shards from the Sendai tephra are very similar to those of the Sōma tephra. Except for the Jōgan tephra, no extensive deposition of felsic volcanic products has occurred during the last 3000 years (Akojima and Danbara, 1991). We conclude that the felsic layers present in the coastal sequences correspond to the tephra produced by the 870-934 volcanic eruption. Two thin arkosic intercalations are present in the Sōma section at a depth of about 100 to 150 cm. It follows that the 2-cm-thick sand layer just beneath the Sōma tephra corresponds to sand layer ③ at Sendai (Fig. 1).

We conducted radiocarbon dating on wood fragments from the organic mud at Sendai (Trench 1) with a scintillation measuring device. The results shown in Figure 2 are calibrated to calendar years. The range for the date of the sand layer just beneath the Sendai tephra is 790-950 (1 s range). This includes the date estimated from the age of the tephra (870-934). From archaeological evidence and geochemical findings, we conclude that the Jōgan tsunami invaded the Pacific coast of northeast Japan and deposited marine sand over extensive areas of the flood plains of Sendai and Sōma just before deposition of the Jōgan tephra.

SEISMOTECTONICS OFF THE SENDAI COAST

The mechanism that triggers earthquakes along the arc-trench boundary of northeast Japan, discussed in various previous studies, is closely related to the westward subduction of the Pacific plate beneath the northeast Japan arc (Hasegawa et al., 1978; Minoura and Hasegawa, 1992). Numerous large-scale earthquakes have occurred in the region offshore Sendai Bay (Usami, 1987). Recent GPS observations (Nishimura et al., 2000) show that the plate boundary is being shortened by east-west compression and strain energy accumulating offshore Sendai. Some past earthquakes have generated tsunami with waves several meters high (Watanabe, 1998). Hatori (1987), who studied many old documents recording historical offshore earthquakes, estimated that the magnitude of the 1793 Kansei earthquake was about 8.2. He judged that the 1611 Keichō tsunami that invaded the coastal area of the Sendai plain (Fig. 1C) was caused by an 8.1 magnitude earthquake. The type of crust deformation and mode of fault movement depend on the tectonic processes. If two sets of fault movement are linked in the accretionary wedge, it is probable that the magnitude will be 8.0 or more offshore Sendai (Earthquake Research Committee of the Japanese Government, 2000).

Considering the hydraulic characteristics of long-wave propagation over the entire area of northeast Japan, the probable source

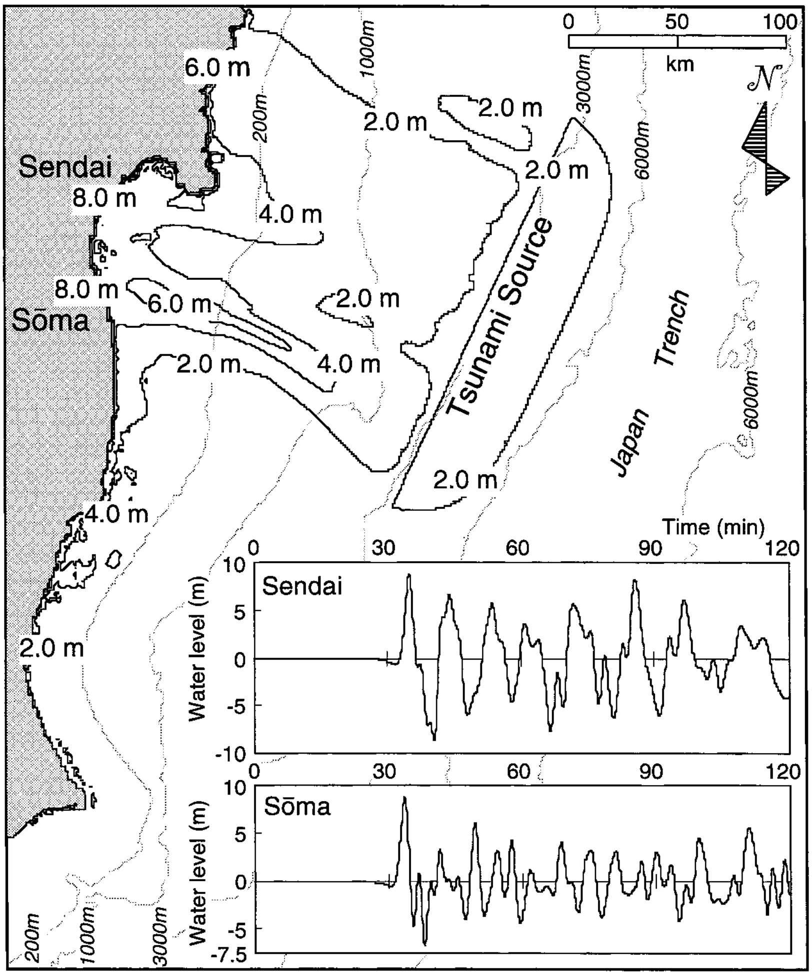

Fig. 3 Results of the numerical simulation of the Jōgan tsunami. Based on historical documents and proposed fault parameters of the Jōgan tsunami (Satō, 1989), a model of the tsunami source was established. The computational region covers the area 37°N to 39°N and 143°E to 144°30'E. An interval of 2 s and spatial grid size of 1 km were used. The simulation covers wave propagation for 5 hours. The maximum water-elevation contours and the time history of the water levels at Sendai and Sōma are shown for 2 hours. After 30 min, a tsunami with waves 8 m high struck the Sendai plain. Thin dotted lines show submarine contours in meters of depth.

of the Jōgan tsunami was shoreward of the continental shelf. The seismic damage and wave heights described in historical documents have maximums along the coast of the Sendai plain (Watanabe, 2000), indicative that the Jōgan earthquake took place in the overlying arc-crust, probably within the accretionary wedge, not in the subduction interface far from land. Focal mechanisms of modern earthquakes and the displacement of major faults in the accretionary wedge off northeast Japan (Zhao et al., 1990) lead to the inference that the fault movement of the Jōgan earthquake was caused by WNW-ESE compressional tectonics.

