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Examination of the largest-possible tsunamis (Level 2) generated along the Nankai and Suruga troughs during the past 4000 years based on studies of tsunami deposits from the 2011 Tohoku-oki tsunami

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Abstract

Japanese historical documents reveal that Mw 8 class earthquakes have occurred every 100–150 years along the Suruga and Nankai troughs since the 684 Hakuho earthquake. These earthquakes have commonly caused large tsunamis with wave heights of up to 10 m in the Japanese coastal area along the Suruga and Nankai troughs. From the perspective of tsunami disaster management, these tsunamis are designated as Level 1 tsunamis and are the basis for the design of coastal protection facilities. A Mw 9.0 earthquake (the 2011 Tohoku-oki earthquake) and a mega-tsunami with wave heights of 10–40 m struck the Pacific coast of the northeastern Japanese mainland on 11 March 2011, and far exceeded pre-disaster predictions of wave height. Based on the lessons learned from the 2011 Tohoku-oki earthquake, the Japanese Government predicted the tsunami heights of the largest-possible tsunami (termed a Level 2 tsunami) that could be generated in the Suruga and Nankai troughs. The difference in wave heights between Level 1 and Level 2 tsunamis exceeds 20 m in some areas, including the southern Izu Peninsula. This study reviews the distribution of prehistorical tsunami deposits and tsunami boulders during the past 4000 years, based on previous studies in the coastal area of Shizuoka Prefecture, Japan. The results show that a tsunami deposit dated at 3400–3300 cal BP can be traced between the Shimizu, Shizuoka and Rokken-gawa lowlands, whereas no geologic evidence related to the corresponding tsunami (the Rokken-gawa–Oya tsunami) was found on the southern Izu Peninsula. Thus, the Rokken-gawa–Oya tsunami is not classified as a Level 2 tsunami.

Keywords: Tsunami deposits, Late Holocene, Suruga Trough, Nankai Trough, Shizuoka Prefecture, 2011 Tohoku-oki tsunami deposit, Level 2 tsunami

Background

The 2011 off the Pacific coast of Tohoku Earthquake, which is the largest earthquake (Mw 9.0) recorded in Japan, occurred on 11 March 2011 off the Pacific coast of the northeastern Japanese mainland (Fig. 1). The earthquake generated a mega-tsunami with a runup height of 10–40 m in coastal areas of Iwate, Miyagi, and northern Fukushima prefectures and resulted in ~20,000 deaths. The tsunami eroded sand from beaches and dunes, and deposited sediments inland (e.g., Goto et al. 2011; Richmond et al. 2012; Szczuciński et al. 2012; Takashimizu et al. 2012). A historical document known as *Sandai-jitsuroku* records a similar mega-tsunami, called the Jogan tsunami, which occurred in AD 869. Abe et al. (1990) reported deposits from the Jogan tsunami on the Sendai Plain. From the Jogan tsunami deposit and two older, prehistorical tsunami deposits, Minoura et al. (2001) estimated that the recurrence interval for large tsunamis in the area is 800–1100 years and concluded that the likelihood of a large tsunami inundating the Sendai Plain is high. The Jogan tsunami

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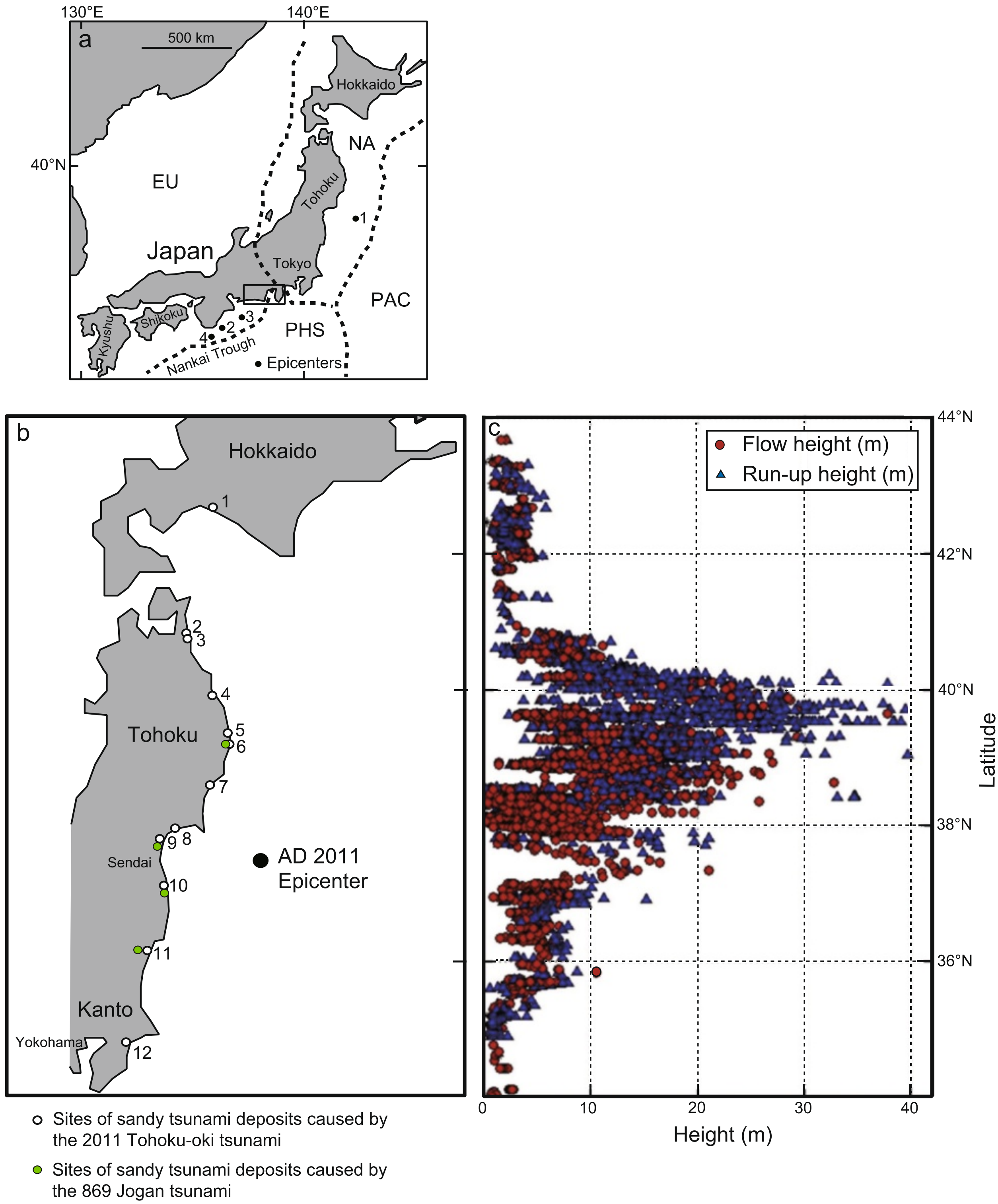

Fig. 1 Locality map. **a** The Japan Islands, showing the plate configuration and the locations of the studied areas. *EU* Eurasia Plate, *NA* North American Plate, *PAC* Pacific Plate, *PHS* Philippine Sea Plate, *1* Epicenter of the 2011 Tohoku-oki earthquake (Mw 9.0), *2* Epicenter of the 1944 Tonankai earthquake (Mw 8.2), *3* Epicenter of the 1854 Ansei-Tokai earthquake (M 8.4), *4* Epicenter of the 1707 Hoei earthquake (M 8.4). *Dashed lines* are plate boundaries. **b** Sites of previous studies of sandy tsunami deposits (numbers refer to those in Table 1) resulting from the 2011 Tohoku-oki tsunami and the 869 Jogan tsunami. **c** Flow height and runup height of the 2011 Tohoku-oki tsunami, modified after Goto et al. (2012)

deposit has also been reported from the coastal plain of northern Fukushima Prefecture (Shishikura et al. 2010; Sawai et al. 2012). These previous studies, which were conducted before the 2011 Tohoku-oki earthquake, demonstrate that tsunami deposits can reveal information about the occurrence and extent of mega-tsunamis over time scales of several thousand years.

