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Evidence for 17th-century tsunamis generated on the Kuril–Kamchatka subduction zone, Lake Tokotan, Hokkaido, Japan

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Abstract

In the seventeenth century, two tsunamis that were generated by earthquakes on the Kuril–Kamchatka subduction zone inundated the eastern coast of Hokkaido, northern Japan. Stratigraphic evidence for these two tsunamis and related land-level change in coastal Hokkaido consists of two landward-thinning sand layers in the sediments of Lake Tokotan, a coastal lagoon on the Hokkaido coast. The marine origin of these sand layers is indicated by the presence of brackish–marine diatoms. The rarity and high degree of fragmentation of diatom valves suggests that the sands were transported in a short time over a considerable distance. Tsunamis at this site were probably generated by great earthquakes along the Kuril–Kamchatka Trench. Volcanic ash deposits lying just above the sands suggest that tsunamis occurred in the late 17th century. Tsunamis during the historic period are not recorded in Lake Tokotan, which suggests that the sand layers were deposited by tsunamis substantially larger than historic tsunamis. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Diatoms; Freshwater coastal lagoon; Lake deposits; Tephrochronology; Tsunami

1. Introduction

The cycle of elastic deformation associated with strain accumulation and release at some subduction zones potentially produces land-level changes (Plafker, 1969), and this may be preserved in the geological record (Shimazaki and Nakata, 1980; Matsuda et al., 1978; Nelson et al., 1996; Atwater and Hemphill-Haley, 1997). At Akkeshi estuary of southeastern Hokkaido, northern Japan, near the Kuril–Kamchatka plate-boundary subduction zone, dramatic changes in diatom assemblages in coastal deposits record at least four episodes of abrupt coastal uplift, with the last event dating from the 17th century (Sawai, 2001; stated below). If these emergence events are the product of great earthquakes at the Kuril–Kamchatka plate boundary, then the great earthquake record can be extended by several centuries.

Deformation of convergent margins during great earthquakes commonly produces large tsunamis, which impact local coastal areas. The eastern Pacific coast of Hokkaido has been struck by numerous large tsunamis (Takahashi and Hatori, 1969; Watanabe, 1985; Minoura et al., 1994; Shimamura and Moriya, 1994: Table 1), some of which were triggered by great earthquakes on the Kuril–Kamchatka plate boundary (Utsu, 1999). If the abrupt emergence events recorded in Akkeshi estuary are the product of great earthquakes at the Kuril–Kamchatka plate boundary, low-elevation sites on this coast may preserve evidence of the accompanying tsunamis. In this paper I describe inferred tsunami deposits in the sedimentary record of Lake Tokotan, a closed coastal lagoon on the eastern Pacific shore of Hokkaido. I examine the hypothesis that the inferred tsunami deposits in Lake Tokotan are contemporaneous with the uplift events recorded in Akkeshi estuary.

Low-energy coasts offer favorable environments, such as lakes and lagoons, for the identification of the deposits of past tsunamis. Marine incursions into lagoons or lakes as a result of tsunami surges disrupt underlying deposits and deposit exotic sediment entrained from offshore, beaches, and backshore areas (Bondevik et al., 1997; Clague et al., 2000). This material commonly consists of coarse-textured sediments with associated allocthonous organisms. Amongst these organisms, diatoms have proven to be one of the most useful groups for identifying past tsunamis 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).

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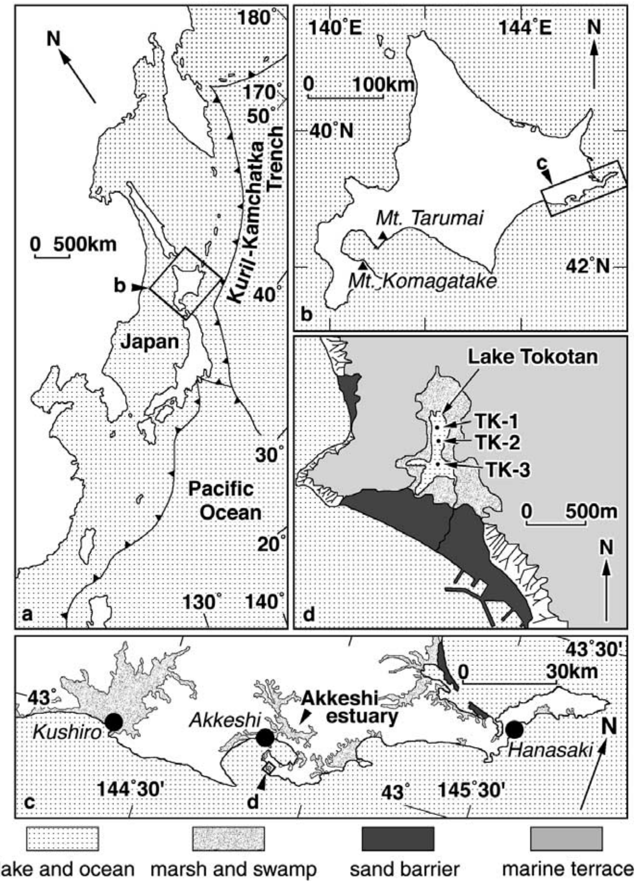

