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A HUGE SAND DOME FORMED BY THE 1854 EARTHQUAKE TSUNAMI IN SURUGA BAY, CENTRAL JAPAN

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ABSTRACT

The 1854 Ansei-Tokai earthquake brought massive destruction to Suruga Bay, central Japan. The earthquake triggered a large-scale tsunami, which surged over the Pacific coast of Japan. Waves exceeding 13.2 m in height attacked Iruma, southeastern coast of Suruga Bay, and provoked peculiar types of tsunami sedimentation. On the coast of Iruma, a huge mound of shoreface sand, reaching more than 11.2 m above sea level, appeared after the tsunami run-up. We performed a historical and sedimentological survey to clarify the origin of the mound. Result of a field excavation and submarine investigation suggests that the sand came from the seafloor with a water depth of 20 to 30 m, and historical data illustrates a dramatic change of the landform by the tsunami run-up. Numerical examination of the tsunami implies that the coastal topography played an important role in excitation of the tsunami, and it induced the characteristic tsunami sedimentation.

KEYWORDS: Earthquake Tsunami, Tsunami Deposit, Sand Dome, Coastal Topography

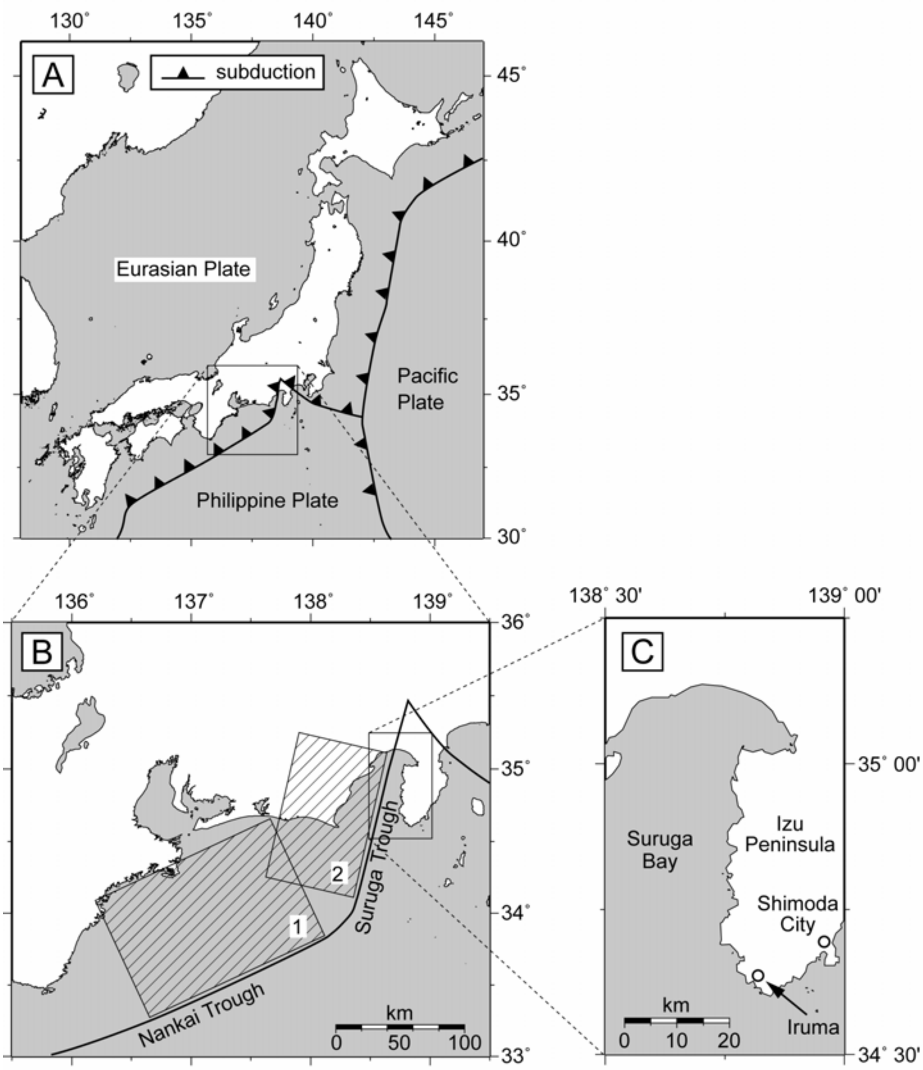
INTRODUCTION

The Pacific coast of central Japan (Tokai region) faces the subduction boundary of the Eurasian and Philippine plates, which forms the Suruga and Nankai troughs (Figures 1(A) and 1(B)). A number of large-scale earthquakes (the Tokai earthquakes) have taken place along the Suruga and Nankai troughs. The Tokai earthquakes have a recurrence period of 100 to 150 years, with each event causing serious damage to the Pacific coast of central Japan. The Tokai earthquakes have been attracting keen social and scientific attention as the major industrial zones are densely located on the Pacific coastline.

