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Tsunami deposits in a lacustrine sequence of the Sanriku coast, northeast Japan

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ABSTRACT

Lacustrine deposits of the Pacific coast of northeast Japan, consisting mostly of black organic mud, contain intercalated thin beds of well-sorted medium sand. Examination of the deposits from a coastal site of Sanriku has revealed that sand grains are of marine origin and are fractions of deposits in marshy ponds, transported from the littoral environment by a great flooding of seawater. The mode of sedimentation shown in the thin beds of sand implies that they were deposited by tsunamis, each with a maximum rise of 1 m or more above sea level.

1. Introduction

The Sanriku coast of northeast (NE) Japan is notorious for repeated invasions of large-scale tsunamis which have caused great damage to cities, towns and villages on the coast. Historical materials document frequent invasions of tsunamis upon the coast during the last three centuries, involving considerable damage and a great loss of life. About a hundred years ago (1896), a high-magnitude tsunami (the Meiji Sanriku Tsunami) took place in the Pacific Ocean, off the coast of Sanriku, and attacked seaside regions with enormous destructive power, killing almost 22,000 people.

In May 1983, the high-magnitude tsunami generated by a great earthquake in the Japan Sea struck low-lying coastal zones of NE Japan, causing a loss of 104 lives and considerable destruction of man-made structures (the Japan Sea Tsunami; Minoura and Nakaya, 1991). On the shoaling beach, incoming waves as high as 14 m above the contemporary high-water mark progressed at least 1 km inland. Turbulent seawater carrying suspended sand grains rushed into a lagoonal pond particularly through gashes formed by seismic shocks of the earthquake, and deposited a thin veneer of coastal sand across the mud surface of the pond bottom. The flooding of marshes caused intermixing of pond water rich in carbonic acids with large volumes of seawater. Reaction between carbonic acids in the pond water and calcium from seawater due to a significant mixing of two water bodies triggered precipitation of calcite, which whitened the pond immediately. The seawater remained for more than several months as a deep layer within the pond. During that time, major ingredients of the seawater were precipitated, infiltrating into the sand layer produced by the tsunami.

The above observations provide a strong basis for the vexed question of sedimentological and geochemical characteristics indicative of ancient tsunami deposits in coastal sedimentary sequences (Minoura and Nakaya, 1991). In the hope of finding traces of ancient tsunamis and also

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evaluating the frequency of tsunami invasion, lacustrine deposits on the Sanriku coast were studied.

2. Locality

Numerous lacustrine ponds and intertidal lakes are scattered along the coast of the Shimokita Peninsula north of Sanriku. Almost all of them are separated from the Pacific Ocean by sand beaches and bars (0.5–1.0 km wide). The Oonuma Pond (0.72 km^2 in area and 3.5 m in average depth), situated in the northern part of the peninsula (Fig. 1), is linked with the ocean by a narrow waterway, through which water streams out of the pond into the Pacific Ocean (Fig. 1). No river flows into the pond. The altitude of the pond surface measures 4.0 m in average in relation to mean high-water, which suggests that seawater never extends to the pond under existing seashore conditions. Geohistorical interpretations of the coast (Uchida, 1991), however, indicate that the pond was in an inter-tidal lagoonal environment until a few centuries ago. It is highly possible, therefore, that ancient tsunamis attacked the Sanriku coast directly going as far as the Oonuma Pond, and left a sign of tsunami invasion there.

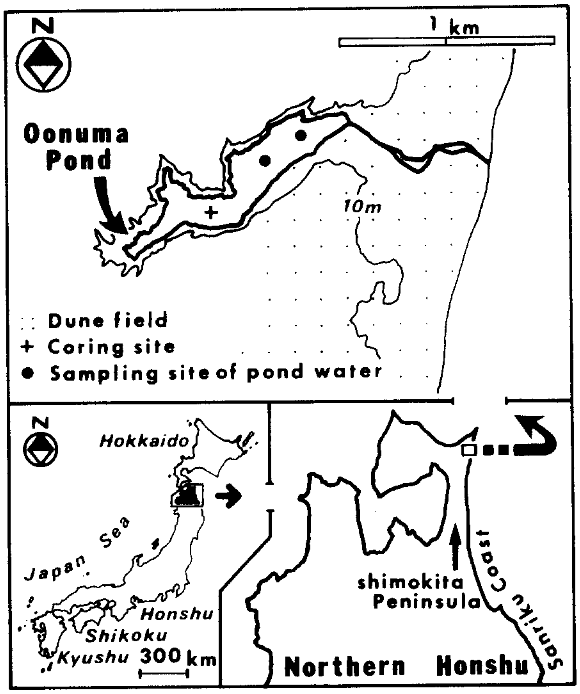

Fig. 1. Location of coring site. Chemistry of the pond was examined at different depths in all seasons.