Fig. 1. Index maps. (a) Plate tectonic setting. (b) Hokkaido, showing the location of Mt Tarumai and Mt Komagatake. (c) Southeastern Hokkaido, showing the location of Lake Tokotan and Akkeshi area. (d) Lake Tokotan, showing core sites.

2. Study site

2.1. Geomorphological setting

The Lake Tokotan study site occurs on the upper plate of the southern Kuril–Kamchatka subduction zone, approximately 350 km northwest of the deformation front (Fig. 1). The lake lies in an embayment surrounded by Pleistocene marine terraces that form coastal cliffs about 40–60 m high. The lake, which has a depth of 1–1.5 m, is isolated from the sea by a sand barrier that is less than 5 m high. Lake Tokotan drains south to the sea via a narrow outlet. No marine water flows into the freshwater lake, and the lake is replenished entirely by rainfall and surface seepage.

2.2. Relative sea-level history at Akkeshi

Diatom assemblages in an alternating sequence of well-dated peat and mud at the Akkeshi estuary, further inland from Lake Tokotan, record at least four cycles of emergence and submergence in the past 3000 years (Sawai, 2001). Prior to ~2000 cal yr BP, dated elevations of sea-level range from −1.8 to −1.5 m relative to modern mean tidal level (MTL). About 2000 cal yr BP, relative sea-level reached −0.6 m relative to MTL. After that, there was a period of gradual relative sea-level rise up to −0.2 m relative to MTL by ~1200 cal yr BP. The level then dropped briefly between 1300 and 1000 cal yr BP. This small dip was followed by rising relative sea-level until ~720 cal yr BP. After this, relative sea-level fell again between 500 and 700 cal yr BP. There was a rise in relative sea-level that ended about the time of Ko-c2 (AD 1694), followed by a sudden relative sea-level fall.

Recent geodetic data show that relative sea-level is continuously rising along this coast. According to tide-gauge at Hanasaki and Kushiro (Fig. 1; Ozawa et al., 1997), relative sea-level is rising at an average rate of 0.8 and 0.9 cm/yr, respectively, over the past 50 years. Akkeshi's recent sea-level history must be similar.

3. Previous work

Identifying tsunami deposits from low-elevation marshy sediments along the Pacific coast of eastern Hokkaido began in the late 1990s (Nanayama, 1998; Shigeno et al., 1999; Nanayama et al., 2000; Nishimura et al., 2000). Their report, possibly related to first written in Japanese, found two or three obvious exotic sand sheets historic tsunamis (AD 1843 and AD 1894? tsunamis) and a pre-historic tsunami further along the eastern coastline from Akkeshi (Nanayama, 1998; Shigeno et al., 1999; Nishimura et al., 2000). After their reports, Nanayama et al. (2000) hypothesized that the existence of more than 10 sand sheets at Kiritappu and near Hanasaki (Fig. 1) could represent recurrences of pre-historic tsunamis generated by great earthquakes over the past 5000 years. Thus low-elevation sites along the Pacific coast of eastern Hokkaido potentially contain historic and pre-historic tsunami deposits, but such information is still fragmented and needs detailed correlations through comprehensive research.

4. Methods

Sediment samples were collected with a 2 m-long, 40 mm-diameter corer at three locations in Lake Tokotan (Fig. 1). In the laboratory, stratigraphic contacts were described as sharp (0.2–0.5 cm) or gradual. Diatom samples were taken at 4-cm depth intervals from core TK-3, and the samples were prepared as follows: (1) A drop of sodium hypochlorite solution was added to about 20 mg of dry sample to remove organic matter. (2) After 30 min, samples were neutralized by repeated rinses in distilled water (centrifuging at 1300 rpm for 8 min). (3) A 1.0-ml aliquot of the treated samples was transferred to a cover slip and dried at about 60°C for 2 or 3 h. (4) The cover slip was then permanently fixed to a glass slide using a synthetic resin with a high refractive index (Naphrax).