Based on reported structural damage, Watanabe (1998) concluded that the seismic intensity of the Jōgan earthquake was 5 or more at Tagajō. If the seismic intensity region of 5 to 6 is within a radius of r km, the relationship between the radius r and earthquake magnitude M is expressed by the equation $\log r = 0.50M - 1.85$ (Muramatsu, 1969). Estimating that the epicenter was 150-200 km offshore Sendai, we calculated the earthquake magnitude as about 8.3.

ORIGIN AND NUMERICAL RECONSTRUCTION OF THE JŌGAN TSUNAMI

Information on the scale and geometry of fault movements facilitates accurate reproduction of tsunami. The distribution of observed aftershocks within the accretionary wedge forms a seismic plane, indicative of a thrust fault dipping around 45° westerly (Hino et al., 1996). For this model, we conducted a numerical simulation of tsunami generation and propagation using TUNAMI-N2 which is based on a shallow-water theory consisting of nonlinear long-wave equations (Minoura et al., 1997, Minoura et al., 2000). In this tsunami model, sediment transport and its energy dissipation are not included because their effects are not significant in the sea region (Takahashi et al., 2001). Bathymetric data were derived from submarine topographic maps (scale 1:250000) published by the Meteorological Agency of Japan. The area was overlaid with a grid of cells, the side of each cell being 1000 m. A grid size of 100 m was used near the coastline. Using the fault parameters presented by Satō (1989) and comparing the simulation results of several fault models and the estimated tsunami heights in the present study, we established a composite-fault model for the most plausible source of the Jōgan tsunami. The proposed tsunami source is location: lat. 37° to 39°N, long 143° to 144°30’E; magnitude: 8.3; fault size: 200 km long; 85 km wide; 1 km deep; fault angle: 25° strike, 45° dip, 90° slip; vertical displacement of the sea bottom 5.6 m. Figure 3 giving results of the numerical simulation of the Jōgan tsunami, shows that a train of waves with a maximum height of 8 m reached the shores of Sendai Bay 30 minutes after the earthquake occurred.

DISCUSSION AND CONCLUSIONS

Despite the moderate wave height (~8 m) scale inferred from the numerical model, the extensive deposition of well-sorted arkosic sand suggests that waves of the Jōgan tsunami reached inland areas of the Sendai plain.

Matsumoto (1985), who studied the Holocene evolution of coastal sequences in northeast Japan, concluded that development of the Sendai plain resulted from the seaward progradation of fluvial systems. He made clear that progradation has continued steadily for the last 5000 years. Using inversion analysis of geodetic data (1966-1995), El-Fiky and Katō (1999) estimated that the Sendai plain subsides at the rate of 6-7 mm/year. This finding shows the Sendai plain to have been susceptible to vertical displacement. We believe that this coastal subsidence was canceled by a following uplift.

Due to agricultural disturbance of subsurface layers (Fig. 2), the depth of the Jogan tsunami deposit varies from 10 to 40 cm (Fig. 1C). On the assumption that the surface elevation was 50 cm lower than at present, we made a numerical simulation of tsunami wave propagation for the on-land region. Results show that the first tsunami wave triggered by an earthquake of magnitude 8.3 would have spread 4 km inland from the then coast. Synthetic marigrams of the shore of Sendai show that the first wave would be the biggest, subsequent waves reaching the coast at about 7.5-min intervals (Fig. 3). The relationship between the surf similarity parameter, ξ, and the classification of tsunami-induced sedimentation (Imamura et al. 1997) also provides information about whether marine sand was deposited by the tsunami on the plain in the area. We estimated a ξ value of 1.4×10^{-2} and a coastal slope of 0.001 using the calculated results for the first tsunami, height 5 meters and wave period 10 minutes, indicative of marine sand being deposited in the area. Run-up simulation that includes the interactive model for wave and sediment is required for the further study of sedimentation. Our simulation suggests that marine sediment was transported by the first wave and that the rapid regular arrival of following waves prevented a rundown of the waters by the first wave, resulting in the flooding of the area.

Two thin layers of arkosic sand that underlie the Jōgan tsunami deposit can be traced inland from the coast for more than 4 km (Fig. 1). Continuity landward tapering, and the sediment-fining pattern indicate a tsunami origin for these sand layers. We believe that the scale of the two early tsunami suggested by sand layers ④ and ⑤ is equal to that of the Jōgan tsunami and that they also were associated with widespread flooding. The depositional ages inferred from ^{14}C dating suggest that gigantic tsunamis occurred three times during the last 3000 years (Fig. 2). The respective calendar age ranges of the lower two layers are BC 140 - AD 150 and ca. B.C. 670-910 (1 σ range). The recurrence interval for a large-scale tsunami is 800 to 1100 years. More than 1100 years have passed since the Jōgan tsunami and, given the reoccurrence interval, the possibility of a large tsunami striking the Sendai plain is high. Our numerical findings indicate that a tsunami similar to the Jōgan one would inundate the present coastal plain for about 2.5 to 3 km inland.

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