Based on the lessons learned from the 2011 Tohoku-oki earthquake, the Cabinet Office, Government of Japan (2013), has presented information on the two types of tsunamis expected in the future in the Suruga and Nankai troughs, where the Philippine Sea Plate is subducting beneath the Eurasian Plate (Fig. 1) (Goto et al. 2014a). One type is large tsunamis (Level 1 tsunami) with wave heights of 5–10 m in coastal areas, which have occurred every 100–150 years in the area since the 684 Hakuho earthquake (e.g., Ando 1975; Watanabe 1998; Sangawa 2001; Figs. 2 and 3). Level 1 tsunami events are caused mainly by Mw 8 class earthquakes. The other type of tsunami is the largest-possible tsunami (Level 2 tsunami) caused by the largest-possible earthquake (Mw 9.1; Cabinet Office, Government of Japan, 2012) that occur along megathrusts in the Nankai Trough (Fig. 2). Level 2 tsunami events will be infrequent but cause widespread damage. In 2012, the government also presented 11 cases of the wave heights of Level 2 tsunamis (Fig. 4). For details of the method used for calculation of wave heights, see Cabinet Office, Government of Japan (2012). The Shizuoka Prefectural Government (2013) used model cases 1, 6, and 8 for the wave heights of Level 2 tsunamis (Fig. 5), because the wave heights in Shizuoka Prefecture in these models are higher than in the other models. A recently constructed coastal dike has reduced the projected inundation area of Level 1 and 2 tsunamis, and affects the comparison of the inundation area and sedimentary deposits resulting from past tsunamis.

The wave height of a Level 2 tsunami would be 1–20 m higher than that of a Level 1 tsunami for all areas in Shizuoka Prefecture (Fig. 5). For disaster preparedness in Japan, it is important to examine the occurrences of Level 2 tsunamis over time scales of several thousand years based on analyses of tsunami deposits. The wave height of a Level 2 tsunami in the Suruga and Nankai troughs (Fig. 4) would be similar to that of the Tohoku-oki tsunami (Fig. 1). In addition, the main morphological elements from marsh through beach ridge to the open Pacific Ocean are similar in both the coastal areas of Shizuoka Prefecture (Fujiwara et al. 2013; Kitamura et al. 2013a, b, 2015a; Kitamura and Kobayashi 2014a, b; Kitamura and Kawate 2015) and the Tohoku area (e.g., Goto et al. 2011; Abe et al. 2012; Takashimizu et al. 2012; Koiwa et al. 2014; Ishimura and Miyauchi 2015). Therefore, the sedimentary characteristics and spatial distributions of the tsunami deposits formed by the Tohoku-oki tsunami are used as a reference for determining the deposits that would be generated by a Level 2 tsunami in the coastal area of Shizuoka Prefecture, Japan.

Methods

The Tohoku-oki tsunami deposits were reviewed by Goto et al. (2012). Here, I summarize this previous review and cover advances made since that study. In addition, I compile existing data on the stratigraphic distribution of prehistorical tsunami deposits and tsunami boulders in Shizuoka Prefecture.

The Tohoku-oki event caused a maximum coastal tsunami wave height of nearly 40 m along the Sanriku coast (e.g., Mori et al. 2012) with a maximum inundation distance of 5 km inland from the beach on both the Ishinomaki and Sendai plains (e.g., Nakajima and Koarai 2011). Previous studies have examined the 2011 Tohoku-oki tsunami deposit in many parts of the 900 km long coastline between southwestern Hokkaido and the northern Boso Peninsula (Fig. 1), except for the area near the Fukushima–Daiichi Nuclear Plant, which was severely damaged by the 2011 Tohoku-oki earthquake and the subsequent mega-tsunami. Table 1 lists the characteristics of sandy tsunami deposits at these sites. Similarly to the findings of the review by Goto et al. (2012), the deposits in all of the study areas have a sharp erosional base, but other sedimentary characteristics vary between the sites. Parallel laminations are commonly observed in the deposits.

It is noteworthy that marine fossils were only detected in a few areas. The presence of marine fossils in sedimentary deposits has been regarded as a key criterion for the identification of paleotsunami events in the geologic record (e.g., Chagué-Goff et al. 2011; Clark et al. 2011). Sugawara et al. (2014) performed numerical modeling to explain the absence of marine fossils, and demonstrated that the tsunami caused a significant amount of erosion on beaches and in coastal forest areas, but was minor on the offshore seafloor where marine organisms are most concentrated.

The 2011 tsunami deposit is up to 40 cm thick and extends up to 4.5 km inland on the Sendai Plain of Miyagi Prefecture (Goto et al. 2011; Takashimizu et al. 2012). Takashimizu et al. (2012) and Goto et al. (2014b) examined the relation between the thickness of the tsunami deposit and flow depth based on spatial variations in the thickness of the 2011 tsunami deposit. The results show that the sediment thickness increased concomitantly with increasing flow depth, and that the thickness reached its peak value when the flow depth was 4–5 m. For flow depths greater than 5 m, almost no deposition occurred; instead, the erosion of surface sediments outweighed the deposition from the tsunami.