A large-scale earthquake along the Suruga and Nankai troughs occurred on December 23, 1854. The earthquake is named the Ansei-Tokai earthquake, and it brought destruction to central Japan. Usami (1975) summarized the damages of the Ansei-Tokai earthquake and subsequent large-scale tsunami. The damage by the earthquake was especially serious in the coastal areas from Numazu to Tenryu River, Shizuoka Prefecture (Figure 2(A)). The percentage of collapsed buildings due to the seismic vibrations was at least 10%, and exceeded 50% in many locations. The earthquake also caused many fires. The damaged area with seismic intensity V (according to JMA old seismic intensity scale) covers almost all parts of central Japan. According to the seismic intensities of damaged areas, the magnitude of the earthquake is estimated to be 8.3 (Usami, 1975). The seismological mechanism of the earthquake was considered to be the movement of thrust faults on the Suruga and Nankai troughs, and the focal region of the earthquake is estimated to be off central Japan (Figure 1(B)), although the epicenter is unknown due to the lack of instrumental observations of the earthquake.

The Ansei-Tokai earthquake triggered a large-scale tsunami (the Ansei-Tokai Earthquake tsunami), which hit many areas along the Pacific coast of central Japan from the south part of Boso Peninsula (east Japan) to Shikoku Island (southwest Japan). The tsunami height is estimated at 3-6 m along the western coast of Izu Peninsula (Figure 2(A)). The tsunami struck Shimoda City (Figure 1(C)) about one hour after the occurrence of the earthquake. The tsunami waves struck the city nine times, and the height of the tsunami run-up was approximately 5 m. About 840 houses collapsed or were washed out completely, and the number of casualties was 122. At the time of the Ansei-Tokai earthquake, Putyatin, a Russian admiral, had visited Shimoda City in order to negotiate a treaty between Japan and Russia. His ship, named Diana, had spun 42 times during the tsunami attack due to the repetition of incoming and outgoing waves. Diana was seriously damaged and finally sunk. The tsunami traveled across the Pacific and reached the western coast of North America. It is reported that the tsunami height in San Francisco was less than or equal to 0.3 m.

Previous investigations have suggested that 8,300 houses collapsed, 600 were destroyed by fire, and 600 casualties in total were due to the earthquake and tsunami, although Usami (1975) has considered these figures to be an underestimation.



	N	E	d (km)	θ	δ	λ	L (km)	W (km)	U (cm)
1	33.90	138.13	3	245	24	113	150	100	400
2	35.14	138.73	2	198	34	71	115	70	400

Fig. 1 (A) Tectonic framework around Japan, (B) Map of central Japan with seismic parameters of the Ansei-Tokai earthquake (hatched squares 1 and 2 represent focal region of the earthquake and correspond to the seismic parameters below; the seismic parameters were determined based on recent geophysical data on Suruga Trench and description of historical documents (Sato, 1989), since the instrumental observation of earthquakes in Japan had not begun at the time of the 1854 earthquake), (C) Location of Iruma and Shimoda City

