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Marine incursions of the past 1500 years and evidence of tsunamis at Suijin-numa, a coastal lake facing the Japan Trench

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Abstract: Sandy deposits of marine origin underlie the floor of Suijin-numa, a coastal lake midway along the subduction zone marked by the Japan Trench. The deposits form three units that are interbedded with lacustrine peat and mud above a foundation of marine, probably littoral sand. Unlike the lacustrine deposits, all three sandy units contain marine and brackish diatoms. The middle unit (B) contains, in addition, graded beds suggestive of multiple waves of long wavelength and period. The uppermost unit (C) probably dates to a time in the area's written history when the lake was separated from the sea by a beach-ridge plain at least 0.5 km wide and several metres high. Units A and B postdate AD 540–870, and unit C postdates AD 1030–1640 as judged from radiocarbon dating of leaves and seeds. Unit B pre-dates AD 915 and unit C postdates that year as judged from a tephra within the peat that separates units B and C. The age constraints permit correlation of unit B with a tsunami in AD 869 that reportedly devastated at least 100 km of coast approximately centred on Sendai. Unit C may represent a later catastrophic tsunami in 1611, or perhaps a storm surge that inundated much of Sendai. The lake lacks obvious signs of tsunamis from the region's largest twentieth-century earthquakes, which were centred to the north in 1933 (M 8.1) and directly offshore in 1936 (M 7.5), and 1978 (Mw 7.6).

Key words: Tsunami deposits, diatoms, coastal lakes, historical records, Japan Trench, late Holocene.

Introduction

Subduction along the Japan Trench conveys the Pacific plate beneath northern Honshu at 8–10 cm/yr. This subduction is believed to be responsible for the region's main historical and recent Miyagi-oki (offshore from Miyagi) earthquakes and tsunamis, although the slip during these earthquakes accounts for just ~25% of the cumulative plate convergence in northeast Japan (Kanamori, 1981). The rest of the plate convergence may be accounted for by prehistoric, unusually large interplate earthquakes. Tsunamis that run kilometres inland can be recorded by sand sheets that they leave behind, as found in Hokkaido (Nanayama *et al*., 2003), Chile (Cisternas *et al*., 2005) and North America (Atwater *et al*., 2005). Such tsunami deposits may aid in estimating the recurrence intervals and relative sizes of prehistoric earthquakes.

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Coastal lakes and lagoons can serve as sediment traps for tsunamis and storms. High energy inflows associated with such events into the lagoon can deposit exotic material derived from offshore, beaches and backshore areas. Accordingly, we selected a closed coastal lake (Suijin-numa) to seek the geologic signatures of tsunamis that might correlate with two of the largest tsunamis known from historical records in northeast Japan: the Jogan tsunami of AD 869 and the Keicho Sanriku tsunami of AD 1611.

Tsunamis in the area's written history

The written history of tsunamis near Sendai begins with a well-documented disaster more than 1000 years ago. It is known from the 'Nihon Sandai Jitsuroku' series of historical documents for the Heian period (AD 794–1192). The documents mention a large

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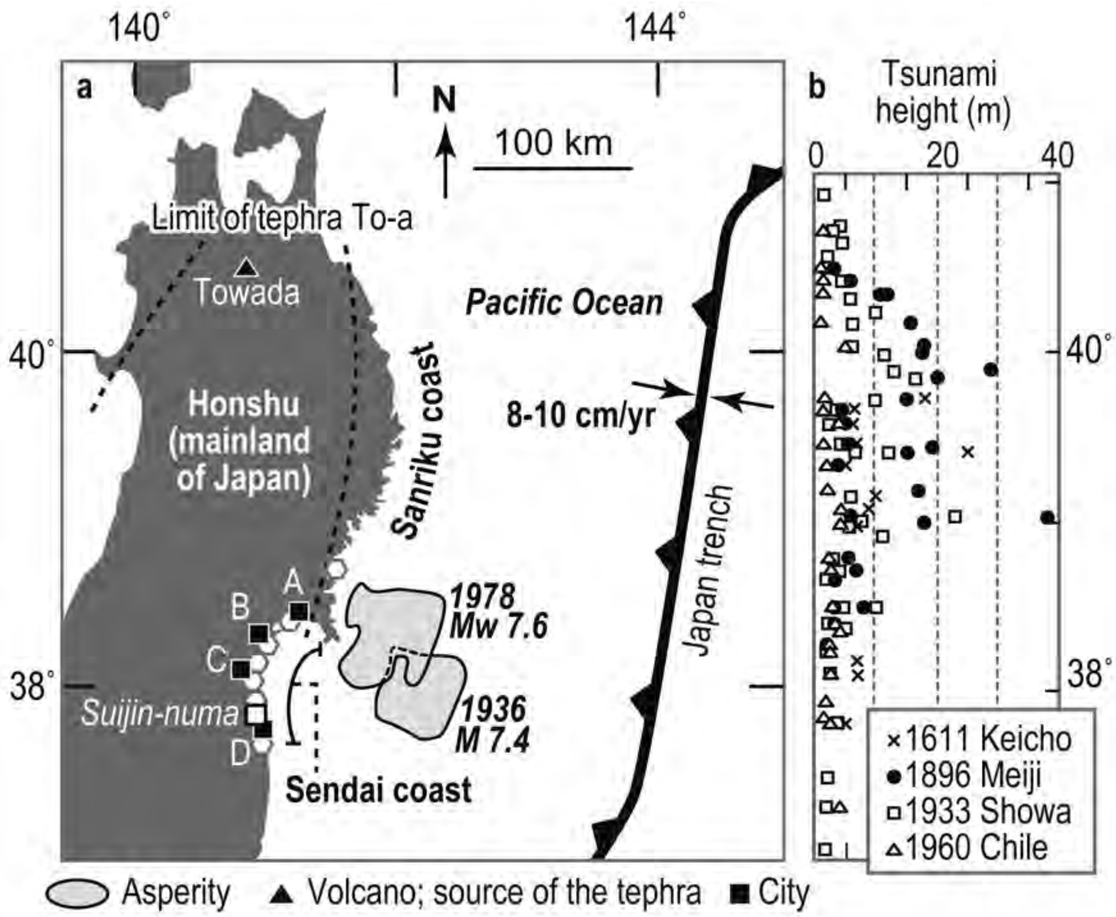

Figure 1 Index map. (a) Northern Honshu (mainland of Japan), near Japan Trench. Asperities of the 1936 and the 1978 Miyagi-oki earthquakes from Yamanaka and Kikuchi (2004). Names of cities: A, Tagajo; B, Sendai; C, Iwanuma; and D, Soma. Limits of tephra To-a from Hayakawa and Koyama (1998). Hexagons along the coast are sites where there are oral or written records of the 896 Jogan tsunami (Watanabe, 2001). (b) Heights of the four tsunamis recorded historically (Imamura and Kawase, 1933; Imamura, 1934; Katô *et al*., 1961)

earthquake and a tsunami on Jogon year 11, 5th month, 26th day (9 July AD 869, in the Julian calendar). As translated by Imamura (1934), the account reads,

> On the 26th of the 5th month a large earthquake occurred in the province of Mutsu (divided since into the five provinces of Iwaki, Iwashiro, Rikuzen, Rikutyu and Mutsu). The sky was illuminated like day-time. A little later, people, panic-stricken by the violent trembling, were lying on the ground; some were buried under fallen houses and others inside wide-opened ground fissures, while horses and cows desperately ran about and trampled each other. A number of castles, towers, and other tall structures collapsed. Then roaring like thunder were heard toward the sea. The sea soon rushed into the villages and towns, overwhelming a few hundred miles of land along the coast. There was scarcely any time for escape, though there were boats and the high ground just before them. In this way about 1,000 people were killed. Hundreds of hamlets and villages were left in ruins.