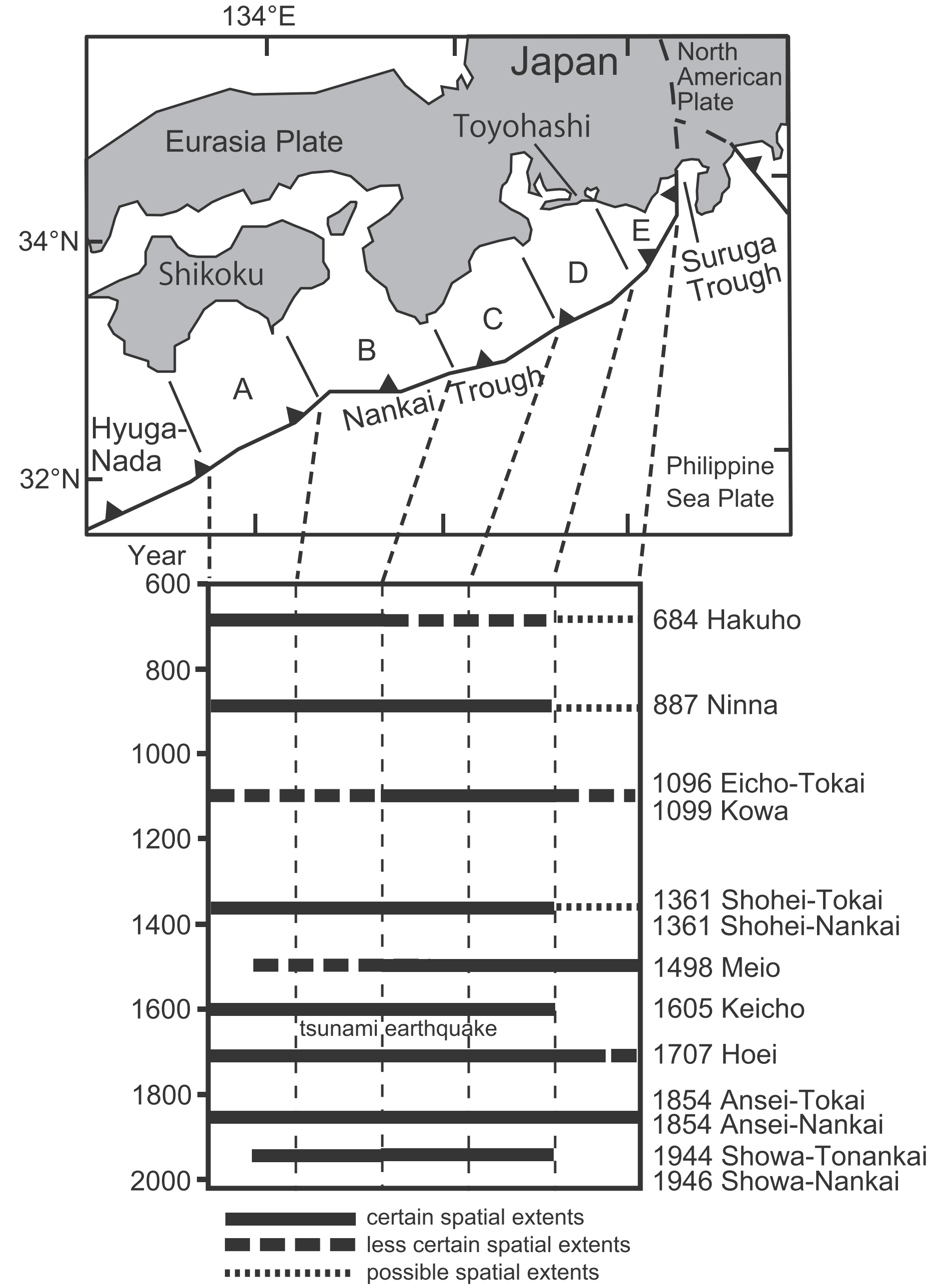

Fig. 2 Spatial–temporal distribution of great earthquakes along the Nankai Trough (Ando 1975; Ishibashi and Satake 1998)

Abe et al. (2012) examined the relationship between the maximum extent of sandy tsunami deposits and the inundation distance of the 2011 Tohoku-oki tsunami on the Sendai Plain. The results showed that ≥0.5 cm thick sandy tsunami deposits on seaward-facing slopes commonly extend to over 90 % of the inundation distance where the inundation distance is less than 2.5 km, whereas the maximum limit of ≥0.5 cm thick sand layers on flat plains is 3 km (57–76 % of the inundation distance) for an inundation distance exceeding 2.5 km. This relationship between the maximum extent of sandy tsunami deposits and inundation distance is consistent with that of the 15 November 2006 Kuril Island tsunami reported by MacInnes et al. (2009).

Namegaya and Satake (2014) compared the distribution of the Jogan sandy tsunami deposit with that of the 2011 sandy tsunami deposit on the Sendai and Ishinomaki plains, and estimated that the rupture length of the 869 Jogan earthquake was at least 200 km and its minimum moment magnitude was 8.6. The

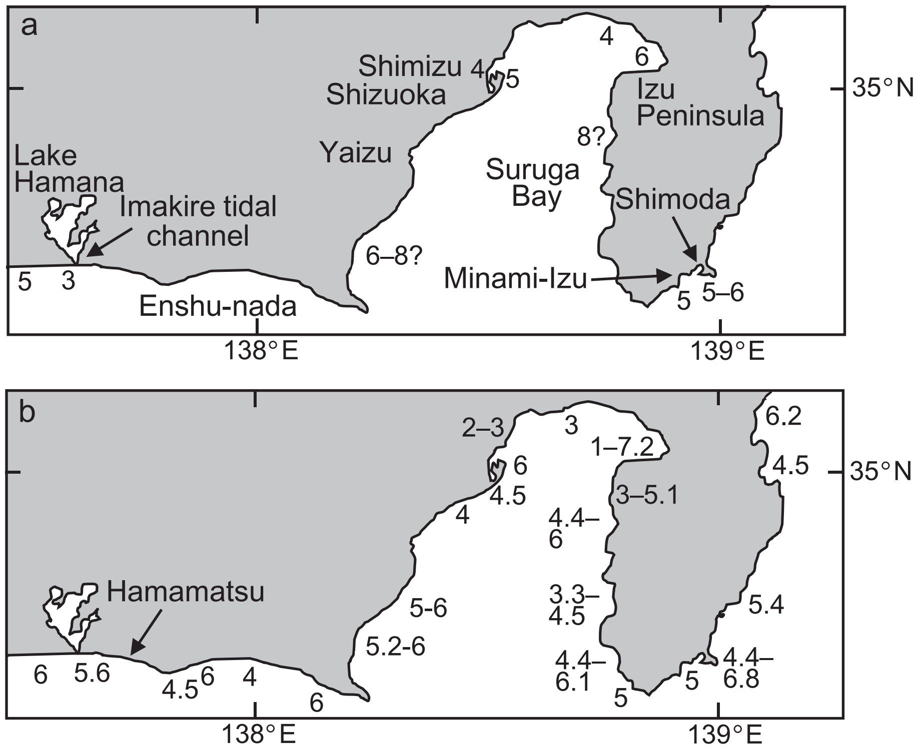

Fig. 3 Inundation heights of tsunamis caused by historical earthquakes. Distribution of inundation (heights in meters) in the coastal areas around Suruga Bay and Enshu-nada, as presented by Hatori (1976) and Watanabe (1998) for **a** the 1707 Hoei earthquake and **b** the 1854 Ansei-Tokai earthquake

Jogan sandy tsunami deposits have also been reported from the Sanriku Coast (Sugawara et al. 2012; Ishimura and Miyauchi 2015) and from Fukushima Prefecture (Shishikura et al. 2010; Sawai et al. 2012).

Results and discussion

Prehistorical tsunami deposits in Shizuoka Prefecture

The prehistorical tsunami deposits in Shizuoka Prefecture have been reviewed by Komatsubara et al. (2006) and Komatsubara and Fujiwara (2007). Here, I summarize the previous reviews as well as more recent information.

Southern Izu Peninsula

The coastal lowland areas of Minami-Izu and Shimoda have been inundated by many large tsunamis during the past 400 years. The estimated wave heights of the 1707 Hoei tsunami were 5 and 5–6 m at Minami-Izu and Shimoda, respectively (Fig. 3a) (Hatori 1977). The wave heights of the 1854 Ansei-Tokai tsunami were 5 and 4.4–6.8 m at Minami-Izu and Shimoda, respectively (Figs. 3b and 6) (Hatori 1977). For a Level 2 tsunami, the predicted tsunami wave heights are 10–20 m (Figs. 5 and 6). On the basis of the faunal compositions and ^{14}C ages of emergent sessile assemblages examined by Kitamura et al. (2015b, c), the southern Izu Peninsula is inferred to have experienced co-seismic uplift in 1256–950 BC, AD 1000–1270, AD 1430–1660, and AD 1506–1815, caused by movement on a reverse fault located off the southern Izu Peninsula. The highest emergent sessile marine invertebrates, dated at 1256–950 BC, occur at 3.40 m above mean sea level (amsl).

Kitamura et al. (2013a), Kitamura and Kobayashi (2014a) and Kitamura and Kawate (2015) analyzed the stratigraphy and paleoenvironmental setting of Holocene deposits in the southern Izu Peninsula based on an outcrop (site 2 in Fig. 6f) and sediment cores (8–11 m long) from 16 sites (1.3–9.1 m amsl) (Figs. 6, 7, and 8). Eleven sites are located within the inundation area of a Level 2 tsunami, and sites S5, S6, and S7 in Shimoda are located within the inundation area of the Ansei-Tokai tsunami (Fig. 6c). The record of the deposits extends back to 7840–7690 cal BP (Site 8 in Fig. 7). Kitamura and Kobayashi (2014a) identified a possible tsunami deposit at site 5 on Shimoda (1.76 m amsl; Fig. 7) that may have formed during the 1707 Hoei event or the 1854 Ansei-Tokai tsunami.