At least 300 diatom valves were identified and counted

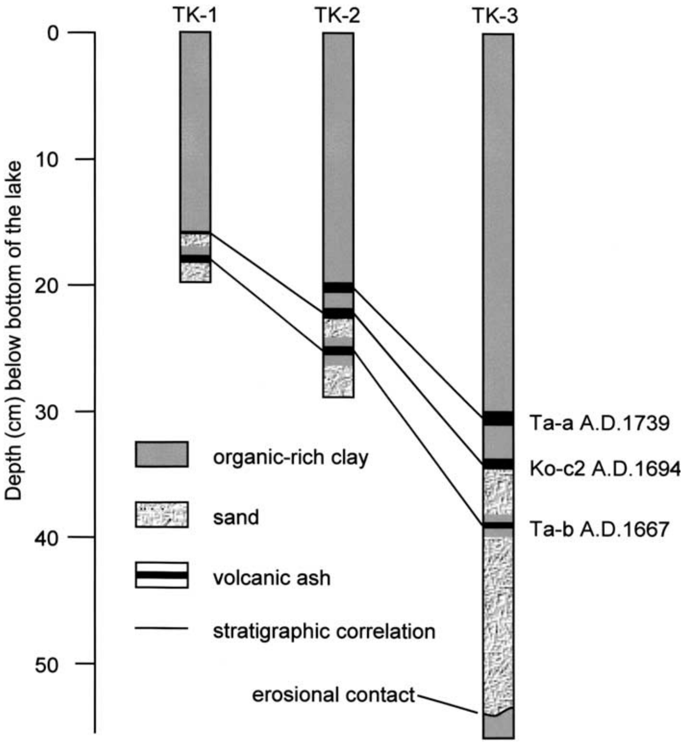

Fig. 2. Stratigraphy of lacustrine deposits in three cores from Lake Tokotan (Fig. 1).

under oil immersion in each sample based mainly on the descriptions in Krammer and Lange-Bertalot (1986, 1988, 1991a,b). Ecological interpretations followed Vos and de Wolf (1993).

Volcanic ash samples were cleaned in distilled water for 30 min using an ultrasonic generator. Elemental concentrations were measured with an electron microprobe on a sample of about 20 shards from each ash layer.

5. Lithostratigraphy of cores

5.1. Core TK-1

The sediments of core TK-1 consist of interlayered deposits of organic-rich clay, volcanic ash, and sand. The upper 16 cm of the 20 cm-long core is light brown organic-rich clay, and contains macrofossils such as twigs and leaves. Thin (0.5–1.0 mm) layers of fine-textured, light gray volcanic ash occur at 18 and 16 cm depth. Just below the tephra deposits are 2 cm-thick layers of massive, well-sorted gray sand. All contacts between volcanic ashes and sand layers are sharp (Fig. 2).

5.2. Core TK-2

The sedimentary sequence in TK-2 is similar to that of TK-1. The upper 20 cm of the 29 cm-long core consists of light brown organic-rich clay, and the lower part consists mainly of volcanic ash and sand. Three volcanic ash layers were recorded in the core at depths of 20, 22, and 26 cm. They are light gray or white, fine-grained, and 0.2–0.5 mm thick. Gray sand layers were noted just below the middle and lower volcanic ash. These sand layers are well-sorted and fine-grained, with sharp upper and lower contacts (Fig. 2).

5.3. Core TK-3

A light brown organic-rich clay containing plant macrofossils (including twigs and leaves) occurs at 0–31 cm depth in core TK-3. Three volcanic ash layers lie at 31, 35, and 39 cm. They are light gray or white, fine-grained, and 0.3–1.0 mm in thickness. The middle and lower ashes are each underlained by fine-grained and well-sorted sand layers. The contact between the lower sand and basal clay is quite sharp, and is probably erosional (Fig. 2).