A long hiatus in written records for the Sendai area began a few decades after the Jogan tsunami. As a result, the area's written history of tsunamis does not resume until the early 1600s, when pacification and taxation under the Tokugawa shogunate (AD 1603–1867; called the Edo period) promoted widespread record-keeping in northeast Japan (Koyama, 1999; Ishibashi, 2004).

The historical records resume with a great tsunami on 2 December 1611. Known in Japan as the Keicho Sanriku tsunami, it is reported to have drowned 5000 persons in the Date domain and another 3000 'people and horses' farther north (Anonymous, 1995, excerpted in Atwater *et al*., 2005). The loss estimates are lower in an official record written in Sendai ('Date Chika Kiroku') with 50 casualties in the Date domain (Earthquake Research Institute, 1982) and 1783 overall (Imamura, 1934; Earthquake Research Institute, 1982).

Based on comparison of flooding at a few places along the Sanriku coast, Imamura (1934) concluded that the 1611 tsunami was 30–40% larger than the 1896 tsunami, the worst tsunami disaster in modern Japanese history with 22 000 casualties (Yamashita, 1997). The 1611 tsunami maximum heights, as inferred by Hatori (1975) from accounts of the flooding and losses, are 6–8 m in Iwanuma and 5–6 m in Soma (Figure 1b). The tsunami reportedly caused extensive inundation on the Sendai coast (Abe *et al*., 1990; Tsuji and Ueda, 1995; Watanabe, 1997, 1998).

The 1611 tsunami poses an enigma because it arrived two hours after ground shaking recorded in Sendai and four hours after shaking recorded in Edo (Tokyo), and also because none of that shaking caused damage (Imamura, 1934; Hatori, 1975, 1995; Watanabe, 1997; Tsuji, 2003). Accordingly, the 1611 earthquake has been called a tsunami earthquake (Aida, 1977), like the earthquake associated with the disastrous 1896 tsunami. Tsuji (2003) inferred that the 1611 tsunami resulted from a submarine landslide.

In addition to the Jogan and Keicho disasters, the written history of Sanriku and Sendai coasts includes many subsequent tsunamis of both nearby and distant origin. Those generated nearby include tsunamis in 1763, 1793, 1856, the 1896 Sanriku (Tsunami Magnitude: Mt 8.2–8.6; Tanioka and Satake, 1996), 1933 Sanriku (Magnitude: M 8.1), and 1960 Chile (Moment Magnitude: Mw 9.5).

Table 1 Summary of historical accounts of six large storms[a]

Gregorian calendar	Japanese calendar[b]	Notes
21 September 1540	Tenbun 9, 8th month, 11th day	Typhoon around Watari (near Suijin-numa)
31 August 1648	Keian 1, 7th month, 13th day	Storm surge in Sendai and Natori
8 September 1699	Genroku 12, 8th month, 15th day	Gale near Sanriku coast
28 September 1790	Kansei 2, 8th month, 20th day	Gale near southern Sanriku coast
24 September 1816	Bunka 13, 8th (a leap) month, 3rd day	Gale near southern Sanriku coast
10 August 1828	Bunsei 11, 6th month, 30th day	Gale and heavy rain near northern Sendai coast

[a] Historical documents are complied by Arakawa *et al.* (1961). We supplemented the records with Endo and Nagasawa (1989) and Watarichoushi Hensan I'inkai (1975).
[b] Years: Japan uses two different ways of counting years; one is western Anno Domini, and the other is Japanese era name on the basis mainly of the emperor's reign. Months and days: because Japan used a lunisolar calendar before 1 January 1873, date in historical documents needs recalculation for the Gregorian calendar. In the present day, the Japanese usually use literal translation for name of the months (eg '1st month' for January).

The 1933 tsunami may have been the largest of these at Suijin-numa. In nearby Isohama (a coastal village near Suijin-numa) it damaged about 11 houses and attained heights of ~4 m (Imamura and Kawase, 1933; Earthquake Research Institute, 1934). The effects of the 1933 tsunami at Suijin-numa itself, however, are unknown to us.

Interplate earthquakes in 1936 (M 7.5) and 1978 (Mw 7.6) (Miyagi-oki earthquakes; Figure 1a) were notable for strong shaking but not for associated tsunamis. The maximum tsunami heights near Sendai were less than 1 m.

Historical and recent storm records

In addition to the tsunamis of AD 869, the Sendai area has a long documented history of storms, some of which we consider below as potential causes of sediment deposition in Suijin-numa. This history appears in a nationwide compilation by Arakawa *et al.* (1961), who examined over 380 old documents. The compilation includes six large storms near Sendai between AD 701 and 1865 (Table 1). Again, because of the documentary hiatus in the tenth through to the sixteenth centuries, this catalogue for Sendai must be considered incomplete. Among the six, the only storm clearly associated with a storm surge occurred on 31 August 1648. It extensively inundated Sendai and Natori and drowned a man and 36 horses. The other five produced little or no reported inundation near Sendai, just strong winds and heavy rains.

We are confident that Suijin-numa has escaped flooding from the sea resulting from storms over the past 80 years. Since the 1930s, Sendai has been hit by five large storms; the 1947 Kathleen typhoon, the 1948 Ione typhoon, the 1950 Flood, the 1986 Typhoon-No.10 and the 2002 Typhoon-No.6. These typhoons and floods inundated much of the Sendai area, but the inundation area excluded the Suijin-numa area. During the highest tide since 1934, in a storm surge on 24 December 1980, the sea surface stood more than 1 m below Suijin-numa's modern beach berm.

Previous studies on tsunami deposits near Sendai

Geological evidence of historical and prehistoric tsunami have also been identified in the Sendai area. Abe *et al.* (1990), Minoura and Nakaya (1991) and Minoura *et al.* (2001) found five sand sheets beneath paddy fields, and correlated two of the sheets with the AD 869 and AD 1611 tsunamis. In similar geomorphic settings, Sugawara *et al.* (2001) identified a tsunami deposit associated with the AD 869 tsunami at Tagajo and Soma, based mainly on diatom assemblages.