Kitamura et al. (2014) reported a tsunami boulder, 3.4 m long and ~32 metric tons in weight, which was rolled by the Ansei-Tokai tsunami onto a coastal plateau at Nabeta Bay (Fig. 6d), based on the ^{14}C ages of the emergent sessile assemblages. In this area, a tsunami height of more than 20 m for a Level 2 tsunami was

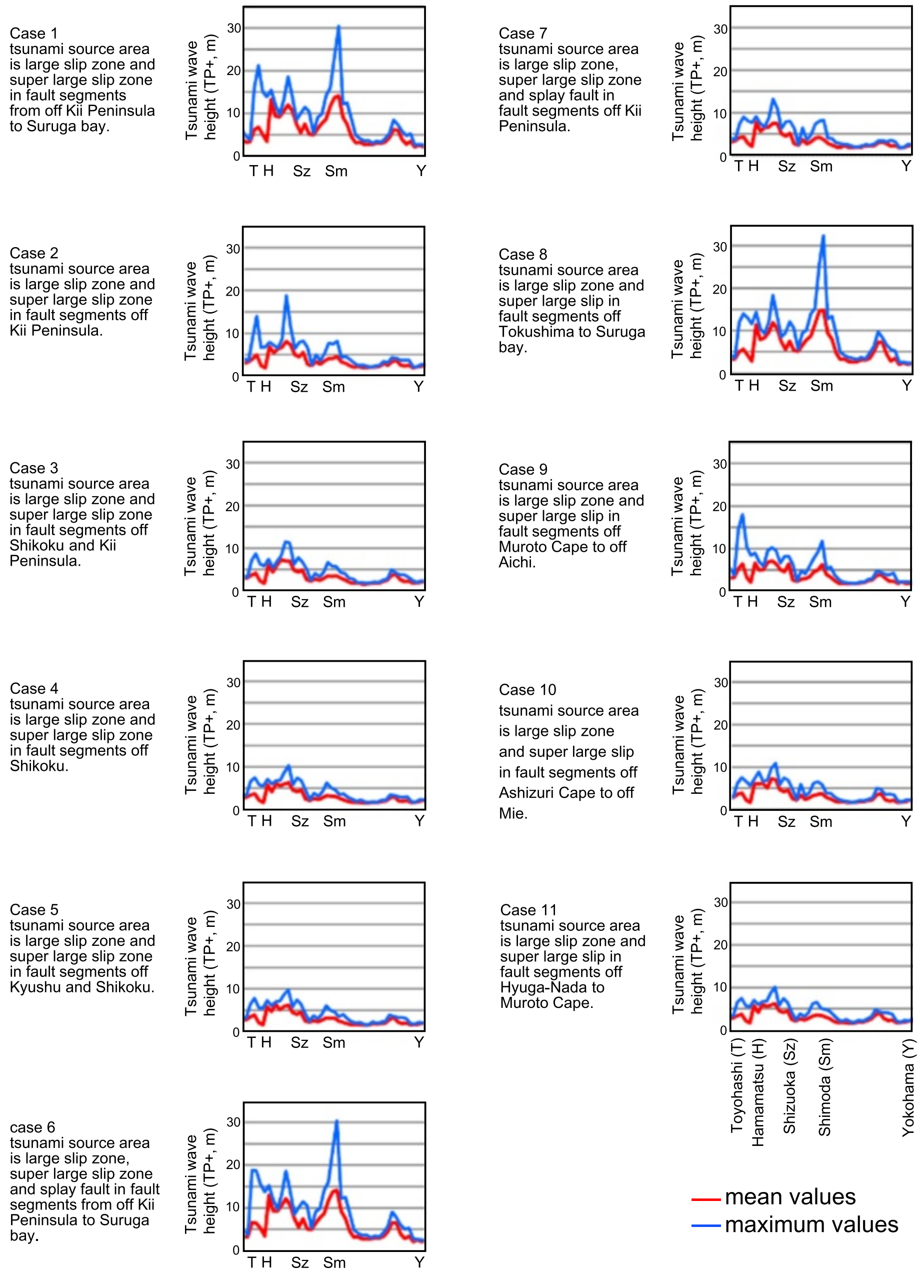

Fig. 4 Model of the tsunami wave height of a Level 2 tsunami. After Cabinet Office, Government of Japan (2012). Place names are shown on Figs. 1, 2, and 3

predicted (Fig. 6). Many large boulders are present on the coastal plateau around Nabeta Bay, although boulders do not occur above the supratidal area.

Shimizu Plain

The Shimizu Plain is adjacent to Orido Bay, which is protected from the open ocean by the Miho Peninsula (Figs. 5 and 9). Low-lying (<5 m amsl) terrain is present along the Tomoe River up to 3 km inland from the coast, and is protected by a coastal dike. The wave heights of the Hoei earthquake tsunami along the Pacific side of the Miho Peninsula and the coastal area of the northern Shimizu Plain are estimated to have been 5 m and 4 m, respectively (Fig. 3a) (Hatori 1977). The wave heights of the tsunami generated by the Ansei-Tokai earthquake were estimated to have been 6 and 3 m on the Pacific coast of Miho Peninsula and the coastal area of the northern Shimizu Plain, respectively (Fig. 3b) (Hatori 1977). However, no evidence of the Ansei-Tokai tsunami has been documented in the coastal area of the

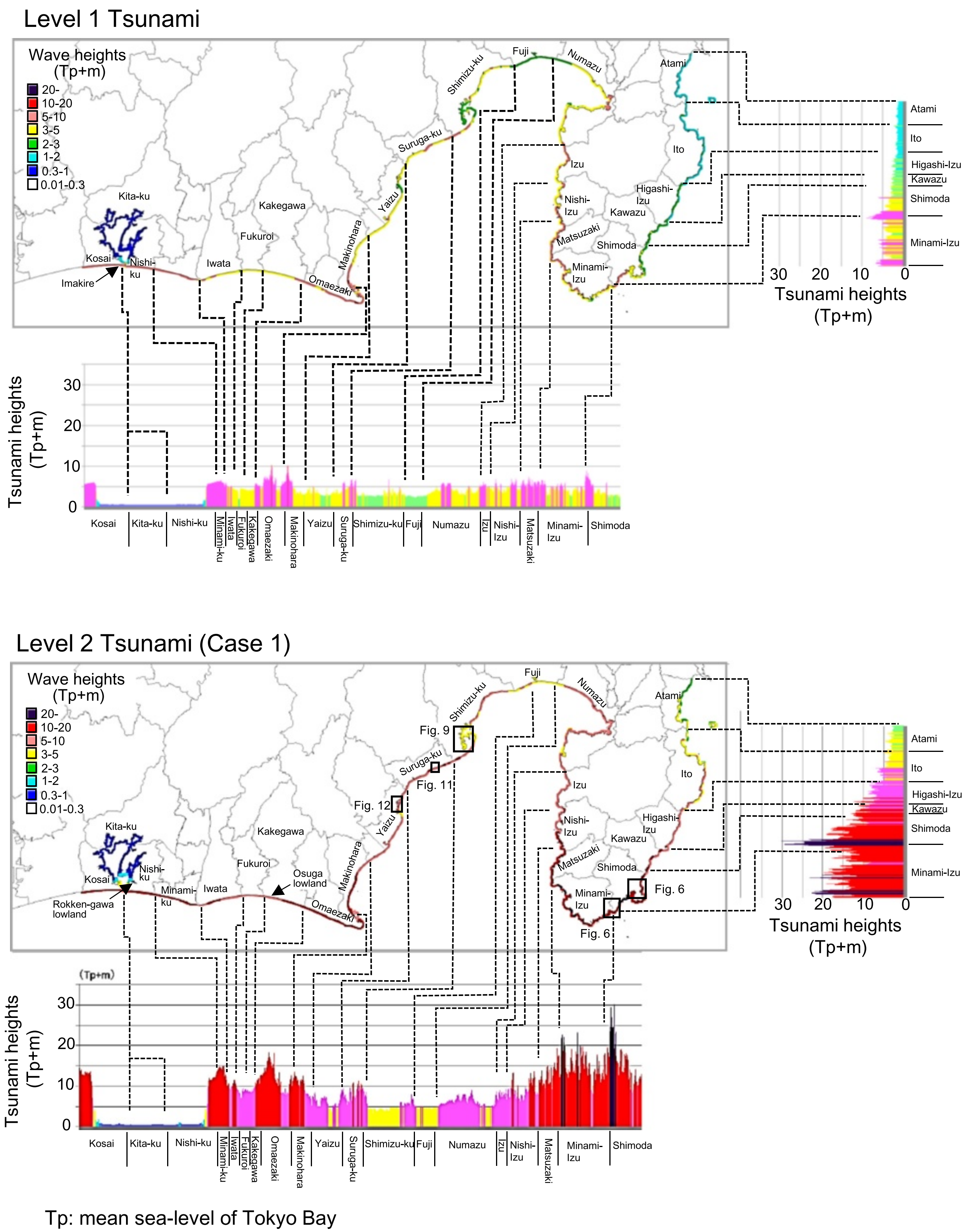

Fig. 5 Wave height (m) of Level 1 and 2 tsunamis in Shizuoka Prefecture. After Shizuoka Prefectural Government (2013)