3. Sediment samples and analysis

Pond deposits were cored (6.5 cm in diameter) at several locations by human power. A single core reaching down to 80 cm from the bottom surface, obtained in the west of the pond (Fig. 1), was selected for analyses. Sliced sediments of the core were examined by X-ray radiography for sediment textures and contents. Sediment samples taken from the core at a stratigraphic interval of 2.5 cm were subjected to sedimentological (grain size, mud and water contents, and organic/inorganic ratios) and geochemical (chemistry of pore fluids and authigenic carbonate minerals, sedimentation rate) analyses.

Pore fluids were filtered at room temperature from the sediments for analysis of interstitial chemistry. A quarter of a gram of the dried sediment sample was rinsed with distilled water at room temperature. Solids were separated, and then air-dried in the laboratory. The dried samples were treated with a weak acetic acid solution to dissolve carbonates in the sediments. Analysis of major cations was done by flame atomic absorption spectrophotometry. Cl^- and SO_4^{2-} were determined by ion chromatography. Sediment samples were also subjected to grain-size analysis after removing clay fractions. The method for this grain-size analysis is described in detail in Minoura et al. (1987).

4. Results

4.1. Sedimentology

Pond deposits, consisting mostly of black organic mud, contain intercalated thin beds of medium sand with incidental pebbles and granules (Fig. 2A). Thirteen sand layers were discriminated within the core (T_D1–T_D13). The sand/mud interfaces of the upper four layers are fairly indistinctive due to sediment bioturbation. Profiles of boreholes reveal that each sand layer is laterally persistent, implying extensive deposition of sand grains. Sharp interfaces between the sand layers and underlying organic mud, together with basal mud surfaces without signs of erosion, seem to indicate that the sand layers were deposited by free settlement of grains through the water column. Flame structures are locally found at the base of thick sand layers, which indicates differential loading resulting from abrupt accumulations of sand layers on mud surfaces. In settling tube analysis, sediment samples from the sand layers form a narrow peak in the distribution of settling velocity, implying that sand grains issued mostly from a littoral environment (Minoura and Nakaya, 1991). Well-sorted beach sand seems to have been transported and re-deposited rapidly in the pond.

4.2. Palaeontology

The results of qualitative diatom analysis performed on sediment samples from the core show that the black mud above and below the sand layers contains most commonly nonmarine planktonic diatoms. The benthic nonmarine diatom *Cocconeis placentula* predominates the diatom population in the uppermost part (0–20 cm) of the sediment column, showing deposition of black mud in a restricted shallow pond during the last 100 years. Abundant occurrences of marine to brackish water species, notably *Cocconeis scutellum*, *Mastogloia* sp., and *Rhoichosphena* spp., in the sand layers, suggest coarse-sediment transport from coastal environments. The presence of those sand layers in organic mud, therefore, indicates the net landward movement of marine material and ensuing deposition of coastal sand in marshy environments.

4.3. Geochemistry

Vertical changes in concentration of sodium, sulphate and chlorine in interstitial water are shown in Fig. 2B as a function of sediment depth. These lines show gradual upward decreases with several peaks being lower than the preceding ones. Each of these peaks suggests a sporadic invasion of seawater into the pond, because these elements are the principal ingredients of seawater and are rare in pond water. Calcium and magnesium concentrations derived from carbonate minerals soluble in acetic acid are given in Fig. 2C for comparison of the temporal trend of major chemical components in interstitial water