Method

Site selection

We chose Suijin-numa for its isolation from floods, storm surges and tsunamis. The lake, surrounded by hills about 30 m high, has only a small drainage basin and almost no fluvial inflow. Its waters come instead from rainfall and groundwater. The lake drains to the sea via a narrow, largely man-maintained outlet that has not, to our knowledge, allowed seawater to enter the lake. This outlet currently crosses a beach-ridge plain now ~700 m wide (Figure 2a, b). According to Matsumoto (1977, 1984), the Sendai coast has three lines of beach ridges. Two of these beach ridges (B1 and B2 in Figure 2a), with present heights less than 3 m relative to the present mean tidal level, separate Siujin-numa from the sea. They are low enough to have been overtopped by the 1933 tsunami (~4 m at Isohama; Earthquake Research Institute, 1934) but not by the tsunamis of 1960 (1.3–1.8 m at Tsurishi, about 3 km far from Isohama; The Committee for Field Investigation of the Chilean Tsunami of 1960, 1961).

Beach ridge B2 may pre-date AD 1600. Historical documents report that people began to build a long canal, called Teizan-Unga, in 1601 at the latest. The position of this canal coincides with a swale between beach ridges B1 and B2. The canal's construction around Tagajo, Sendai and Iwanuma continued until early in the Meiji era (AD 1868–1912) (Figure 1a).

Sample collection

We sampled deposits at five sites below the floor of Suijin-numa with a 3 m geoslicer, consisting of a sample tray and a shutter plate (Nakata and Shimazaki, 1997; Takada *et al.*, 2002). On a plastic raft we first pushed down the sample tray with a small vibrator, then drove the shutter plate and finally pulled up both tray and shutter together by means of a tripod-mounted winch.

Observation of lithostratigraphy

To observe sediment samples, we made peels using OH-1, a hydrophilic grout widely used by archaeologists and geologists in Japan and also applied in the USA (Takada and Atwater, 2004). The more permeable the sediment, the further the OH-1 penetrates. The difference in penetration yields topographic relief on the peel that brings out bedding defined by differences in grain size. We estimated mean grain size from the peels by hand lens and feel. We logged stratigraphic contacts as sharp if spanning less than 2 mm; otherwise we call them gradual.

Diatom analysis and radiocarbon dating

Subsamples for diatom analysis were taken at 5 mm to 2 cm depth intervals from core 1. The subsamples were treated using a method described in Sawai (2001). At least 300 diatom valves

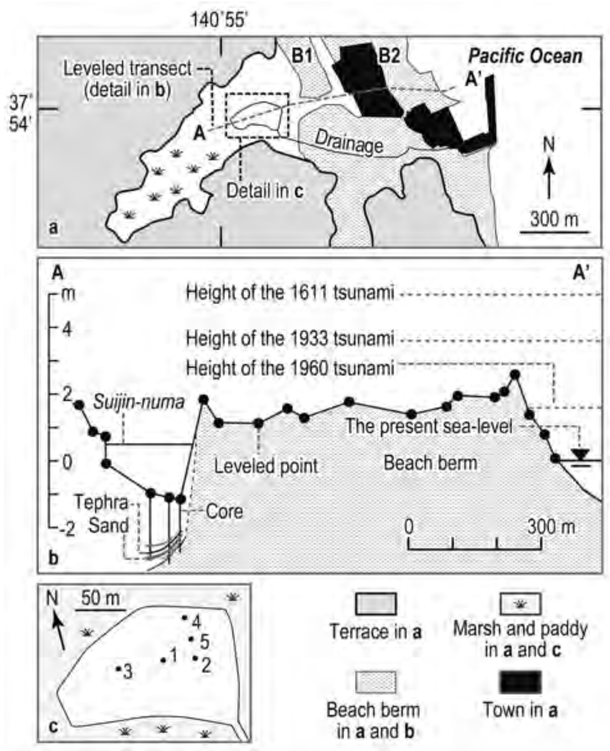

Figure 2 (a) Geomorphology around Suijin-numa. A levelled transect is across marsh, paddy, and beach berm (A–A′). (b) Cross-section view of the transect A–A′. Vertical exaggeration is ~75. Tsunami height refers Imaizumi-Nakamura (now Soma) (1611 tsunami: 5–6 m; Hatori, 1975), Sakamoto (near Suijin-numa) (1933 tsunami: 3.7 m; Imamura and Kawase, 1933) and Tsurishi-Imaizumi (near Soma) (1960 tsunami: 1.3–1.8 m: The Committee for Field Investigation of the Chilean Tsunami of 1960, 1961). (c) Core locations in Suijin-numa

were identified and counted under oil immersion in each sample. Plant macrofossils and charcoals for radiocarbon dating were selected under a binocular microscope. The selected samples were washed with distilled water to remove soil humus and roots. The radiocarbon analyses were made by accelerator mass spectrometry (AMS) at Beta Analytic Radiocarbon Laboratory.

Stratigraphy

Deposits beneath the lake bottom are dominated by peat that rests on sand (unit S), contains several sand units (A, B and C) and also a volcanic ash layer (Figures 3–5). We divide the peat into biozones 2, 4, 6, 7 and 9 by plant macrofossils and diatom assemblages and by peat texture (Figure 6), and correlate four sand units based mainly on lithostratigraphic characteristics and their ages (Figure 3).

Peat

The peat of the lowest biozone (2), found in cores 1 and 2, is dominated by freshwater diatoms *Aulacoseira granulata*, *A. crassipunctata* and *Pinnularia* spp. and by a few seeds of *Carex* sp. (Figure 6). Radiocarbon ages of the peat (Biozone 2) range from 2000 to 1000 cal. yr BP (No. 5 and 7 in Table 2). Diatoms and plant macrofossils in the peat differ little between bottom of the peat and the tephra (Biozones 2, 4 and 6). Above the tephra, peat decreases mud fractions, and becomes dominated by benthic freshwater diatoms. Dominant species are *Cocconeis placentula*, *Encyonema mesiana*, *Eunotia* spp. and *Synedra ulna* (Biozone 7). Still higher in the peat, in Biozone 9, the peat contains more mud than below, and the diatom and plant macrofossil assemblages change. Common taxa include freshwater diatoms, *Melosira undulata* and *Aulacoseira italica*, and many seeds and leaves of *Trapa bispinosa*. This composition is the same as the modern bottom sediments of Suijin-numa.

Sand units

Cores 1, 2, 4 and 5 penetrated the basal sand unit (S) but did not reach material beneath it. Change in grain size shows normal grading around the top of unit S. This sand has parallel or low angle cross laminations near the top of the unit. The sand includes many shells (bivalves and gastropods), brackish benthic diatoms, *Diploneis smithii* and *Rhaphoneis surirella*, and marine planktonic diatoms, *Thalassionema nitzschoides* and *Chaetoceros* spp. (Figure 6). Lower part of the sand unit S includes only marine-brackish species, whereas the upper part is characterized by mixture assemblages of marine-brackish and freshwater diatom species. In core 4, a bivalve *Nuttallia olivacea*, which lives from intertidal to subtidal (~10 m below the mean tidal level) range, is on the hinge and likely to have been buried in a living position.