6. Chronology

Volcanic ash layers derived from the eruptions of Mt Tarumai in AD 1739 and AD 1667 (tephra Ta-a and Ta-b, respectively), and Mt Komagatake in AD 1694 (tephra Ko-c2) are widely distributed at depths of about 30 cm in soils in eastern Hokkaido (Tokui, 1989; Furukawa et al., 1997). Although the volcanic ash layers in the cores from Lake Tokotan seem to be correlative with these deposits, it is difficult to identify tephras from stratigraphic position alone (Tokui, 1989). According to Tokui (1989), concentrations of major elements, especially K_2O and TiO_2, are critical for discrimination of these ash layers. It is apparent from

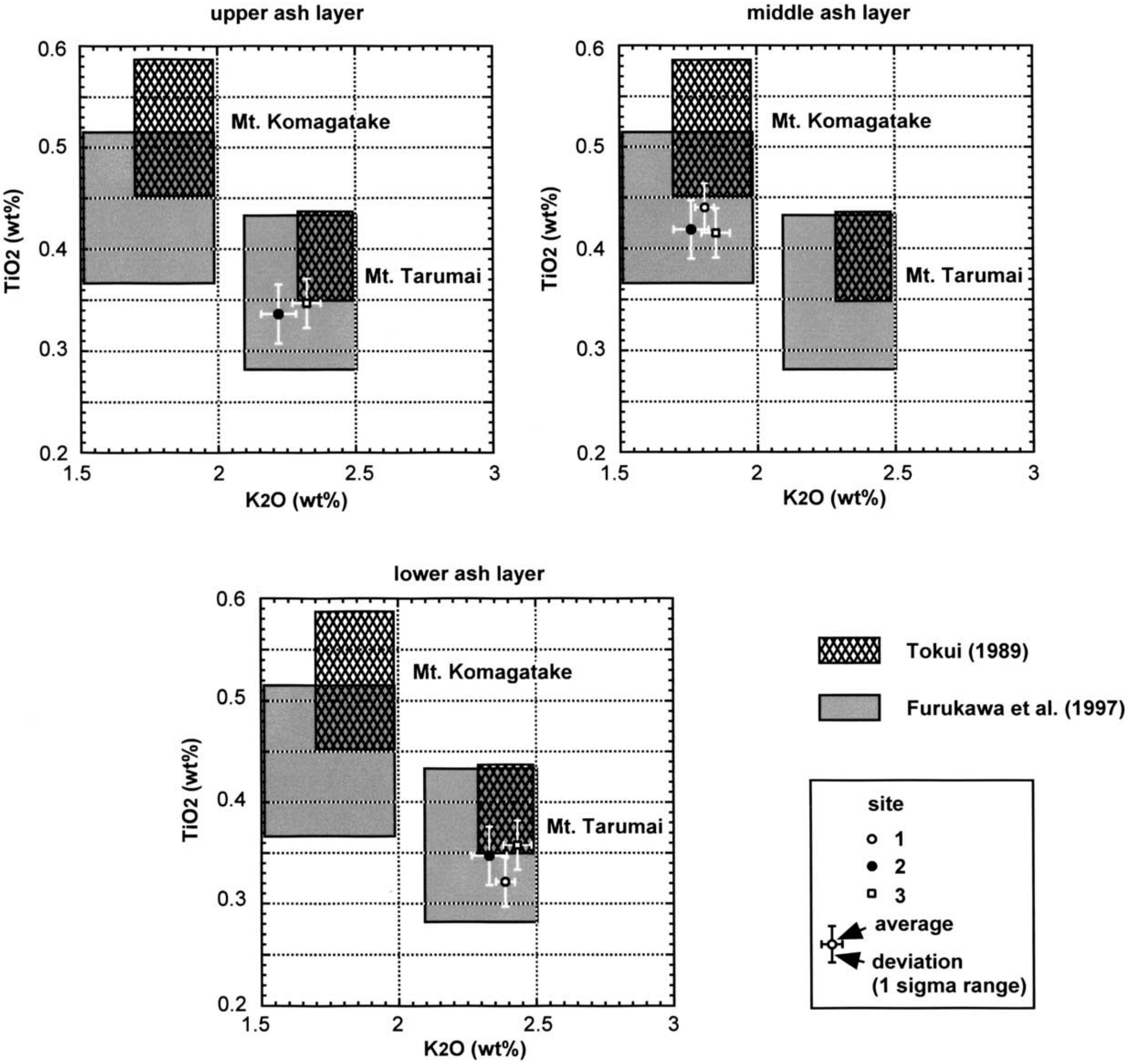

Fig. 3. K_2O and TiO_2 cross plots of three ash layers at the studied sites. Rectangles show range in elemental concentrations of known volcanic ash layers documented by Tokui (1989) and Furukawa et al. (1997).