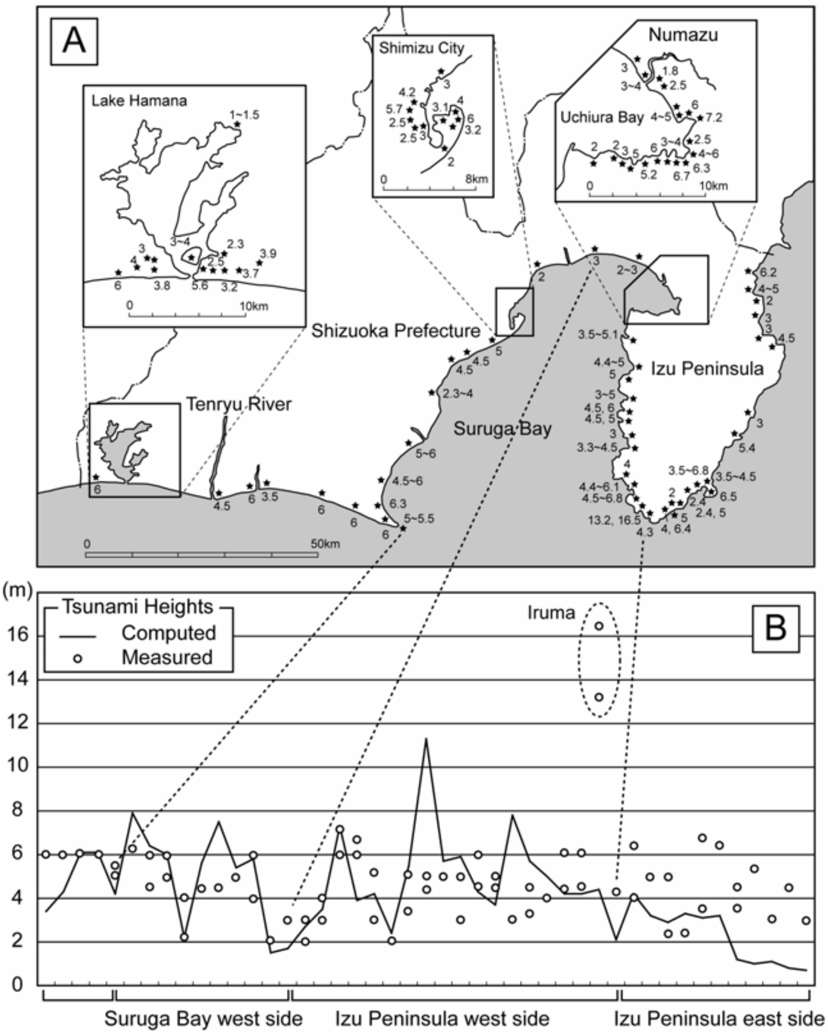


Fig. 2 (A) Measured trace heights of the 1854 Ansei-Tokai Earthquake tsunami in Shizuoka Prefecture (cited and modified from Antiseismic Division (1986)), (B) Comparison of computed and measured tsunami heights

In this study, we have carried out a detailed historical and sedimentological investigation on a peculiar tsunami deposit in Iruma, southwest Izu Peninsula, in order to clarify the origin and sedimentological characteristics of the tsunami deposit.

GEOGRAPHY OF SURVEY AREA

Izu Peninsula is located on the east part of central Japan, projecting approximately 50 km southward in the Pacific (Figure 1(B)). The basement rock of the peninsula is mainly composed of sea-bottom volcanic rocks and clasts in Neogene, and volcanic eruptions in Diluvial to Holocene cover the basement in the north half of the peninsula (Uemura and Yamada, 1988). Moderate mountains and hills make up most of the topographic configuration of the peninsula, with a small alluvial plain along narrow rivers. Due to the geologic and geographic settings, the coast of Izu Peninsula consists of rocky cliffs and inlets with a small sandy beach.

Suruga Bay is situated west of Izu Peninsula. The water depth above the sea floor of the bay increases toward the center axis of the bay, up to 2,500 m at the mouth and 1,500 m at the head of the bay, forming a deep trench of subduction zone (Suruga Trough) between the Eurasian and Philippine plates. According to Uemura and Yamada (1988), the continental shelf of the east side of Suruga Bay is covered mostly by muddy sediment, although the other side is covered by conglomerate and sand derived from the land.

Iruma (Figure 1(C)) is a small settlement located on the head of a V-shaped bay. The moderate sandy beach of Iruma abruptly changes into a huge mound on which many houses are located (Figure 3(A)). The mound has an elliptical dome shape, and the height of the mound seems to be no less than 10 m (Figure 3(B)). Total volume of the mound is estimated around 700,000 m^3, although the elevation of the basement of the mound is unknown (Asai et al., 1998, 1999). Previous investigation concluded that the mound is composed of marine sand originated from the Ansei-Tokai Earthquake tsunami (Antiseismic Division, 1986); however, this inference was based only on verbal evidence from local people. According to the measured trace heights of the Ansei-Tokai Earthquake tsunami in Shizuoka prefecture, the tsunami heights in the western coast of Izu Peninsula range between 3-6 m; however, abnormal tsunami heights of 13.2 and 16.5 m occurred at Iruma (Figure 2(A)).