Sand unit A, found in cores 1 and 2, is 2–3 cm thick (Figure 4). Its basal contact is sharp and its upper contact gradual. It lies merely about 2 cm above the top of sand unit S. In core 1, unit A contains a lower subunit of fine sand (A1) that is capped by plant detritus. The sand above A1 shows inverse and normal grading (A2 and A3) and is capped by faintly laminated muddy very fine sand (A4). The sand contains mixed assemblages of brackish and marine diatoms (*Diploneis smithii*, *Rhaphoneis surirella* and *Thalassionema nitzschoides*) and freshwater taxa (*Aulacoseira italica* and *A. crassipunctata*).

Sand unit B, 8–13 cm thick, contains multiple beds of upward fining sand and plant detritus (Figures 4 and 5). Like unit A, it has a sharp contact with underlying peat, and the upper contact is gradual. The lowest part of unit B (B1) consists of poorly sorted coarse-medium sand that includes a few pebbles. This basal subunit is overlain by a pair of upward fining beds (B2 and B3). The tops of each of these beds have parallel laminae or low angle cross-laminae (Figures 4 and 5). B3 is capped by ~5 mm of plant detritus (B4), which is in turn overlain, abruptly, by fine to very fine, normally graded sand with ripple (?) laminae (B5). The subunit above B5 is sandy mud that contains plant fragments (B6) and 0.1–1.0 cm of very fine sand (B7). Sand B contains brackish and freshwater diatoms. Dominant species include a brackish diatom, *Diploneis smithii*, and the freshwater taxa *Aulacoseira italica* and *A. crassipunctata*.

Sand unit C, ~0.5 cm thick, is the only sand unit above the tephra layer (Figure 5). We found it in cores 1 and 3 only. Its diatom assemblages are a mix of brackish and freshwater taxa dominated by *Diploneis smithii*, *Aulacoseira italica* and *Melosira undulata*. We could not see any laminations in sand unit C.

Tephra

We recognized one volcanic-ash layer in the geoslices from Suijin-numa. It probably correlates with a white ash layer previously found at Tagajo and Soma (Yamada and Shoji, 1981; Sugawara *et al*., 2001). Radiocarbon ages of the white tephra from Tagajo gave an age range of AD 870–934, and correlated with To-a, a tephra erupted in 915 from Towada volcano (Hayakawa and Koyama, 1998; Machida and Arai, 2003), about 250 km north of Suijin-numa (Figure 1a). Radiocarbon ages from Suijin-numa independently support this correlation with To-a. Ages from plant materials just below the tephra (No. 14 and 15 in Table 2) cover the age of the eruption of Towada volcano.

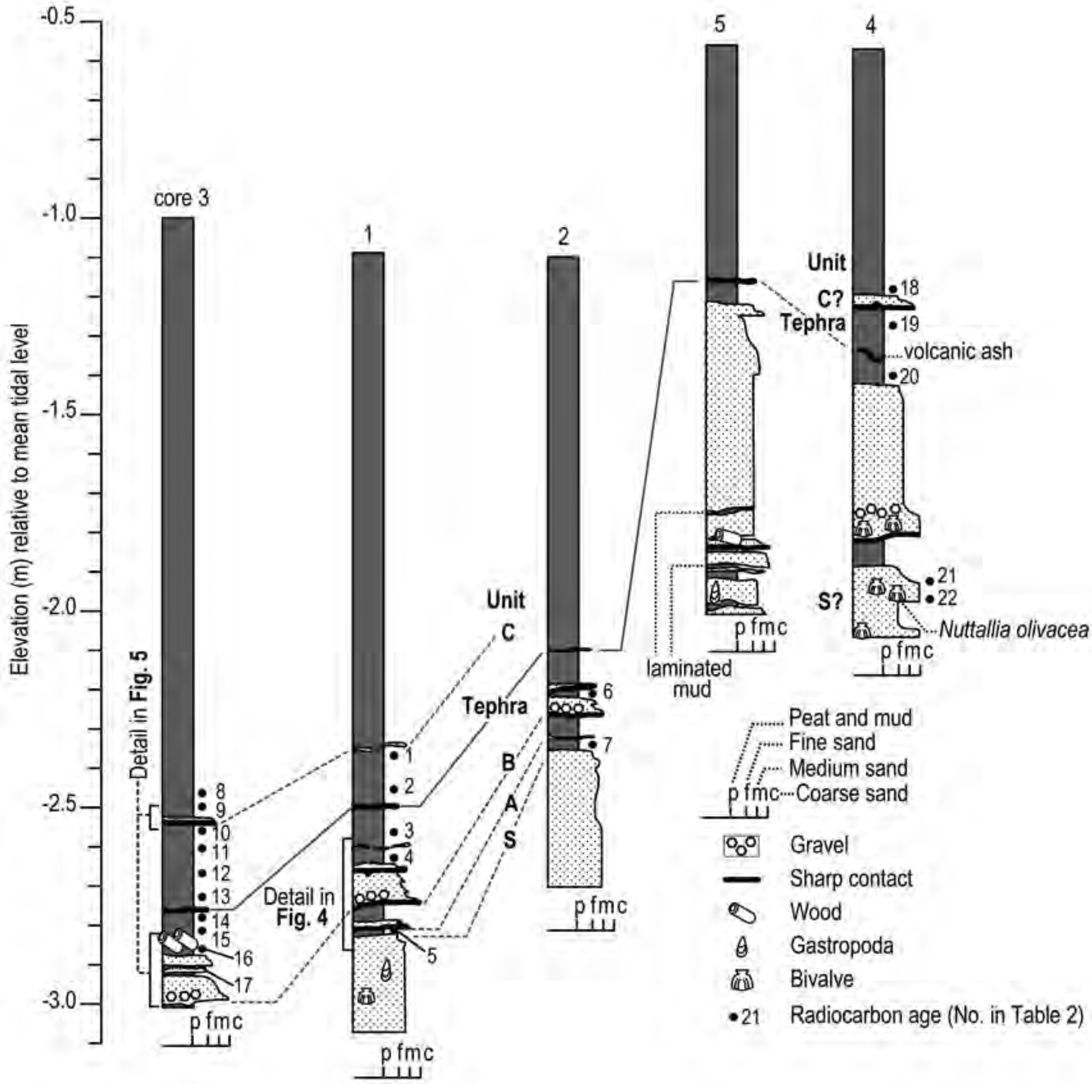

Figure 3 Lithostratigraphy of Suijin-numa. Radiocarbon details in Table 2

Palaeoenvironmental history at Suijin-numa

The stratigraphy at Suijin-numa records an overall change from marine to fresh water. The marine conditions are marked by the basement sand unit S. Its fossils include the growth-position remains of an inter- and subtidal bivalve species *Nuttallia olivacea*, as well as marine planktonic diatoms. This assemblage gradually changes into mixture assemblages of freshwater, brackish and marine diatoms around peat-over-sand stratigraphic contact (Biozone 1). Above Biozone 1, the dominant species of the diatom fossil assemblages become freshwater only. This change in biostratigraphy shows that Suijin-numa became isolated from the sea and formed around the time of lowest peat-over-sand contact. This isolation established a freshwater lake at the site of Suijin-numa (Biozones 2–9).