plots of K_2O and TiO_2 concentrations in the ash samples (Fig. 3) that the uppermost and lowest layers overlap with tephras from Mt Tarumai, whereas the middle layer is akin to tephras from Mt Komagatake. Therefore, I correlate the upper volcanic ash with the tephra derived from the most recent eruption of Mt Tarumai (Ta-a), the middle ash with tephra Ko-c2, and the lower ash with tephra Ta-b.

7. Fossil diatom assemblages and inferred environments

The fossil diatom assemblages from core TK-3 were divided visually into six diatom zones on the basis of species dominance relative to total diatom valves counted (Fig. 4). The present lake is completely fresh, and this is reflected in the planktonic freshwater diatom assemblage of the uppermost sediments. Benthic freshwater diatoms are uncommon in this assemblage. The oldest zone (zone I) is similar in overall composition and relative abundance of diatom valves to the modern lake and likely represents a similar environment.

In contrast to zone I, diatoms in the lower sand layer (zone II) are very rare, and most valves are fragmented. The zone contains a few specimens of *Cocconeis placentula* and other benthic diatoms characteristic of freshwater marshes. Fragmentation of diatom valves is often indicative of post-mortem transportation (Voorrips and Jansma, 1974; Heyworth et al., 1985), so the rarity and poor preservation of diatom valves in zone II may indicate long-distance transport during a high-energy event. In zone III, the preservation and the absolute abundance of diatom valves increases compared to the upper part of zone II. Along with freshwater species, the assemblage contains *Diploneis smithii*, a taxon characteristic of brackish–marine environments. This