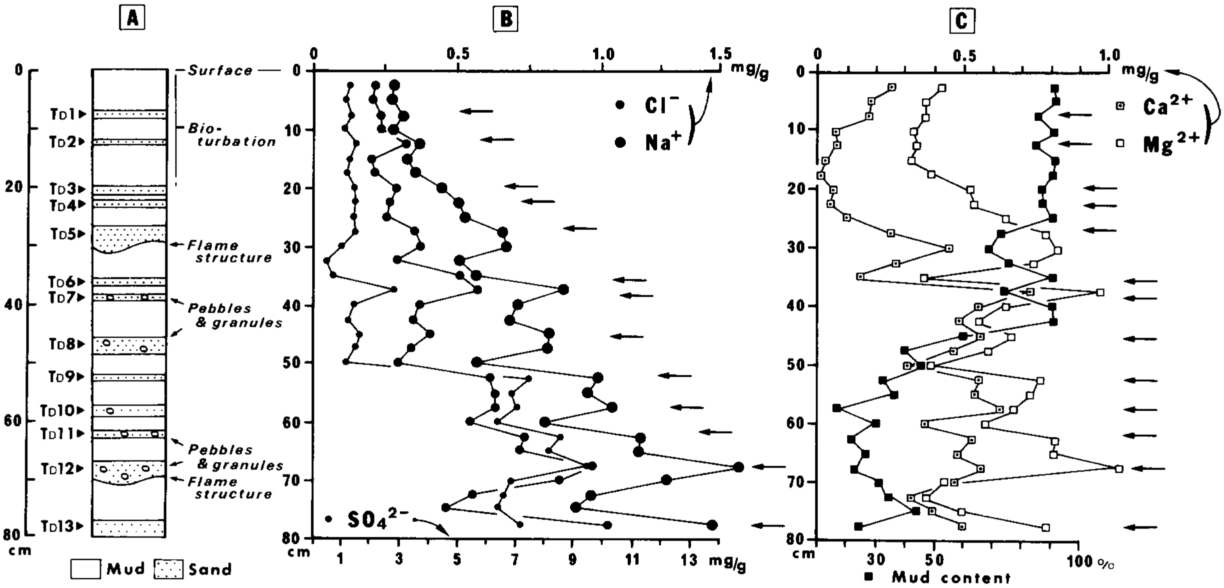

Fig. 2. Schematic sediment sequence (A), vertical changes of interstitial chemistry (B), and calcium and magnesium contents in carbonates (C). Solid arrows in B and C indicate stratigraphic positions of the top of sand layers. T_D1–T_D13: tsunami deposits.

and carbonates. Also shown are measured mud contents. It is evident from both carbonate and interstitial water analyses that there is an increase of seawater elements at the stratigraphic level of each sand layer (although the concentration is reduced in the upper section).

5. Dates for sediments

Exact dating of deposits is extremely important for defining sand layers as traces of ancient tsunamis, and for further evaluating the frequency of occurrence of prehistoric tsunamis. We estimated sediment ages from the accumulation rate of pond deposits adopting the lead isotope (^{210}Pb) method (Robbins and Edington, 1975; Matsumoto, 1975). C^{14} dating has not been possible, because sample materials for reliable age determination are too scarce in cored deposits and also experimental errors on measurements occurred by a Suess effect. Only a radioisotopic date of 570 ± 55 yr B.P. was obtained for a branch chip of an evergreen from a stratigraphic depth of 29.0 cm (T_D5) of the core, determined by accelerator mass spectrometry (AMS) at Teledyne Isotopes.

Sedimentological results indicate that sand accumulation was effectively instantaneous. Accordingly, the sedimentation rate of the pond deposits can be obtained by disregarding sand layers in the column. Fig. 3 shows dpm (disintegration per minute) values per 1 g of sediment samples vs. the depth of sediments without sand layers. ^{210}Pb determinations were made by the ^{210}Bi method on weighed sub-samples of dried sediment (finer than 150 μm following the procedures described by Matsumoto (1975). The water content of mud layers is constant throughout the column (23.0 wt% in average) except for a surficial layer (30.0 wt%), which indicates that the sediments have not undergone significant compaction. Thus original mud properties are likely to be preserved. A good correlation between dpm and depth (correlation coefficient = 0.99) seems to reflect that black mud has been accumulating at a constant rate. Putting the decay constant of ^{210}Pb at 0.0311/yr, we calculated the sedimentation rate of the mud at 0.19 cm/yr. The dpm value of a superficial sample is small, deviating from the regression line. The reduction of radioactivity in the surface layer is interpreted as having been caused by sediment bioturbation.