Radiocarbon ages suggest that this isolation occurred between 3200 and 1100 cal. yr BP (No. 5 from core 1, No. 7 from core 2, No. 21 and 22 from core 4 in Table 2). This range is consistent with previously reported ages of beach ridges near Sendai. The beach ridges blocking Suijin-numa from the sea developed between ~2500 and ~730 ^{14}C yr BP, according to bulk-peat ages obtained by Matsumoto (1984).

In the few thousand years since the lake's isolation, marine sand has accumulated on the floor of Suijin-numa at least three times, marked by sand units A, B and C. Both brackish-marine planktonic and benthic diatoms are present in each of these three units. However, the marine incursions were temporary, as shown by the freshwater peat of Biozones 2–9. Furthermore, freshwater conditions like those of modern Suijin-numa have prevailed since the most recent of the marine incursions (marked by unit C), as judged from the diatoms and plant macrofossils of Biozone 9 (Figure 6).

Ages of sand units

We estimated limiting-maximum ages for the marine incursions marked by sand units A, B and C by radiocarbon dating of 12 samples, each consisting of plant detritus or charcoal fragments collected just below or within the sand (Table 2). In addition, we sought to bracket the time of each incursion by treating, as limiting-minima, ages of delicate plant detritus from peat above the sand.

The age of the sand unit A is constrained by four radiocarbon ages (No. 5, 7, 14 and 15 in Figure 3 and Table 2). Two of them, measured from seeds just below sand unit A in core 2 and leaves in core 1, suggest that unit A postdates AD 540–870 (from 1410 to

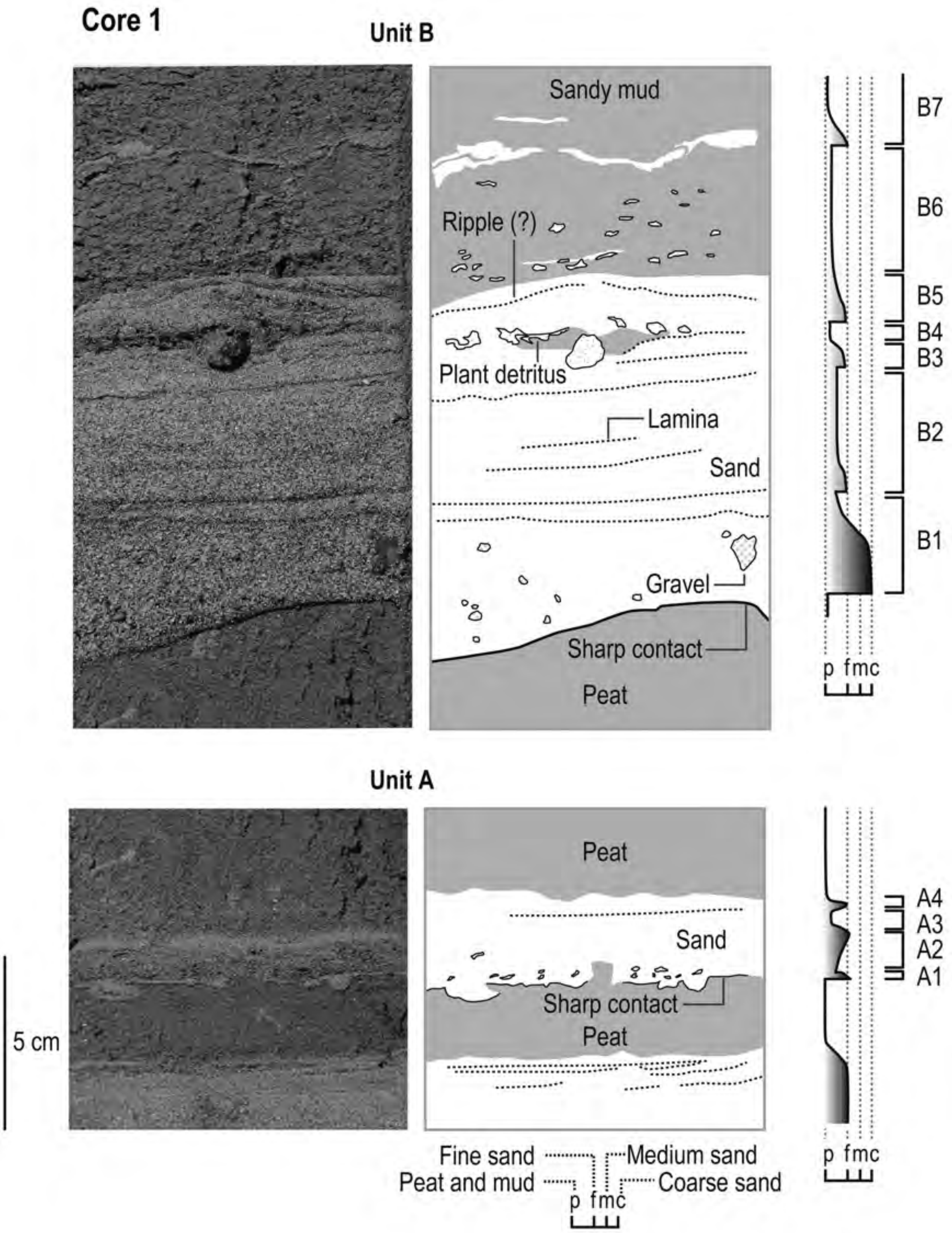

Figure 4 Peels of units A and B in core 1, shown in photographs (left) and sketches (right)

1080 cal. yr BP). The others, on seeds and charcoals in core 3, suggest that the unit pre-dates AD 1020 to 1260 (from 930 to 690 cal. yr BP) (No. 14 and 15 in Figure 3 and Table 2). Combined in OxCal (Bronk Ramsey, 1995, 2001), the four ages yield a sand-unit age of AD 690–1020 (1260–930 cal. yr BP; 95% probability) (Table 3).

The age of sand unit B is constrained by nine radiocarbon ages (No. 3–7, 14–17 in Figure 3 and Table 2) and the To-a tephra. Its limiting maximum ages, from samples collected below and within the sand, range from 40 BC to AD 1170 (from 1990 to 780 cal. yr BP) (No. 3–7, 16, and 17 in Figure 3 and Table 2). Of these samples, five are from plant material and charcoal fragments within unit B (No. 3 and 4 from core 1, No. 6 in core 2, No. 16 and 17 in core 3), and the others are from leaves and seeds that settled before unit B had deposited (No. 5 in core 1, No. 7 in core 2). Limiting minimum ages, from samples collected below the tephra, range from AD 1020 to 1260 (from 930 to 690 cal. yr BP) (No. 14 and 15 in Figure 3 and Table 2). Combining four ages from samples above and below the sand (No. 5, 7, 14 and 15 in Figure 3 and Table 2), an event age is yielded as AD 780–1120 (1170–830 cal. yr BP; 95% probability) (Table 3).