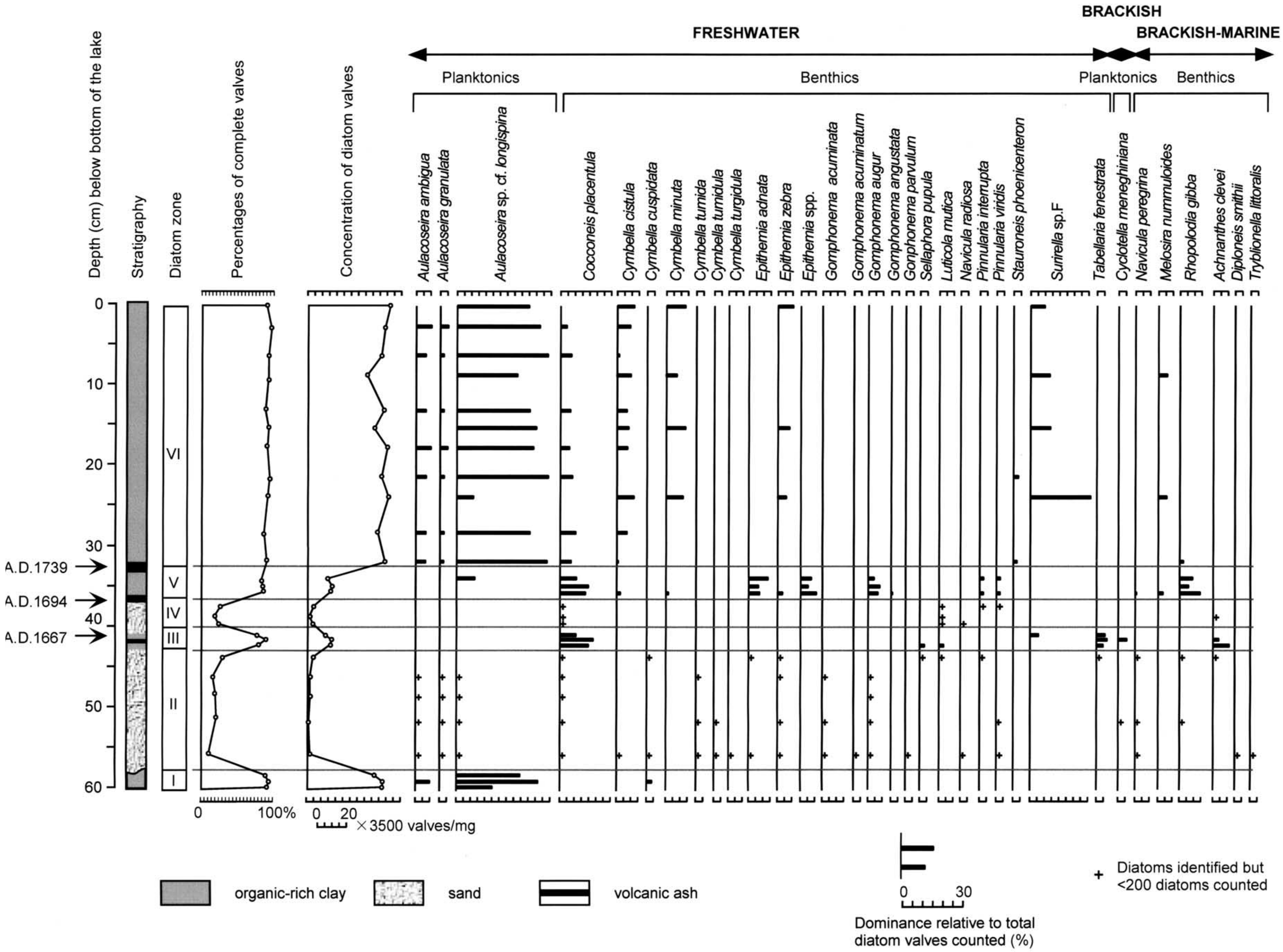

Fig. 4. Changes in diatom assemblages at site TK-3. Diatom zones are defined visually.

assemblage change suggests that the lake environment became a brackish–marine lagoon just after deposition of the lower sand layer. The absence of marine planktonic or tychoplanktonic species in this diatom community, however, indicates that the lagoon was likely shallow with limited tidal exchange.

Zones IV and V, which post-date the eruption of Mt Tarumai in AD 1667 (Ta-b), form a sequence similar to that of zones II and III. The diatom assemblages in zones IV and V are very similar to the assemblages of zones II and III, respectively, except for the absence of *Diploneis smithii* and high abundance of *Rhopalodia gibba* in zone V. The latter taxon is a common member of diatom communities in fresh-brackish environments. The concentration and preservation of diatom valves in zones IV and V show the same trend as in zones II and III. Based on the volcanic ash chronology, the sand layer in diatom zone IV was deposited immediately prior to the eruption of Mt Komagatake in AD 1694 (tephra Ko-c2).

After the eruption of Mt Tarumai in AD 1739 (tephra Ta-a in zone VI), the diatom species composition abruptly shifted to freshwater, and the concentration and preservation of diatoms remains essentially unchanged to the present day. Therefore, the environment of the post-AD 1739 lake (diatom zone VI) is equivalent to the lacstrine environment of zone I, the oldest diatom zone identified in the lake.

8. Tsunami impact at Lake Tokotan

8.1. Evidence for 17th-century tsunamis

The absence of river inflow into Lake Tokotan eliminates fluvial deposition as a possible origin for the two sand layers in the cores. The sand layers thicken seaward suggesting landward transport of the sand. The diatoms in these layers are very rare and fragmented, which suggests that they were deposited by strong currents. The most probable explanation for the sand layers in the Lake Tokotan cores is that they were deposited by unusually large storm surges or tsunamis. Although it is generally difficult to distinguish tsunami from storm surge deposits (Foster et al., 1991; Clague et al., 1999), a storm surge origin for these deposits seems less likely than a tsunami origin because Lake Tokotan is protected by a sand barrier and connected to the sea by a shallow and narrow outlet. The current velocities through