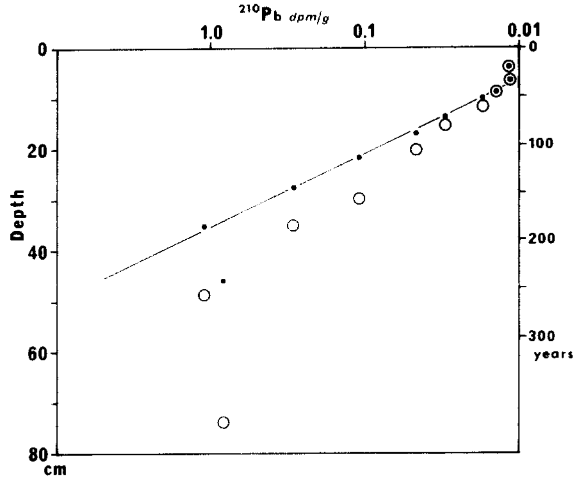

Fig. 3. ^{210}Pb activity (horizontal axis) vs. core depth (left axis), showing an apparent sedimentation rate (circles). A more practical sedimentation rate was obtained by disregarding sand layers in the column (dots), provided the depositional rate of black mud has been constant. The regression line gives appropriate ages of tsunami deposits (right axis).

The dates of the sand layers estimated from the sedimentation rate are listed in Table 1. These values, each standing for the age of the top

TABLE 1

Correlation of estimated dates of tsunami deposits with ages of ancient tsunamis

Tsunami deposists (T_D1~T_D13) and their ^{210}Pb dates (AD)		Ancient tunamis and their historical ages (AD)		
		Tokachi, Hokkaido	May 16, 1968	- m
		Concepcion, Chile	May 22, 1960	- s
T_D1	1948	Tokachi, Hokkaido	Mar. 4, 1952	- m
T_D2	1930	Sanriku, N. Honshu	Mar. 3, 1933	- s
T_D3	1905	Sanriku, N. Honshu	Jun. 5, 1896	- s
T_D4	1887	Iquiqe, Chile	May 9, 1877	- m
T_D5	1861	Arica, Chile	Aug. 13, 1868	- m
T_D6	1853	Sanriku, N. Honshu	Jul. 23, 1856	- m
T_D7	1843	Sanriku, N. Honshu	Jul. 20, 1835	- m
T_D8	1805	Sanriku, N. Honshu	Jan. 7, 1793	- m
T_D9	1787	Urup, Kuril	Jun. 29, 1780	- m
T_D10	1772	Sanriku, N. Honshu	Dec. 16, 1763	- m
T_D11	1769	Sanriku, N. Honshu	Mar. 15, 1763	- m
T_D12	1742	Concepcion, Chile	May 25, 1751	- m
T_D13	1710	Concepcion, Chile	Jul. 8, 1730	- m

Data on the ancient tsunamis are from historical materials and the recent literature (Iida and Ohta, 1960; Takahashi and Hatori, 1960; Watanabe, 1985; Minoura et al., 1987). Tsunami scale refers to maximum run-up of tsunami wave: severe (s) > 3 m, 3 m ⩾ moderate (m) > 1 m.

of every sand layer, have an average error of about ±5 years. The age difference between fossil wood and the matrix sediments (sand layer T_D5) implies that the chip derives from older deposits.

6. Discussion

6.1. Traces of tsunamis

It can be seen in geochemical records that calcium and magnesium abruptly increase in concentration at the horizons of probable seawater influx. The increase means deposition of carbonates resulting from a sudden mixing of voluminous seawater with pond water rich in carbonic acids and also contribution from marine skeletal carbonate carried in with sand grains. Upward decreasing concentrations of seawater elements as well as excursions of Ca^{2+} and Mg^{2+} without clear peaks in the upper part of the column seem to reflect gradual isolation of the pond from the Pacific Ocean. The corresponding characteristic is an upward increasing trend in mud contents of the middle section. The geochemical properties suggesting seawater invasions are commonly recognized at every level of sand layers, implying sand and skeletal carbonate grains of marine derivation.