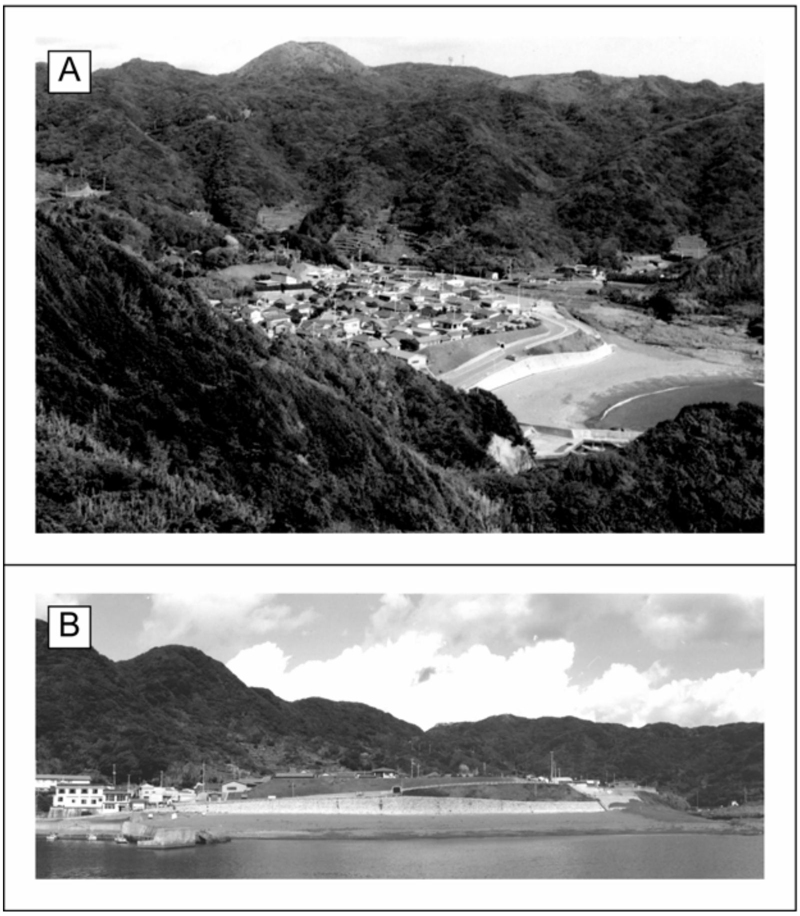


Fig. 3 (A) Bird's-eye photograph of Iruma, (B) Photograph of Iruma taken from the ocean side (The 1854 Ansei-Tokai Earthquake tsunami completely destroyed the settlement of Iruma and deposited a huge sand dome; afterwards, the survivors rebuilt their houses on the dome; the height of the dome is more than 10 m, and the total volume is estimated as 700,000 cubic meters (Asai et al., 1998))

RESULT OF NUMERICAL MODEL

In order to examine the possibility of the abnormal tsunami height at Iruma, we performed a numerical simulation of the Ansei-Tokai Earthquake tsunami. The propagation of the tsunami was computed using the numerical code, which is based on the linear long-wave equation and solved using the finite difference method (Shuto et al., 1990). Initial water level for tsunami source was calculated according to the method of Mansinha and Smylie (1971), applying the focal parameters of the Ansei-Tokai earthquake (Sato, 1989; Figure 1(B)). The calculation covered the tsunami propagation for 2 model hours in the Pacific coast of central Japan. The computed data is compiled along with the measured tsunami heights, and time histories of wave height at specific locations are recorded. Figure 2(B) shows generally good consistency between the computed and measured tsunami heights, meaning that the seismic model and numerical simulation well represent the Ansei-Tokai Earthquake tsunami. However, difference between the measured and computed tsunami heights is quite significant at Iruma. The measured tsunami heights at Iruma are 3-4 times larger than the computed heights.

Figure 4(A) shows the computed result of the time history of wave height at the mouth of Iruma Bay. The wave height of the tsunami is not significant (2.8 m) at the mouth of the bay. A spectrum of the tsunami waves (Figure 4(B)) was calculated by applying the Fourier transformation to the time history of tsunami height. Remarkable peaks of wave number are observed between 9.5 and 11.5, corresponding to the tsunami periods from 313 to 379 seconds. Therefore the numerical result suggests that the Ansei-Tokai Earthquake tsunami had a prominent tsunami period around 5-6 minutes at the mouth of Iruma Bay.

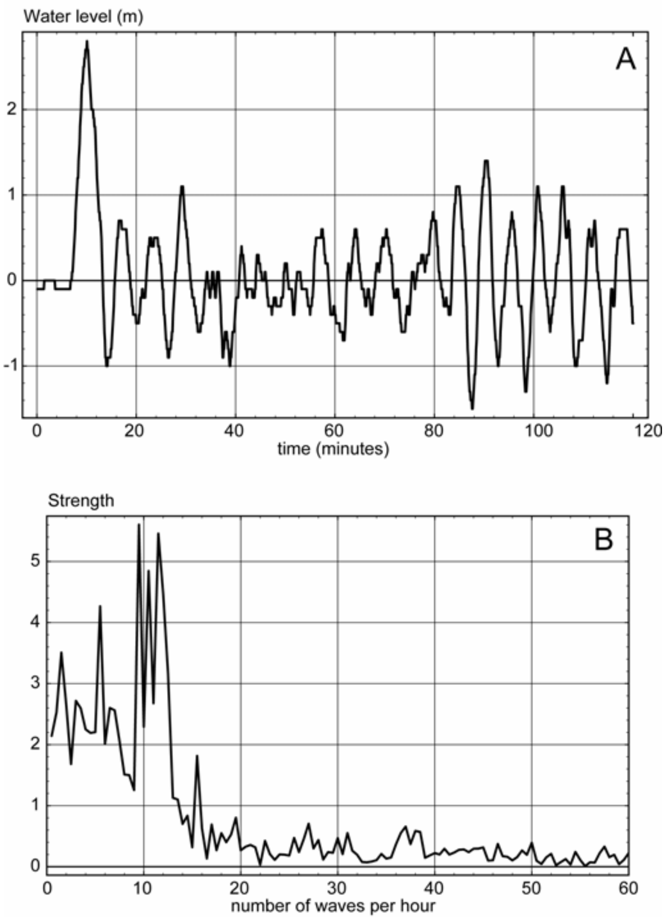


Fig. 4 (A) Computed time history of the tsunami at the mouth of Iruma Bay, (B) Fourier transformation of the time history of the tsunami (significant peaks appeared between 9.5 and 11.5 in the transverse axis)

HISTORICAL DATA

Geographical changes at Iruma after the Ansei-Tokai Earthquake tsunami were clarified by interviewing Mr. Tonooka, a person of the local important family of Iruma. According to the tradition of his family, people in his house were able to look at his farmland several hundred meters away from the house before the occurrence of the Ansei-Tokai Earthquake tsunami (Figure 5). Presently, people cannot see his farmland from his house, because the ground level between the two sites has changed. The elevations of Mr. Tonooka's house and his farmland are measured as 9.6 and 11.2 m, respectively. If we assume the height of 1.6 m for the eye level of an observer on Mr. Tonooka's house, both elevations become equal. Location survey by previous studies provided measured elevations of the ground surface from 15 m at the west half to 19 m at the east half of the sand dome (Asai et al., 1998, 1999); the ground now obstructs the line of sight from Mr. Tonooka's house to his farmland.