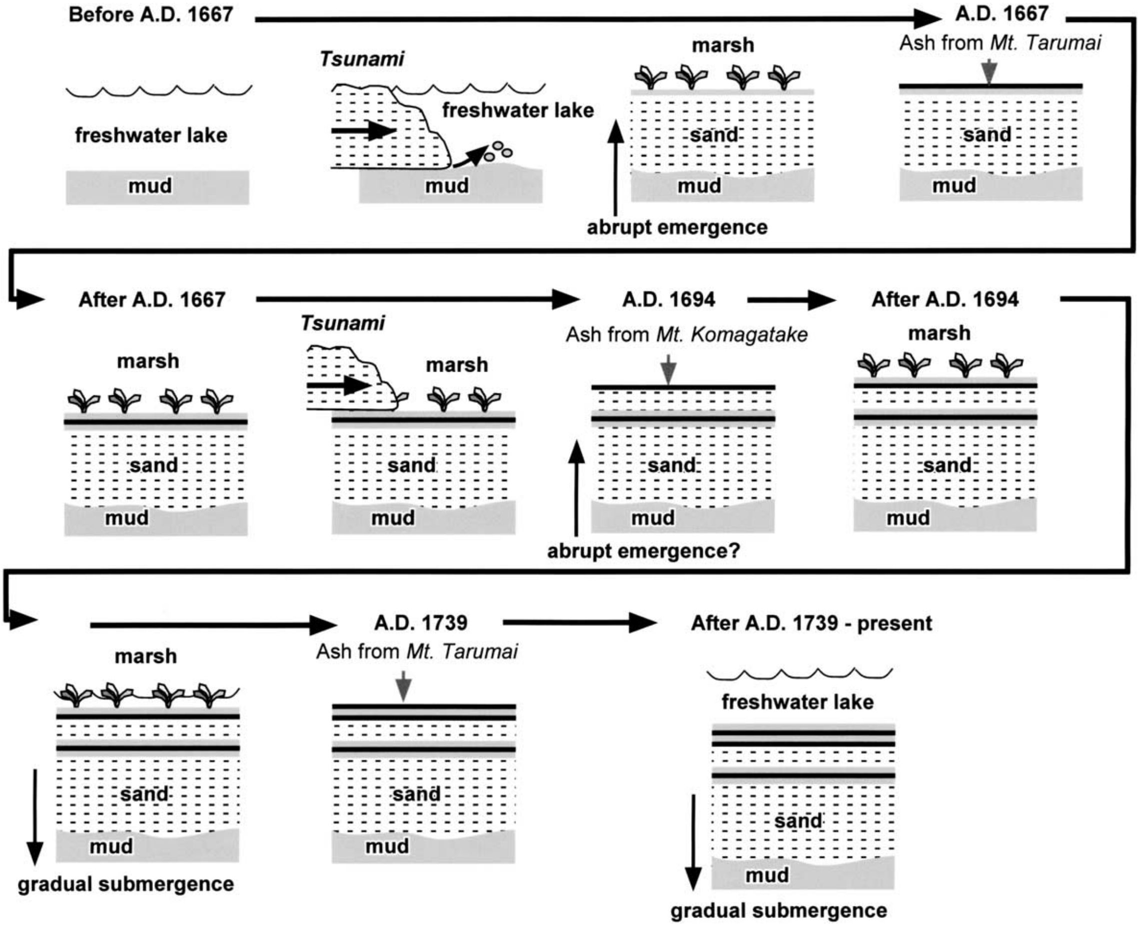

Fig. 5. Summary of environmental reconstructions at Lake Tokotan. Two tsunamis about the time of abrupt emergence are inferred just before AD 1667 and AD 1694.

Table 1
Historical tsunamis invading the Pacific coast of Japan mentioned in the recent literature, listed in chronologic order (Source: Minoura et al. (1994, Table 1) and Shimamura and Moriya (1994); only tsunamis with wave heights of 1 m or more are included.)

Location of source of tsunami	Date that tsunami inundated Japan coast
Nemuro, Hokkaido	June 17, 1973
Tokachi, Hokkaido	May 16, 1968
Iturup, Kuril	October 13, 1963
Concepcion, Chile	May 22, 1960
Tokachi, Hokkaido	March 4, 1952
Sanriku, Honshu	March 3, 1933
Urup, Kuril	September 8, 1918
Sanriku, Honshu	June 5, 1896
Nemuro, Hokkaido	March 22, 1894
Iquiqe, Chile	May 9, 1877
Arica, Chile	August 13, 1868
Sanriku, Honshu	July 23, 1856
Nemuro, Hokkaido	April, 25, 1843
Sanriku, Honshu	July 20, 1835
Sanriku, Honshu	January 7, 1793
Urup, Kuril	June 29, 1780
Sanriku, Honshu	December 16, 1763
Sanriku, Honshu	March 15, 1763
Concepcion, Chile	May 25, 1751
Concepcion, Chile	July 8, 1730

this narrow entrance during a storm surge are unlikely to be strong enough to transport sand and gravel across the floor of the lagoon (Peterson and Darienzo, 1996). I therefore infer that the sand layers were deposited by tsunami waves that overtopped and caused severe erosion of sands in the outlet channel. On the basis of the tephrochronologic data, I infer that both events occurred in the mid to late 17th century.