Table 1 Summary of sandy tsunami deposits related to the 2011 Tohoku-oki earthquake

	Region	Height amsl (m)	Maximum thickness (cm)	Numbers of layers	Inner structure	Laminations	Sorting	Presence of marine fossils	Presence of rip-up clasts	References
1	Atsuma river, Hokkaido	3.53 (inundation height)	ca. 20	6	(1) Erosinal basement. (2) Sand layers seperated by mud drape.	Parallel > > cross	Well	Diatoms	No detection	Oota et al. 2012
2	Misawa coast, Aomori Prefecture	3.5–8.8 (flow height)	56	1	(1) Erosinal basement. (2) Normal grading.	Massive > parallel > cross	Well to moderately	No detection	No detection	Nakamura et al. 2012
3	Southern Misawa coast, Aomori Prefecture	8 (run up height)	48	1 to 3	(1) Erosinal basement. (2) Normal grading > reverse grading.	Parallel	–	No detection	No detection	Koiwa et al. 2014
4	Mouth of Fudai river, Iwate Prefecture	23 (run up height)	60	1	(1) Erosinal basement. (2) Normal grading.	Parallel	Poorly	No detection	No detection	Seo and Okushi 2012
5	Miyako City, Iwate Prefecture	28.1 (flow depth at the coast)	ca 100	1	(1) Erosinal basement. normal and inverse grading	Massive	–	No detection	Presence	Yamada et al. 2014
6	Koyadori, Iwate prefecture	26-29 (run up height) 13-18 (inundation height)	20	2	(1) Erosinal basement. (2) The lower unit is composed of coarse sediments with normal grading. The upper unit comprises finer sediments.	Partially laminated	–	–	No detection	Ishimura and Miyauchi 2015
7	Rikuzen Takada, Iwate Prefecture	19.9 (run up height) 14-15 (inundation height)	31.5	1 to 4	(1) Erosinal basement. (2) The normally graded subunit was generally thicker than the inverse-graded one.	Parallell > > cross	Moderately to poorly	Ostracoda	No detection	Naruse et al. 2012
8	Beach along Matsushima bay, Miyagi Prefecture	8-14 (flow height at the coast)	–	–	–	–	–	Molluscs	–	Fujiwara et al. 2014
9	Sendai Plain, Miyagi Prefecture	11 (flow height at the coast)	ca 70	1 to 2	(1) Erosinal basement. (2) Normal grading > > massive.	Parallell > > cross	Well	Very rare diatoms	Presence	Goto et al. 2011; Kitamura and Wakayama 2011; Shishikura 2011; Abe et al. 2012; Pilarczyk et al. 2012; Szczuciński et al. 2012; Takashimizu et al. 2012; Putra et al. 2013; Fujiwara and Tanigawa 2014; Goto et al. 2014a, b
10	Minami-Souma, Fukushima Prefecture	–	30	Multiple layers	(1) Erosinal basement. (2) Normal grading.	Laminar	Poorly	–	–	Iijima et al. 2013
11	Kita-Ibaraki, Ibaraki Prefecture	5.47 (flow height at the coast)	28	1 to 4	(1) Erosinal basement. (2) Sand layers were often seperated by mud drape. (3) Massive > normal grading.	Massive > parallel	Well	Molluscs	No detection	Yamada and Fujino 2013
12	Norther Boso Peninsular, Chiba Prefecture	6 (flow height at the coast)	35	4	(1) Erosinal basement. (2) The fine alternation of sand sheet and overlying mud drape.	Massive	–	Molluscs	No detection	Fujiwara et al. 2012

innermost part of Orido Bay. In this area, predicted wave heights for a Level 2 tsunami are 5–7 m (Fig. 5).

The Shimizu Plain experienced ~1.2 m of uplift during the Ansei-Tokai earthquake (Fig. 10) (Kitamura and Kobayashi 2014b), and the area has subsided gradually (~6 mm/year) during the present interseismic period.

Kitamura and Kobayashi (2014b) analyzed Holocene sediment cores (9–23 m long) from 12 sites (2.1–8.2 m amsl) in the fluvial–coastal lowland of Shimizu Plain (Fig. 9). Six sites are located within the inundation area of a Level 2 tsunami (Fig. 9). Sites 1, 3, 4, and 12 are located within the inundation area of the Ansei-Tokai tsunami (Shizuoka Prefectural Government 2011).

Kitamura and Kobayashi (2014b) identified four prehistorical tsunami deposits (T-I to T-IV) from shallow-water (from low tide to 40 m depth) muddy-bay deposits (Fig. 9). The deposits yield ^{14}C ages of 6180–6010 to 5700–5580 cal BP for T-I, 5700–5580 to 5520–5320 cal BP for T-II, 4335–4125 to 4250–4067 cal BP for T-III, and 3670–3540 to 3500–3360 cal BP for T-IV. Kitamura and Kobayashi (2014b) also found three event deposits (beds 1–3) at site 1-1, and concluded that these beds may have formed during the 1498 Meio or 1707 Hoei earthquakes.

Shizuoka Plain

The Oya lowland, to the southeast of the Shizuoka Plain, is bounded by the Udo Hills to the east and by the Abe River fan to the west (Figs. 5 and 11). Beach ridges and dunes up to 10 m high protect the lowland from Suruga Bay. At present, a large area of the Oya lowland has an artificially raised ground level (by ~2 m), with a height of 7–8 m amsl. Historical evidence of tsunamis in Shizuoka Prefecture demonstrates that the area was affected by six major tsunami events between the 1096 Eicho earthquake and the 1944 Tonankai earthquake; however, there are no historical documents suggesting the occurrence of tsunamis on the Oya lowland (Hatori 1977). In this area, predicted wave heights are 5–10 m for a Level 2 tsunami (Figs. 5 and 11).

Kitamura et al. (2013b) analyzed the stratigraphy and paleoenvironmental setting of Holocene deposits based on sediment cores (8–9 m long) from seven sites (6.2–7.8 m amsl) in the Oya lowland (Fig. 11). All sites are located outside the inundation area of a Level 2 tsunami. The area is protected by a coastal dike. Sites 1, 3, and 4 are located within the inundation area of the Ansei-Tokai tsunami (Shizuoka Prefectural Government 2011). Kitamura et al. (2013b) identified three possible tsunami deposits: sand beds T0 (around AD 1000), T1 (3565–3486 cal BP), and T2 (around 4000 cal BP) from a lagoonal mud sequence. Sand bed T1 was observed at five sites (3.2–4.5 m amsl), whereas sand beds T0 and T2 were detected at only one site each, site 4 and site 2, respectively (Fig. 11).

On the basis of temporal changes in diatom assemblages, Kitamura et al. (2013b) suggested that sand bed T1 formed as a result of ruptures along megathrusts in the Suruga and/or Nankai troughs. At one archeological site (Nagasaki remains) on the northern Shizuoka Plain (Fig. 11a), Shizuoka Prefecture Archaeological Survey Institute (1991) found faulted layers (Seilacher 1969) immediately below undeformed sediment including the Kawagodaira Pumice (Kg), which was erupted between 1210 and 1187 cal BC (95.4 % confidence level; Tani et al. 2013). As the age of formation of the sediment-deformation structures is similar to that of the deposition of sand bed T1, it is likely that they were caused by the same earthquake. Kitamura et al. (2013b) concluded that the youngest sand bed, T0, may be correlated with the 1096 Eicho earthquake, although the possibility of the 1099 Kowa earthquake was not excluded.