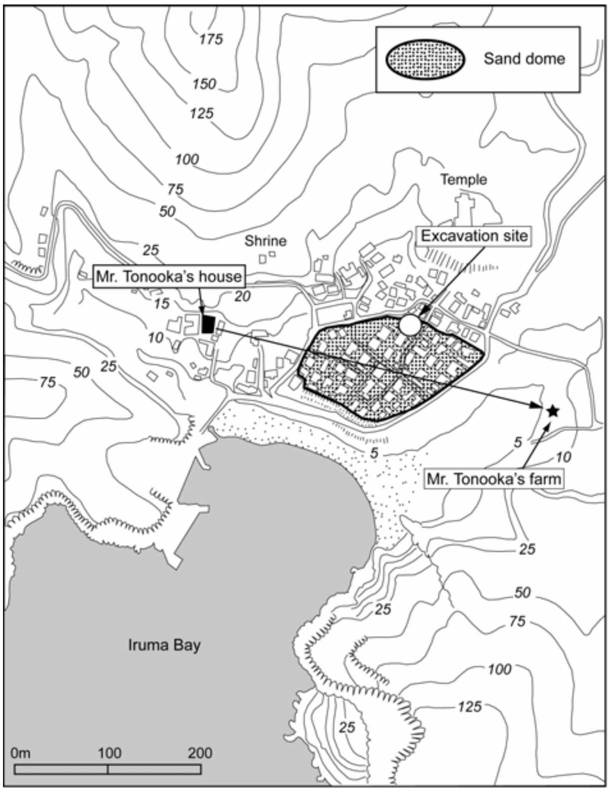


Fig. 5 Geographical map of Iruma (numbers indicate the elevations by meters)

Local history of Iruma (see 'Local History of Misaka Village' brought out by 'Parent's Society of Children in Misaka Higher Elementary School' in Japanese in 1932) from the library in Minami-Izu town (composed of Iruma and several other settlements) describes the origin and history of the sand dome: "Residential section of Iruma was a flat place in the past. On one occasion, the houses were washed away and sediments piled up on the center of Iruma due to a large-scale tsunami. The goodman of Tonooka's family once escaped to the mountain behind his house. However he went back to his house for important documents and treasures during the tsunami attack. Owing to great waves of the tsunami, he failed to bring his documents and treasures back, and he had been washed away by the waves instead. It is said that almost every important documents of Tonooka's family has been lost because of the incident. A massive fire at January 11, 1924 burned all houses in Iruma. A residential land development was planned after the fire, and the bumpy surface of the mound was scraped down."

Previous investigation mentioned that the goodman of Tonooka had left his hair on the branch of cedar, which is identified near the present Mr. Tonooka's house (Antiseismic Division, 1986). The measured ground elevation at the cedar and height of the branch are 13.2 m and 16.5 m, respectively.

Based on the verbal evidence of the local people and the description of the historical document, the sand dome originated from the invasion of the Ansei-Tokai Earthquake tsunami. In addition, the sand dome and residential area in Iruma experienced a massive fire and significant land modification.

EXCAVATION OF THE SAND DOME

A field excavation was carried out on the sand dome. The location of the excavation site is shown in Figure 4. The excavation reached 1.5 m under the present ground surface of the sand dome. Figure 6 shows the shallow stratigraphic column of the sand dome. The stratigraphy can be divided into three layers: upper sand, old soil and lower sand layer. The upper sand layer was found from 0 to 75 cm in excavation depth. The upper and lower sand layers were both homogeneous in sedimentological structure and did not show any laminations or vertical grading of particles. Abundant shell fragments and Batillus with operculum were detected from both sand layers. The difference between upper and lower sand layers is the existence of rounded pebbles and artificial ingredients; the upper sand layer yields a lot of fragments of roof tiles. The old soil layer was found from 75 to 80 cm in excavation depth. The old soil layer contains rounded pebbles and roof tiles as in the upper sand layer. Numerous charcoal fragments were detected from the interface of the upper sand and old soil layer. Samples for grain-size analysis were collected from seven horizons (A1-A7 in Figure 6) of the lower sand layer.