Probably both of the sand–mud sequences recognized in the lake deposits record extensive tsunami inundation and the nature of the ensuing post-tsunami environment. The overlying mud layers (diatom zones III and V) contain a benthic diatom flora that includes some brackish–marine species. This assemblage is indicative of shallow water environments. On the basis of the diatom assemblage, I infer that the lake salinity changed temporarily to non-tidal brackish due to inundation of marine water accompanying each tsunami. Either of the two inferred emergence events may correlate with the inferred abrupt uplift recorded further inland at Akkeshi estuary (Sawai, 2001). The uplift was shown by a mud–peat contact in estuarine stratigraphic sequence sometime before the deposition of tephra Ko-c2 (i.e. pre-AD 1694) (Sawai, 2001). However, in the absence of volcanic ash Ta-b (AD 1667) at Akkeshi estuary (Sawai and Mishio, 1998), it is not possible to identify which of the two inferred tsunamis at Lake Tokotan best correlates with the emergence at Akkeshi. On the other hand, the earlier inferred tsunami can be correlated with Nanayama's Ts3 tsunami event, about 1 cm below tephra Ta-b, identified at Kiritappu and near Hanasaki, but any Nanayama's event analog to the later is absent (Nanayama, 1998; Nanayama et al., 2000). This may mean that the earlier inferred tsunami inundated extensive area along the Pacific coast of eastern Hokkaido but the later was local and/or in patches along the coast. Following the later emergence at the lake, the lake changed from a marsh to a freshwater lake. This was likely caused by a rise in the water table owing to the recent regional submergence of this area (Fig. 5) (Ozawa et al., 1997). If this modern submergence is a result of strain accumulation at the Kuril–Kamchatka convergent margin, Lake Tokotan may record the environmental changes accompanying interseismic deformation.

8.2. Historic tsunamis

Historical documents record numerous tsunamis on the Pacific coast of Japan during the past 250 years (Takahashi and Hatori, 1969; Watanabe, 1985; Satake et al., 1996). Amongst these events, only tsunami heights of 1 m or more above mean high tide level (Table 1) have led to severe inundation of low-lying coastal areas (Minoura et al., 1994). I cannot estimate tsunami size quantitatively from the field data. However, a record of the tsunami that accompanied the March 4, 1952 Tokachi-Oki earthquake (Inoue, 1954) helps estimate the size of the tsunamis identified in the deposits of Lake Tokotan. The primary tsunami wave generated by the Tokachi-Oki earthquake had a height of 2 m above the sea surface at Lake Tokotan. The wave was partially blocked by a sand barrier but swept inland as much as 400 m from the coastline. Although the southern coastal marshes around Lake Tokotan were inundated with marine water by the tsunami, the wave was quite weak and slow (Inoue, 1954). There is no clear description of a marine incursion into Lake Tokotan during the Tokachi-Oki earthquake; apparently the tsunami was not vigorous enough to transport sand and gravel from the coastal sand barrier into the lake.

Historic tsunamis 1 m or more above high tide level have been widely documented on the Pacific coast of Japan (Minoura et al., 1994). However, there is no trace of them, including historic tsunamis identified in the other area (Shigeno et al., 1999; Nishimura et al., 2000), in the deposits of Lake Tokotan. Like the tsunami during the Tokachi-Oki earthquake, other historic tsunamis were probably too weak and slow to transport sand and gravel from the barrier. This suggests that the two tsunamis identified in the deposits of Lake Tokotan were substantially larger than any of the tsunamis of the historic period.

9. Conclusion

Two instances of tsunami inundation dating from the 17th century are identified at Lake Tokotan, southeastern Hokkaido coast, northern Japan. The environmental changes accompanying these tsunamis, depicted schematically in Fig. 5, were inferred from changes in lithology and diatom assemblages in three cores. The inferred tsunamis and accompanying inferred uplift are probably associated with great earthquakes along the Kuril–Kamchatka trench. During historic times, tsunamis have not invaded Lake Tokotan, or at least have left no evidence. Based on the absence of evidence of historic tsunami inundation and the presence of two inferred 17th-century tsunami deposits in Lake Tokotan, I conclude that the two mid to late 17th-century tsunamis were substantially larger than any tsunamis that occurred within the historic period.

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