The tephra To-a sets a loose limiting-maximum age of AD 915 for Unit C. The unit is several centuries younger than that according to six radiocarbon ages on unidentified plant fragments, fruits

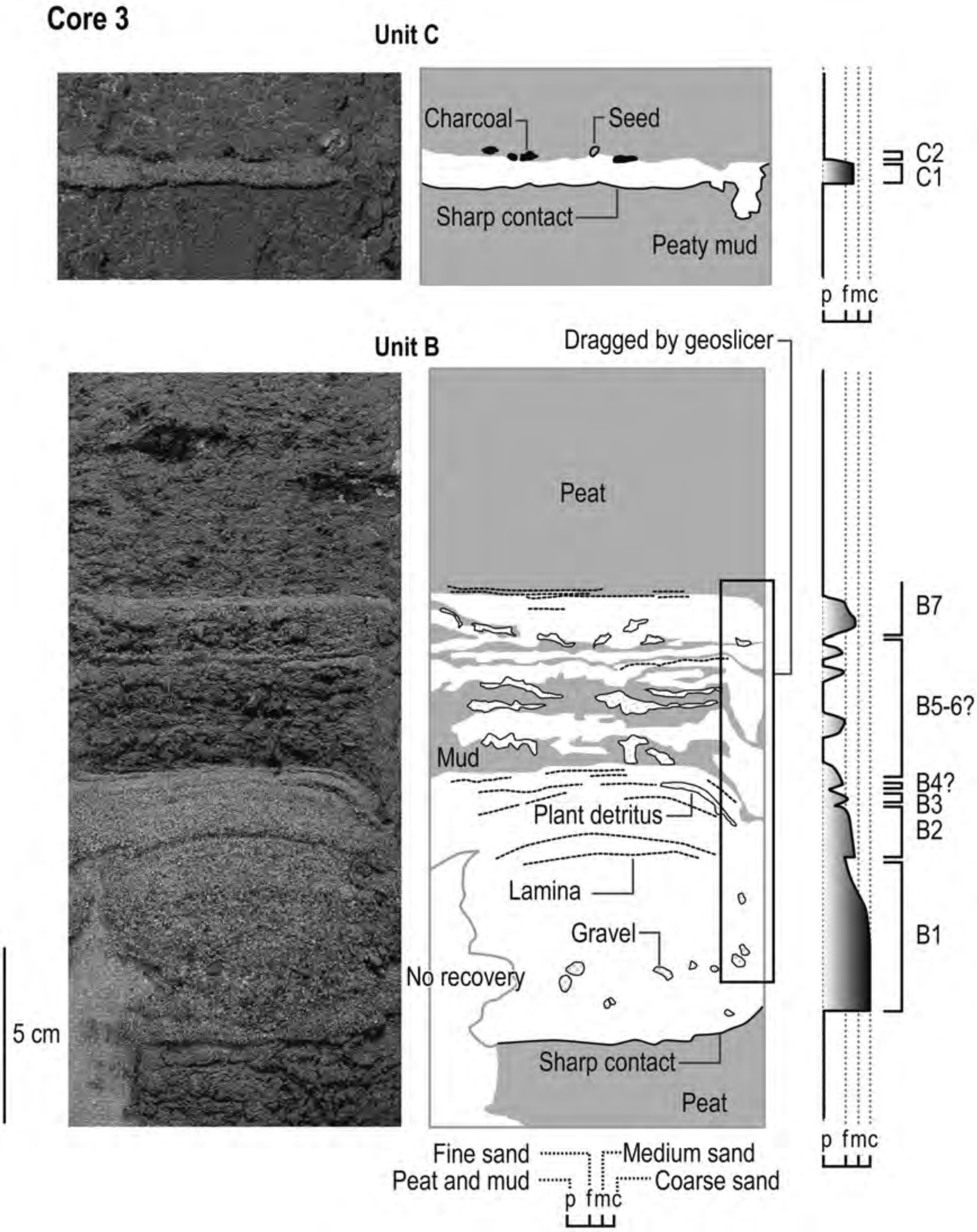

Figure 5 Peels of units B and C in core 3, shown in photographs (left) and sketches (right)

of *Trapa japonica*, and seeds of *Carex* spp. and *Brasenia schreberi* below Unit C (No. 1 and 2 in core 1, No. 10-13 in core 3). For limiting-minimum ages we use unidentified plant fragments and materials and *Trapa japonica* fruits (No. 8 and 9 in core 3). Combined in OxCal, the age is in the range AD 1440 to 1600 (510–350 cal. yr BP at 95% probability) (Table 3).

Tsunamis recorded by sand units at Suijin-numa

Criteria for identifying tsunami deposits

We evaluated the origin of the sand units based on (1) fossil records within sand units, (2) palaeoenvironmental setting, (3) correlation with historical documents in Japan and (4) sedimentary facies. As alternatives to tsunamis, we considered floods (eg, Hutchinson *et al*., 1997; Witter *et al*., 2001; Kelsey *et al*., 2005), storm surges and storm waves (Liu and Fearn, 1993; Otvos, 1999), slopewash from beach ridges, and vented-sand volcanoes from earthquake shaking (Eden and Page, 1998; Monecke *et al*., 2004). Diagnostic criteria used elsewhere include fossil records, environmental settings, thickness of the deposits, lateral extent of deposits and correlation with land-level changes. We tailored four criteria to the local conditions at Suijin-numa.

(1) Fossil records

Fossil assemblages within sand unit can be key information to estimate the origin of the sand. Unusual high-energy flow into