The above interpretation indicates that deposition of thin, laterally persistent sand layers in the lacustrine pond can be attributed to catastrophic seawater invasions upon low-lying coastal land. An enormous seawater run-up caused by the Japan Sea Tsunami and consequential deposition of marine sand and carbonates should be placed in an arguable kind of causal context. Available evidence suggests that storm surges on the coast of NE Japan are unlikely to transport littoral material landward on a large scale (Minoura et al., 1987). A number of known tsunamis moved coastal sediments into the land, depositing regionally extensive layers of marine sand (Atwater, 1986; Dawson et al., 1988; Long et al., 1989, 1990). Profiles of boreholes on the Sendai plain, NE Japan, reveal that ancient tsunami deposits form inland tapering layers of marine sand extending over 3 km beyond the former coastline (Minoura and Nakaya, 1990).

6.2. Tsunami deposits and historical tsunamis

A critical review of historical descriptions of ancient tsunamis which have attacked the Japan Sea coast (Minoura et al., 1987) and observations of tsunamis taken place in recent years on the Pacific coast (Takahashi and Hatori, 1960; Iida and Ohta, 1960) lead to the conclusion that only those tsunamis which rose 1 m or more above the contemporary high water mark could inundate coastal marshes. Historical materials document that the Sanriku coast has been repeatedly hit by variable-scale tsunamis originating both from around the Japan Trench and from more distant regions. Out of these tsunamis only those with run-up values of 1 m or more above the contemporary sea level are listed in Table 1 for comparison with the ages of tsunami traces in our sediment cores. The dates of probable tsunami invasions are generally equivalent to the ages of the historical tsunamis except for the latest two cases (Table 1), which lack sand layer counterparts. This demonstrates that tsunamis with waves rising 1 m or more above the contemporary high-water mark are accurately recorded in our lacustrine sequences. Although the Meiji Sanriku Tsunami in 1896 was very severe (Watanabe, 1985), the trace is small in scale. This thin layer of deposits brought by the tsunami can be ascribed to complete separation of the Oonuma Pond from the ocean, which is well reflected in definitely reducing seawater elements as well as high contents of mud from around 35 cm deep upward in the section. The reason why tsunami deposits referable to the latest two tsunamis are missing from the cored sequence can be explained by the isolation of the pond in the same manner.

A large number of big fossil trees standing erect are found buried in dune sand on the coast. Their dendrochronologic ages are 300 years in average. A radiocarbon age of 890 ± 30 yr A.D. has been obtained for one of them. The sample for dating was collected from the core of a big tree, so that the radioisotopic data should indicate the date of germination of those trees. The extinction of some forest trees is interpreted to have resulted from floods of seawater (Niki, 1979) probably caused by a tsunami. The radiocarbon age of the branch (570 ± 55 yr B.P.), which is much younger than that of the core, may indicate the date of the tsunami occurrence. The extinct trees were buried under sand dunes due to the expansion of coastal dune fields triggered by sea-level lowering (Niki, 1979), and preserved from biotic lignin degradation. It appears, therefore, that the Meiji Sanriku Tsunami (1896 A.D.) led to rapid surface erosion of dunes and transport of fragments of exposed fossil trees, together with sand, into the pond.

7. Conclusion

Marine sand in a succession of lacustrine deposits; together with interstitial carbonates and pore water rich in seawater ingredients within sand layers, is distinct evidence for tsunami-genic sedimentation. Thirteen thin sand layers were found to be intercalated within pond deposits of the Sanriku coast. Detailed sedimentological and geochemical work demonstrates that the sand layers were laid down as a result of tsunamis. The dates of these tsunami deposits are mostly equivalent to the ages of the moderate to severe ancient tsunamis documented in historical materials, suggesting that tsunamis with waves having reached a maximum height of more than 1 m on the coast caused net sediment transport landward and accumulated thin sand beds in the pond.

The estimation of potential hazards to coastal zones afforded by tsunamis is especially important, and an accurate knowledge of the frequency of destructive tsunamis is essential for assessment of the hydro-engineering security of high-risk facilities such as coastal nuclear power stations. There is a pressing need of learning more about earthquake-related tsunamis and the cause of earthquake initiation in and around subduction zones. Our methods adopted here can be applied to other coastal areas in the active margin, and may provide useful information on the risks of tsunamis.

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