Yaizu Plain

The Yaizu Plain is located on the northern area of the fan delta of the Ooi River and the delta of the Seto River (Figs. 5 and 12). The plain was inundated by a tsunami generated by the 1498 Meio earthquake that occurred in the Nankai and Suruga troughs. The wave height of the tsunami is estimated to have been 6–8 m (Hatori 1977). There are no historical documents that mention the Ansei-Tokai tsunami in this area. The co-seismic uplift caused by the Ansei-Tokai earthquake is estimated to have been 1.8 m in the area located 4 km northeast of the Yaizu Plain (Fig. 10) (Ishibashi 1984). The area has subsided gradually during the present interseismic period (Kitamura et al. 2015a). In this area, predicted wave heights for a Level 2 tsunami are 5–10 m (Figs. 5 and 12).

Kitamura et al. (2015a) analyzed late Holocene sedimentary sequences from sediment cores (8–9 m long) collected at nine sites (1.8–4.5 m amsl) in the coastal area of the Yaizu Plain (Figs. 12 and 13). Six sites are located within the inundation area of a Level 2 tsunami, and four sites are located within the inundation area of the Ansei-Tokai tsunami (Shizuoka Prefectural Government 2011). The Kawagodaira Pumice is located 1.5 m and 0.5 m above the base of the succession at sites 1 and 8, respectively. Tsunami deposits were not identified at any of the sites. Kitamura et al. (2015a) concluded that the coastal area of the Yaizu Plain has subsided during the past 3200 years.

Osuga lowland, Kakegawa

The Osuga lowland extends ~2 km from the shoreline at Kakegawa (Fig. 5). The wave height of the tsunami

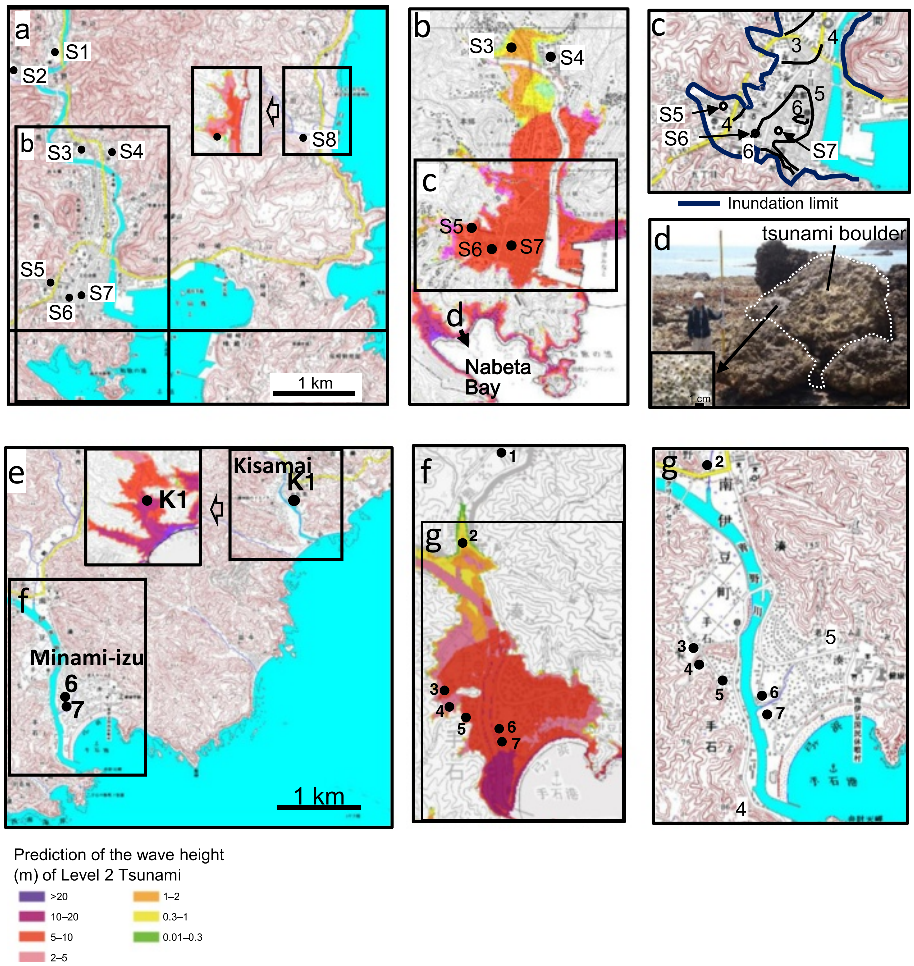

Fig. 6 Map of the study area in the southern Izu Peninsula. The locations of core sites and predictions of wave heights for a Level 2 tsunami and the 1854 Ansei-Tokai tsunami are shown (after Shizuoka Prefectural Government 2013; Kitamura and Kobayashi 2014a; Kitamura and Kawate 2015). **a** Topographic map of central and eastern Shimoda. The base map is the Shimoda 1:25,000 topographic map published by the Geospatial Authority of Japan. **b** Prediction of the wave height of a Level 2 tsunami around Shimoda. **c** Wave heights (above mean sea level, unit: meters) of the Ansei-Tokai tsunami in Shimoda (modified from Hatori 1977). **d** Tsunami boulder on a wave-cut bench at Nabeta Bay. The *inset* shows well-preserved small barnacles on the tsunami boulder. **e** Topographic map of Minami-Izu and Kisami. The base map is the Mikomojima 1:25,000 topographic map published by the Geospatial Authority of Japan. **f** Prediction of the wave height of a Level 2 tsunami around Minami-Izu and Kisami. **g** Wave heights (above mean sea level, unit: meters) of the Ansei-Tokai tsunami in Minami-Izu. Modified from Hatori (1977)

during the Ansei-Tokai earthquake is estimated to have been 4 m in the area 6 km east of the lowland (Fig. 3), and there are no historical documents of a tsunami disaster caused by the Hoei tsunami in and around this area. The co-seismic uplift caused by the Ansei-Tokai earthquake is estimated to have been 0.9 m in this area (Fig. 11) (Ishibashi 1984). Predicted wave heights are 8–10 m for a Level 2 tsunami (Fig. 5).

Uchida (2002) collected many cores using a hand corer in an inter-dune marsh on the Osuga lowland and detected nine sandy event beds, although that study did not provide a map of the locations of the core sites. Based on the stratigraphic distribution and occurrence of marine diatom assemblages in these beds, Uchida (2002) interpreted that one bed was caused by a tsunami. The deposit was dated at 1729–1514 cal BP (Fig. 14) (calibrated by Komatsubara et al. 2006).

Rokken-gawa

The Rokken-gawa lowland is located on the southeast coast of Lake Hamana (Figs. 5 and 15), and is behind a 2–3 m high sand dune. There are no historical documents of tsunami disasters caused by the Hoei and Ansei-Tokai tsunamis in this area. As this area is located beside the lake, the predicted tsunami height is less than 1 m for a Level 2 tsunami.