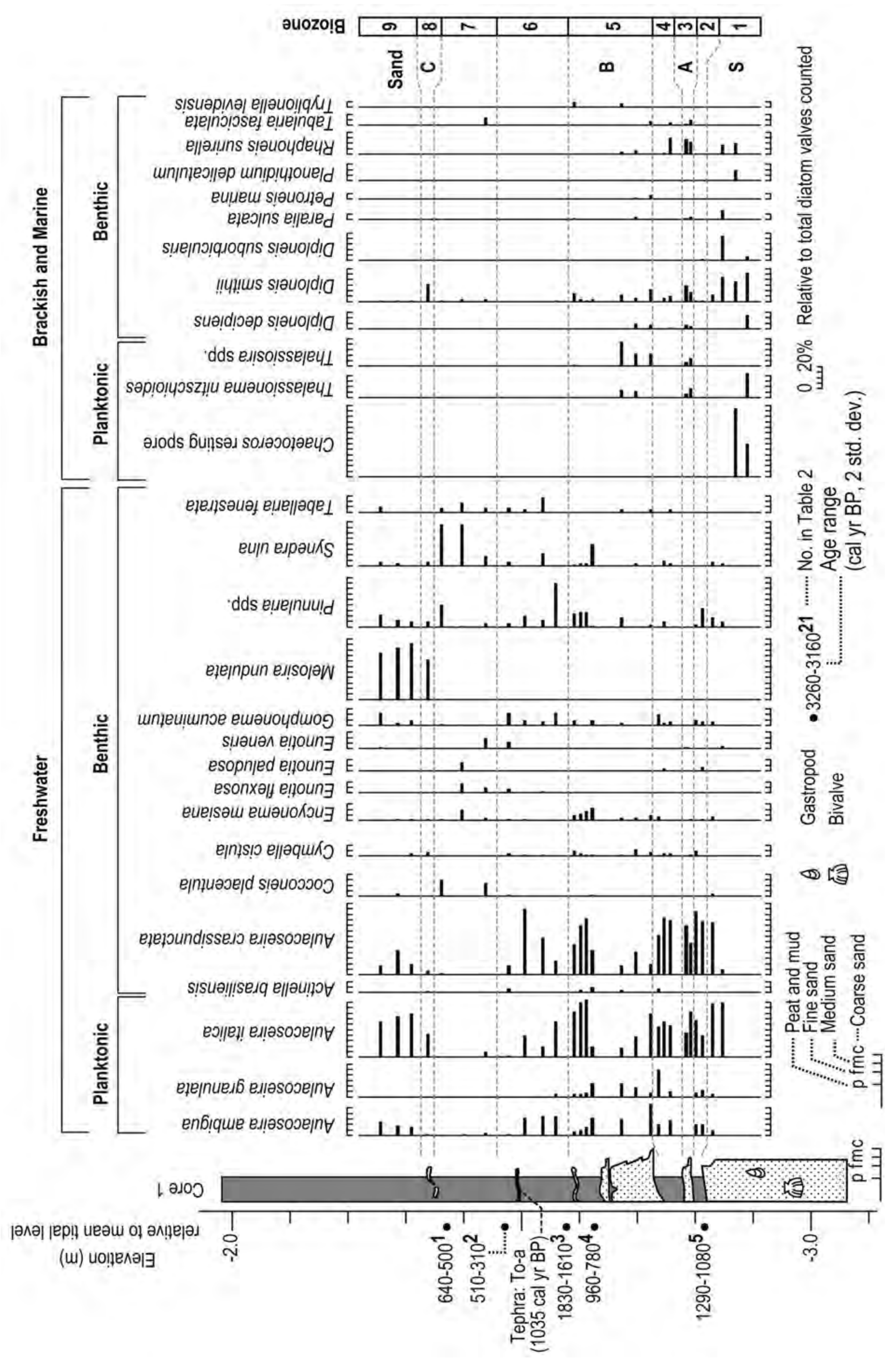

Figure 6 Fossil diatom assemblages in core 1

Table 2 Radiocarbon ages of plant macrofossils and charcoals

Sample no.	Core	Material	Position	Age (^{14}C yr BP)	Age (cal. yr BP)[a]	Lab no. (Beta-)[b]	Comments
1	1	Charcoal fragments	Below sand C	520±40	640–500	208546*	Limiting max. age of C
2	1	Fruits of *Trapa japonica*	Above tephra	370±40	510–310	208547*	Limiting max. age of C
3	1	Charcoal fragments	Within sand B	1800±40	1830–1610	208548	Limiting max. age of B and C
4	1	Plant materials	Within sand B	960±40	960–780	208549	Limiting max. age of B and C
5	1	Leaves	Below sand A	1260±40	1290–1080	207419*	Limiting max. age of A,B, and C
6	2	Seeds	Within sand B	1420±40	1390–1280	207420	Limiting max. age of B and C
7	2	Seeds	Below sand A	1450±40	1410–1290	207423*	Limiting max. age of A, B, and C
8	3	Fruits of *Trapa japonica*	Above sand C	310±40	490–290	208550*	Limiting min. age of C
9	3	Plant materials	Above sand C	540±40	650–500	208551*	Limiting min. age of C
10	3	Plant materials	Below sand C	390±40	520–310	208552*	Limiting max. age of C
11	3	Seeds of *Brasenia schreberi*	Below sand C	580±40	660–520	208553*	Limiting max. age of C
12	3	Seeds	Above tephra	900±40	920–730	208554*	Limiting max. age of C
13	3	Seeds of *Carex* spp.	Above tephra	620±40	670–540	207644*	Limiting max. age of C
14	3	Seeds	Below tephra	880±40	920–690	207643*	Limiting min. age of A and B, Limiting max. age of C
15	3	Charcoal fragments	Below tephra	920±40	930–740	208555*	Limiting min. age of A and B, Limiting max. age of C
16	3	Twig	Within sand B?	1310±40	1310–1170	208556	Limiting max. age of B and C
17	3	Charcoal fragments	Within sand B?	1930±40	1990–1740	208557	Limiting max. age of B and C
18	4	Leaves and seeds	Above sand B?	480±40	630–470	207425	
19	4	Seeds	Within sand B?	1140±40	1180–960	207424	
20	4	Leaves and seeds	Above sand B?	830±40	900–670	208558	
21	4	Shell of *Nuttallia olivacea*	Basal sand (S)	3350±40	3340–3070	207426	Living position
22	4	Shell fragment of *Nuttallia olivacea*	Basal sand (S)	3320±40	3320–3040	207427	

[a] Range at two standard deviations, computed with the calibration data of Reimer *et al*. (2004) and Hughen *et al*. (2004) and the calibration software OxCal 3.10 of Bronk Ramsey (1995, 2001).
[b] Ages of * were used for the OxCal program to estimate ages of tsunami deposits.

Table 3 Ages of events estimated using OxCal

Unit (event)	Age (cal. yr BP)	Age (AD)
C	510–350	1440–1600
B	1170–830	780–1120
A	1260–930	690–1020

low-energy depositional environments commonly associates with an allocthonous mixture of organisms from offshore, beaches, backshore and the area surrounding the study site. Among the organisms, diatoms have proved to be one of the most useful groups to detect whether the high-energy flow was from marine or fresh water, because of their adaptation to a variety of aquatic environments and the high preservation potential of their siliceous valves (Cullingford *et al*., 1989; Minoura *et al*., 1994; Hemphill-Haley, 1995, 1996; Hutchinson *et al*., 1997, 2000; Clague *et al*., 1999). We used diatoms to distinguish between salt and fresh water. However, by diatoms alone it is difficult to distinguish between tsunami and storm, or between a tsunami deposit and a vented-sand volcano erupted from marine sand.

(2) Documented effects of historical storms

Where the approximate position of the shoreline is similar to today, the effects of historical storms can serve as a guide to the likelihood of producing a storm sand bed on the floor of a coastal lake. The long written history of storms near Sendai aids in the use of this modern-analogue approach.

(3) Correlation with historical documents

Historical records provide reliable information on local storms and tsunamis. As stated above, northeast Japan has historical records of tsunamis and storms since the eighth to ninth centuries. If ages of event deposits are consistent with historical records, the origin of an event may be estimated.

(4) Sedimentary facies of sand units

Criteria for identifying subaerial tsunami and storm deposits may not be applicable directly for Suijin-numa. Tsunami deposits are commonly viewed as extending further inland (kilometres in the biggest examples) than do storm deposits (eg, Dawson *et al*., 1991; Nanayama *et al*., 2003; Cisternas *et al*., 2005). Also, normal grading is commonly reported from tsunami deposits (Dawson *et al*., 1991; A. Dawson *et al*., 1996; Benson *et al*., 1997; Minoura *et al*., 1997; Bondevik *et al*., 1998; Bourgeois *et al*., 1999). However, we could not assess them in Suijin-numa, because Suijin-numa is too restricted to permit the tracing of sand units laterally. Also, it is difficult to discuss the origin of event deposits only by grading in grain size. In small coastal lagoons, graded sand beds on the lake bottom might result not only from tsunamis and storms but also from earthquake-induced slumping and consequent turbidity currents (Otvos, 1999; Monecke *et al*., 2004).