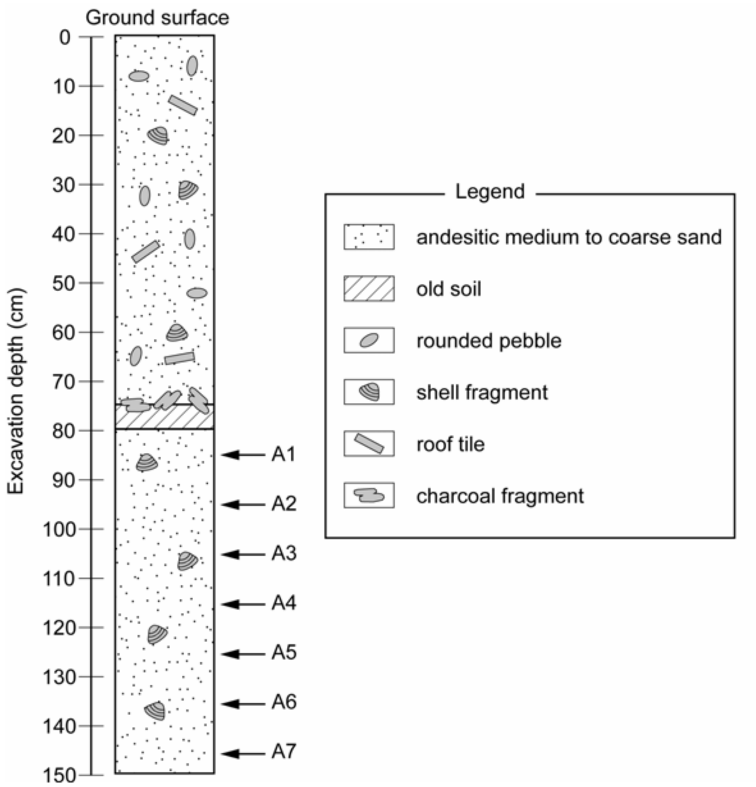


Fig. 6 Geological column of the sand dome (old soil layer was found at 80 cm in excavation depth; presence of roof tiles and charcoal fragments supports the reliability of historical documents that describes a massive fire and consequent land development; samples for grain-size analysis were picked at 10 cm intervals from the underlying layer of the old soil (A1-A7))

SUBMARINE INVESTIGATION

The distribution of marine sand was examined by a submarine investigation in Iruma Bay. The sea bottom of the bay is mainly composed of medium to coarse sand, which is similar to the sand retrieved from the excavation site on the sand dome. The sandy sea bottom extends 1,000 to 1,500 m offshore, corresponding to water depths of 20 to 30 m (Figure 7). The water depth of the sea bottom ranges from 30 to 40 m at the mouth of Iruma Bay. It is supposed that most of the sea floor of the bay is covered by sand. Samples for grain-size analysis were collected from six locations in the bay (Figure 7).

GRAIN-SIZE ANALYSIS

We performed a grain-size analysis in order to compare sedimentological characteristics of the sand dome and sea bottom. A grain-size analyzer with settling tube system (Minoura et al., 1988) was used, which is designed based upon the Stokes' law. The diameter measured by the grain-size analyzer is called Stokes' diameter. The settling velocity of a sedimentological particle with certain Stokes' diameter (ϕ) corresponds to that of a quartz-perfect sphere with the same geometrical diameter. The grain-size distribution curves of the sand of the mound show a good sorting of grain size, and each of the curves has a prominent peak from 0.8 to 0.9ϕ (Figure 8(A)). These peaks do not show significant vertical changes. The grain-size distribution curves of the sea-bottom sand have prominent peaks at 1.0 to 1.5ϕ, which is generally finer than that of the sand dome (Figure 8(B)).

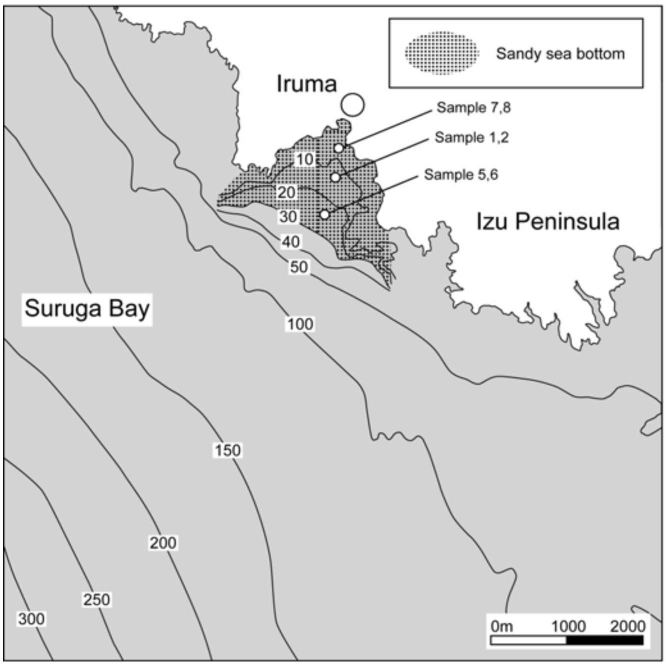


Fig. 7 Bathymetric map of the southern coast of Izu Peninsula (most parts of Iruma Bay are covered by sand; white circles indicate the sampling sites of sea-bottom sand; abstracted and modified from Bathymetric Chart No. 6362, Hydrographic and Oceanographic Department, Japan Coast Guard, 1980)