Fujiwara et al. (2013) examined the stratigraphy and paleoenvironmental setting of Holocene terrestrial deposits based on sediment cores (2–3 m) from 20 sites (0.6–1.0 m amsl) (Fig. 15). All sites were located outside

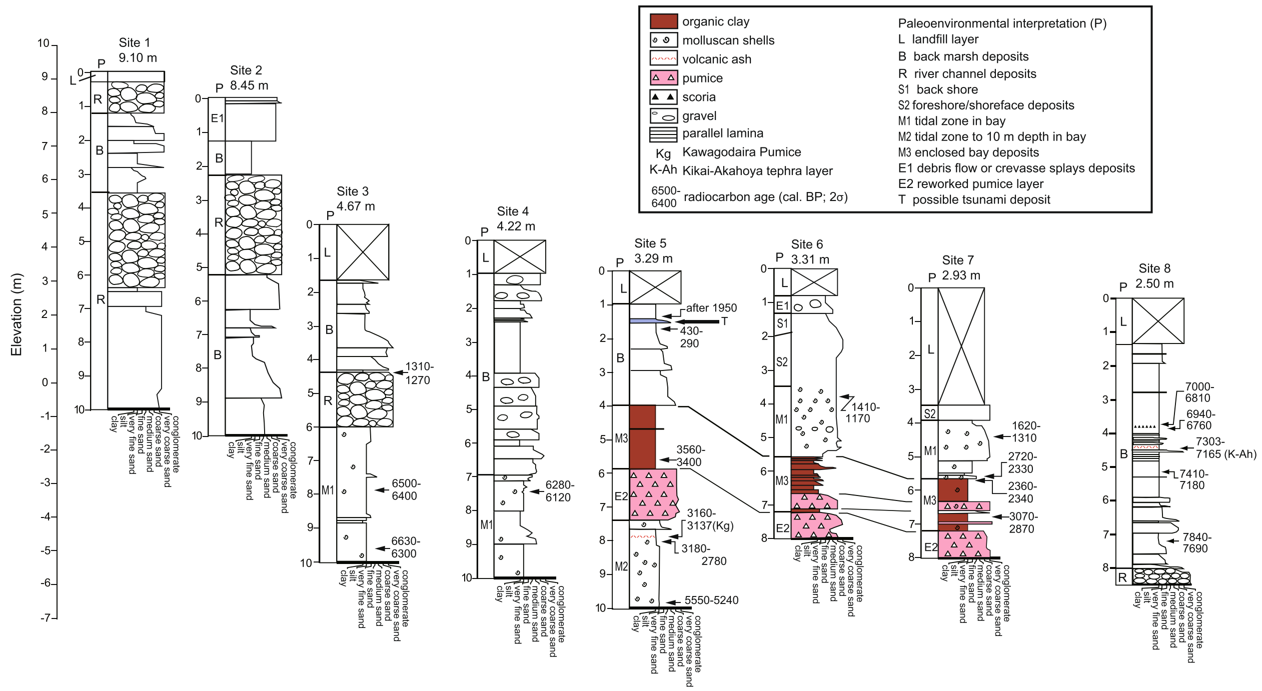

Fig. 7 Columnar sections of the study sites in central and eastern Shimoda. Modified from Kitamura and Kobayashi (2014b)

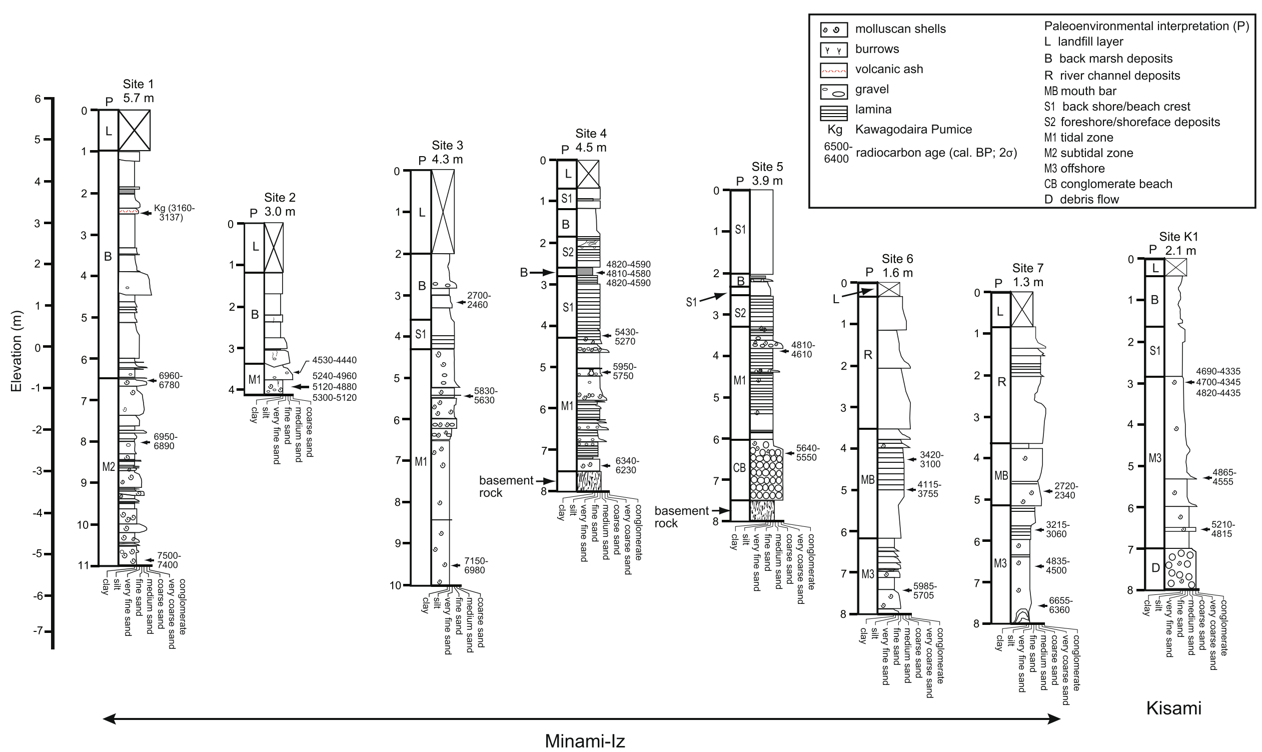

Fig. 8 Columnar sections of the study sites at Minami-Izu and Kisami. Modified from Kitamura and Kawate (2015)