Recently, some papers have recorded vertical changes in sedimentary structures observed in modern tsunami deposits on subaerial sites (eg, Nishimura and Miyaji, 1995; Sato *et al*., 1995; Shi *et al*., 1995; Gelfenbaum and Jaffe, 2003; Nanayama and Shigeno, 2006), and have attempted to distinguish between tsunami and storm deposits (eg, Nanayama *et al*., 2000; Goff *et al*., 2004; Tuttle *et al*., 2004; Morton *et al*., 2007). The authors inferred that vertical changes in the sedimentary structures of modern tsunami deposits were produced by changes in current direction (inflow and outflow) and changes in current velocities of tsunami waves. We appeal to these modern examples as grounds for interpreting sedimentary facies in the geoslices from Suijin-numa.

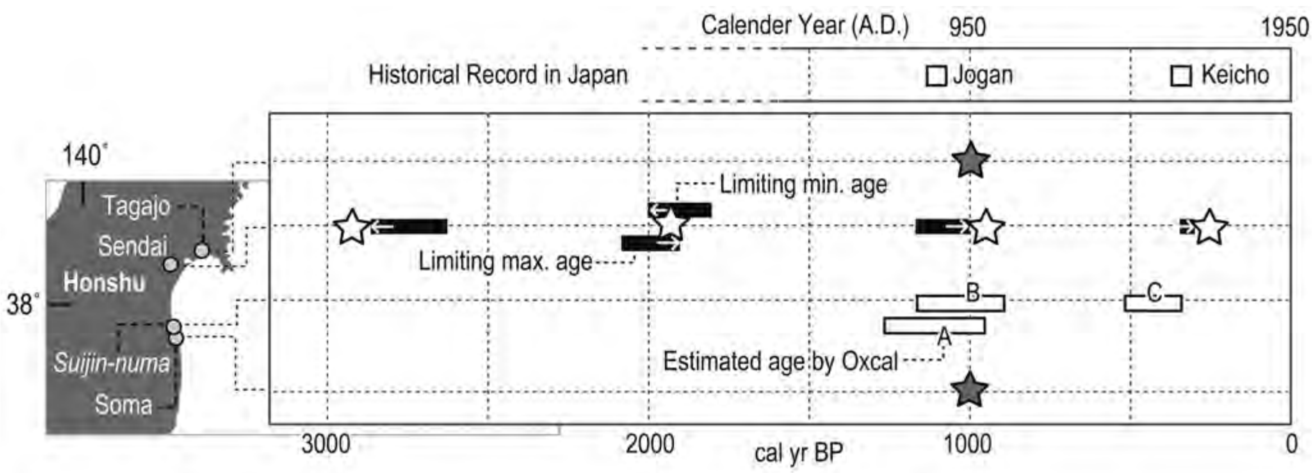

Figure 7 Summary of reported tsunami deposits and historical tsunamis along the Sendai coast. Open star: tsunami events estimated using radiocarbon ages (Abe *et al*., 1990; Minoura and Nakaya, 1991; Minoura *et al*., 2001). Grey star: tsunami events estimated by stratigraphical positions (not using radiocarbon ages) (Sugawara *et al*., 2001). Limiting minimum and maximum ages of tsunami deposits in Sendai are from Minoura *et al*. (2001)

Evidence for tsunami deposition at Suijin-numa

Using the above criteria, we infer that sand unit B represents a tsunami, and that units A and C are of uncertain origin. First of all, diatom assemblages including brackish and marine species in sand units rule out a possible fluvial origin for any of the three sand units. Many of the marine planktonic diatom species, such as *halassionema nitzshioides* and *Thalassiosira* spp. suggest that they were incorporated with marine incursions into the sand units. Mixture assemblages in sand units including freshwater and brackish and marine species are consistent with observations in modern and prehistoric tsunami deposits (S. Dawson *et al*., 1996; Tuttle *et al*., 2004; Dawson, 2007).

In addition to diatom assemblages, sand unit B contains graded bedding and layers of plant detritus and muddy sand best explained by tsunami. These features repeat two or three times (B1–4, B5–6 and possibly B7 in Figures 4 and 5). We infer that each repetition began with a fast velocity stage that produced the coarsest part of the graded bed, and that each repetition concluded with slackened currents that allowed mud and plant fragments to settle. The time required for settling can be explained most simply by the long period typical of tsunamis generated by widespread seafloor displacement during a great subduction earthquake. Wave periods of tsunami range from 100 to over 2000 seconds, which is enough for mud and plant fragments to settle (Satake, 2002; Bernard *et al*., 2006; Fujii and Satake, 2007), whereas wave periods of storms are from 10 to 25 seconds (Morton, 1988; Fujiwara, 2008; Morton *et al*., 2007).

Historical records permit correlation of the AD 869 Jogan tsunami with sand units A and B, which pre-dates AD 915. As described above, in the section on written records, the Jogan tsunami caused extensive inundation in the vicinity of Suijin-numa, with the report probably referring to Tagajo or Iwanuma (Figure 7).

Unit C is most probably deposited by the 1611 Keicho tsunami, though deposition by the 1648 storm surge cannot be entirely ruled out. Either possibility is close to the unit's age, which is bounded between AD 1440 and 1600. The main piece of evidence against the 1648 storm hypothesis is the canal construction, which indicates that by 1648 Suijin-numa had already been separated from the sea by beach ridges B1 and B2 (Figure 2a). Because no storm surge since 1934 has come close to overtopping both these ridges, we doubt that even the disastrous 1648 storm surge was able to deposit sand on the floor of Suijin-numa. By contrast, the 1611 tsunami attained estimated heights near Suijin-numa a few meters higher than those beach ridges (Figures 1b and 2b).

Other hypotheses

Aeolian sand deposition into Suijin-numa is unlikely for sand units A–C. If winds routinely transport sand into the lake, the peat beneath the lake floor should abound in dispersed sand grains. We found no such sand in the peat. Though a tsunami may account for sand unit A, the thin peat layer between sand units S and A leaves shows that unit A accumulated shortly after Suijin-numa had become isolated from the sea. At that time it may have been just behind an active beach where even small storm waves and surges would be able to enter the lake.

Relative sizes of tsunamis inferred from sand units beneath Suijin-numa

The 1933, 1936 and 1978 tsunamis provide a way to estimate the relative size of earlier tsunamis recorded geologically at Suijin-numa. Because none of these registered at the lake as widespread sand beds, they set limiting minima for the sizes of earlier tsunamis that postdate completion of beach ridge B2. This reasoning is consistent with the correlation of sand unit C with the 1611 Keicho tsunami. For the earlier tsunamis recorded by sand units at Suijin-numa, uncertainty about palaeogeography prevents us from estimating relative size.

Conclusion

As many as three marine incursions in the past 1500 years are recorded by sand beds beneath the floor of Suijin-numa on northern Honshu, Japan. The youngest of these corroborates historical evidence that the 1611 Keicho event was the area's largest in the past 400 years.

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