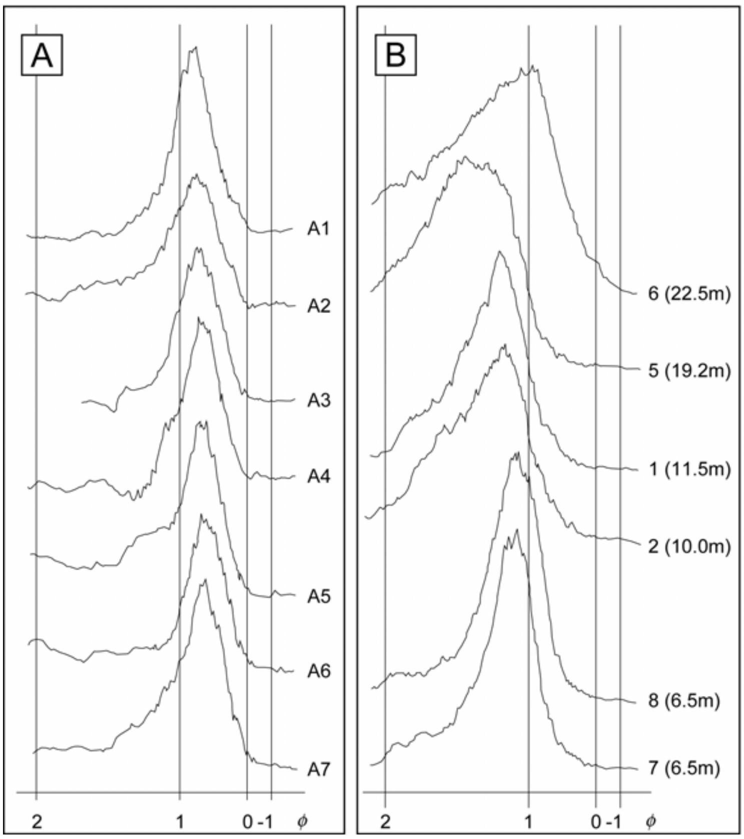


Fig. 8 Grain-size analysis of (A) sand dome and (B) sea bottom (values in parentheses are the water depths of sampling sites; grain-size distributions of the sand dome do not change vertically, and they are generally coarser than sea-bottom sand)

DISCUSSION

Data from the field excavation supports the description of the historical document, and sedimentological characteristics suggest a sea origin of the sand dome. The old soil layer yields a lot of charcoal fragments, which may be the trace of a massive fire in 1924. The artificial ingredients within the upper sand layer, such as rounded pebbles and roof tiles, are the result of the residential land development after the massive fire. Thus, the upper sand layer has been disturbed due to the land development described in the historical document, and the lower sand layer preserves an original condition of the sand dome. Abundant shell fragments and Batillus with operculum in the upper and lower sand layers suggest a sea origin of the deposit. The Batillus might have been transported from the shallow sea bottom, and buried alive in the sand dome. The grain-size distributions of the lower sand layer are quite similar to that of the sea-bottom sand of Iruma Bay. Both historical and sedimentological data show a good consistency; therefore, we can conclude that the huge sand dome in Iruma is a tsunami deposit, which was formed by the 1854 Ansei-Tokai Earthquake tsunami.

Invasion of large-scale tsunamis induce the transportation of sediments in coastal areas. Sands on shallow sea bottom and beach are mixed up in seawater due to the high turbidity of tsunamis. The sediment is transported landward and finally settles on land; it forms characteristic layers in coastal sedimentary sequences (Minoura and Nakaya, 1991). Previous studies on tsunami sedimentation mapped the distributions of historical and pre-historical tsunami deposits in the world (Bourgeois and Minoura, 1997), and revealed common sedimentological characteristics of tsunami deposits. Most onshore tsunami deposits have been found in coastal flats (e.g., Dawson et al., 1991), tidal marshes (e.g., Atwater and Moore, 1992) and lagoons (e.g., Foster et al., 1993). Tsunami deposits on coastal flats are typically sheets of beach or marine sand with the thickness of several millimeters to several tens of centimeters, which forms tapering wedges landward (Dawson et al., 1991; Minoura et al., 2001). The grain-size composition of tsunami deposits usually becomes finer landward, corresponding to a gradual loss of flow energy (Minoura et al., 1996). Repetition of the tsunami waves often forms multiple layers of sand sheets (Nanayama et al., 2000), and vertical variations of grain-size composition are interpreted as a temporal variation of flow regime (Shi et al., 1995). For example, fining upward sequence in tsunami deposit is related to deposition from turbulent suspension, which means a gradual decrease of flow velocity (Gelfenbaum and Jaffe, 2003).

However, the distribution and sedimentological characteristics of the tsunami deposit in Iruma are completely different from those of typical onshore tsunami deposits. The tsunami deposit in Iruma has a dome shape with a possible height of no less than 11.2 m and a quite limited distribution on the head of small bay. The lower sand layer is homogeneous in sedimentological structure (Figure 6) and does not show any vertical change in grain-size composition (Figure 8), which may suggest an abrupt decrease of flow velocity and rapid sedimentation of marine sand. The grain-size distribution of the tsunami deposit is much coarser than that of a typical tsunami deposit (e.g., Minoura et al., 1996). Concentration of coarser particles suggests a higher intensity current and a greater settling velocity compared with finer particles. No other example for this type of tsunami sedimentation has been reported by previous studies on tsunami deposit.

The formation of the huge sand dome in Iruma is probably due to the abnormal tsunami height of 13.2 and 16.5 m, which can be explained by harbor resonance. The resonant period in a rectangular bay with constant water depth is calculated by using the equation,

$$T_* = 4l/\sqrt{gh} \tag{1}$$

where T_* is the resonant period in rectangular bay, l is the length of bay, g is the acceleration due to gravity, and h is the water depth at the mouth of bay.

According to the numerical diagram by Kajiura (1982), the resonant period in V-shaped bay with linearly sloping bottom varies depending on the ratio between the width of bay mouth and length of bay. The width and length of Iruma Bay are measured using the bathymetric map of the southwestern coast of Izu Peninsula (Figure 7). If we adopt 1,500 m for the bay width and 1,500 m for the bay length, the resonant period in V-shaped bay is described by the equation,

$$(T - T_*)/T_* = 0.05 \tag{2}$$

where T is the resonant period in V-shaped bay.

The water depth of 30 m at the mouth of the bay can also be determined by using the bathymetric map. The resonant period in rectangular bay is calculated to be around 350 seconds in this case, therefore, the resonant period of Iruma Bay is nearly 368 seconds. On the basis of the numerical diagram of relationships between a dimensionless wave number (this can be converted from the resonant period) and the amplification factor in the head of a V-shaped bay (Kajiura, 1982), the resonant period of 386 seconds corresponds to the amplification factor of 4.8 at Iruma Bay. The result of our numerical model suggests that the Ansei-Tokai Earthquake tsunami at the mouth of Iruma Bay had a maximum wave height of 2.8 m and a prominent period at 5-6 minutes (Figure 4). The prominent periods of the tsunami and the resonant period in Iruma Bay overlap with each other. The overlap of the tsunami and resonant periods in the V-shaped bay may cause a significant amplification of the tsunami (Honma, 1973). Therefore, the abnormal tsunami height can be explained by the harbor resonance in Iruma Bay. The Ansei-Tokai Earthquake tsunami at Iruma might have had enough hydrodynamic energy to transport a huge amount of sea-bottom sand toward the head of Iruma Bay.

A sufficient quantity of sediment supply is necessary for the formation of the huge sand dome in Iruma. Our submarine investigation revealed that the greater part of Iruma Bay was covered with sand. Continuous supply of marine sand to the seawater might have taken place during the inversion of the Ansei-Tokai Earthquake tsunami. According to the grain-size analysis, the particle compositions of the tsunami deposit and sea-bottom sand in Iruma Bay are coarser than that of a typical tsunami deposit. The rapid sedimentation of the sand dome might have resulted from a greater settling velocity of the coarser particles.

Taking into account the topographic configuration and the extreme amplification of the tsunami at Iruma Bay, backwash of the tsunami might have been strong enough to relocate sediments, including the newly made sand dome. Kon'no (1961) reported that the backwash of tsunami at a bay head converges on trenches and rivers, and it acts as an agent of erosion. In this case, the ground elevation of the east side of the sand dome is relatively low and it makes a moderate valley with a small channel (Figure 5). It is possible that the strong backwash of the tsunami occurred mostly on the small valley, and this probably reduced the total volume of the sand dome.

The formation of the huge sand dome in Iruma is a local phenomenon; however, the geographical change of the coastal area is quite significant. Investigation of the sedimentation process of the tsunami deposit may lead us to a good understanding of the development of coastal topography, which will contribute to the assessment of tsunami hazard.

CONCLUDING REMARKS

We investigated the huge sand dome in Iruma, southwest coast of Izu Peninsula, central Japan. The historical and sedimentological data show good consistency, which suggests that the 1854 Ansei-Tokai Earthquake tsunami with the abnormal tsunami height of 13.2 and 16.5 m might have formed the sand dome. The numerical examination of the tsunami suggests that the prominent periods of the tsunami and resonance period in Iruma Bay overlap each other, and the amplification factor is estimated to be 4.8. This may have caused an extreme amplification of tsunami waves. According to the submarine investigation, most of Iruma Bay was covered by medium to coarse sand. It is supposed that high-energy turbulent flow caused by the amplified tsunami waves mixed up a huge amount of sediment, which finally accumulated at the head of Iruma Bay.

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