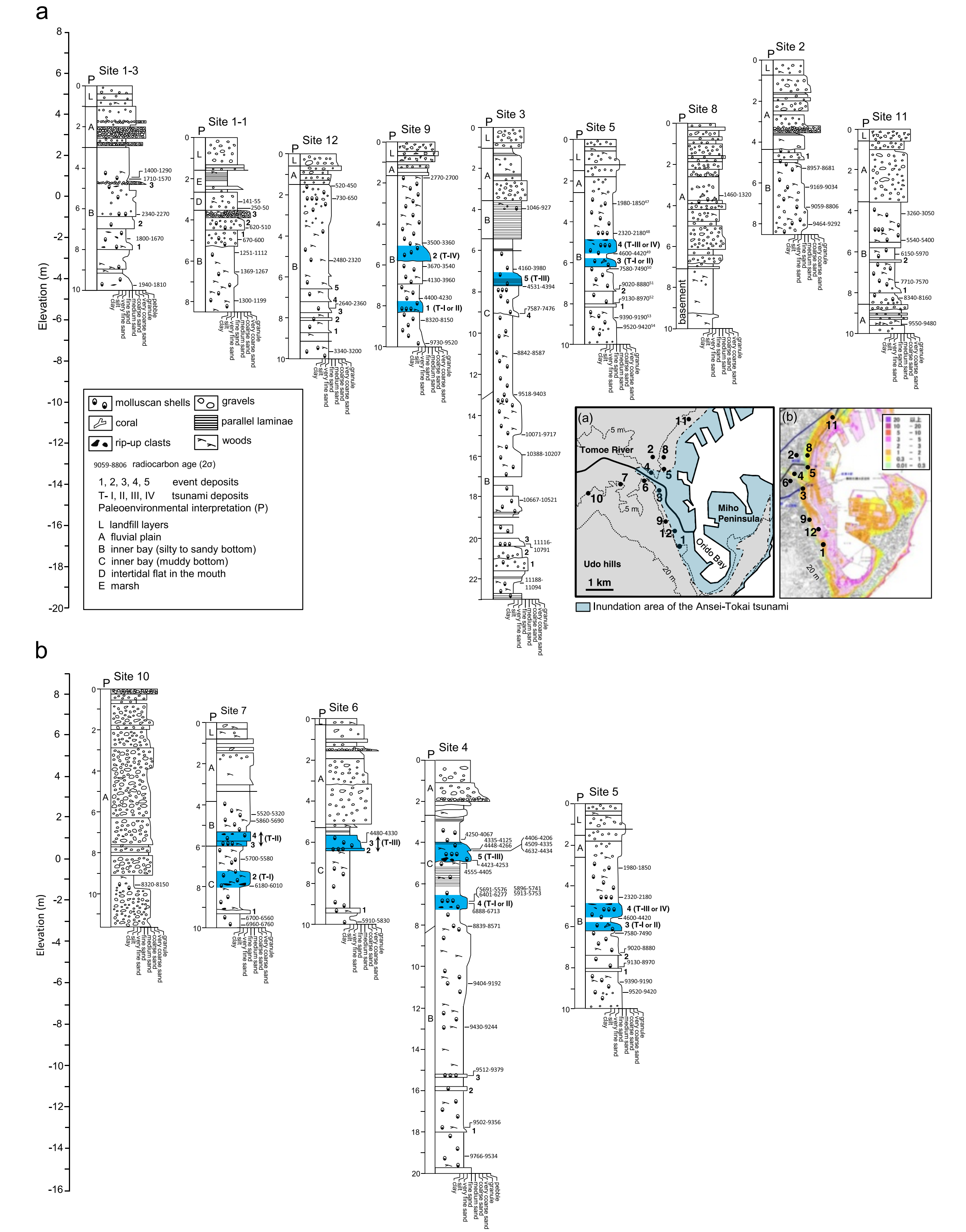

Fig. 9 Columnar sections of 12 sites on the Shimizu Plain studied by Kitamura and Kobayashi (2014b). **a** Topographic map and inundation area of the Ansei-Tokai tsunami (after Shizuoka Prefectural Government 2011). **b** Prediction of the wave height of a Level 2 tsunami (after Kitamura and Kobayashi 2014b; Shizuoka Prefectural Government 2013)

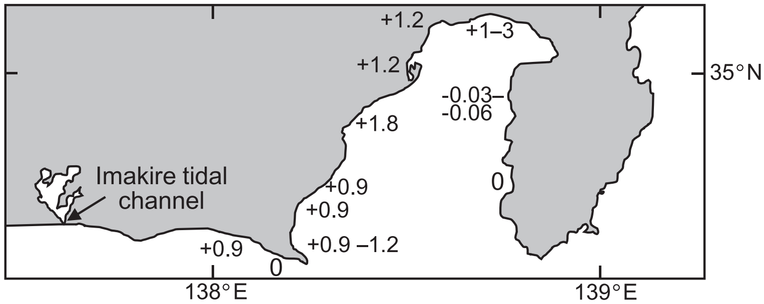

Fig. 10 Estimated co-seismic vertical crustal displacement of the 1854 Ansei-Tokai earthquake along the Suruga Bay coast. Units are meters. Figure is after Ishibashi (1984) and Kitamura and Kobayashi (2014b)

the inundation area of a Level 2 tsunami, although these sites are located within the inundation area of the Ansei-Tokai tsunami (Shizuoka Prefectural Government 2011). Fujiwara et al. (2013) identified a sandy tsunami deposit dated at ca. 3400–3300 cal BP within a cored transect (Fig. 14). The sand deposit, which is composed of cross-stratified, well-sorted, fine to very fine sand, has a maximum thickness of ~25 cm and extends over 600 m inland from the former coastline. The sand sheet is divided into lower and upper sub-layers by a mud drape. The lower sub-layer is characterized by current ripples indicative of a landward flow direction and shows inverse-graded bedding. The sand sheet is located immediately below the Kawagodaira Pumice. The deposition

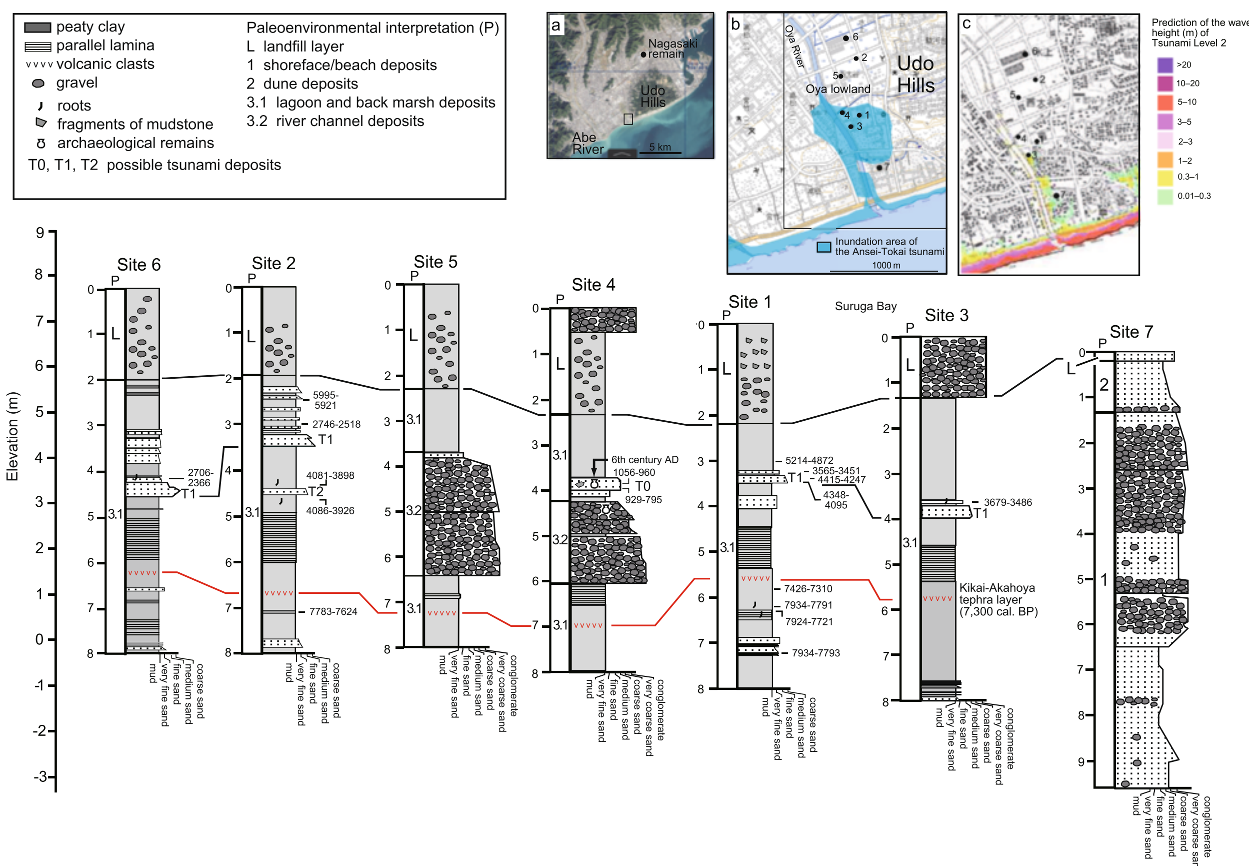

Fig. 11 Columnar sections of the study sites on the Oya lowland of the southeastern Shizuoka Plain. **a** Aerial photograph of the study area (source: website of Geospatial Information Authority of Japan, http://maps.gsi.go.jp/#12/34.985566/138.420353). **b** Inundation area of the Ansei-Tokai tsunami, after Shizuoka Prefectural Government (2011). The *base map* is the Shizuoka Tobu 1:25,000 topographic published by the Geospatial Authority of Japan. **c** Prediction of the wave height of a level 2 tsunami. After Kitamura et al. (2013b) and Shizuoka Prefectural Government (2013)

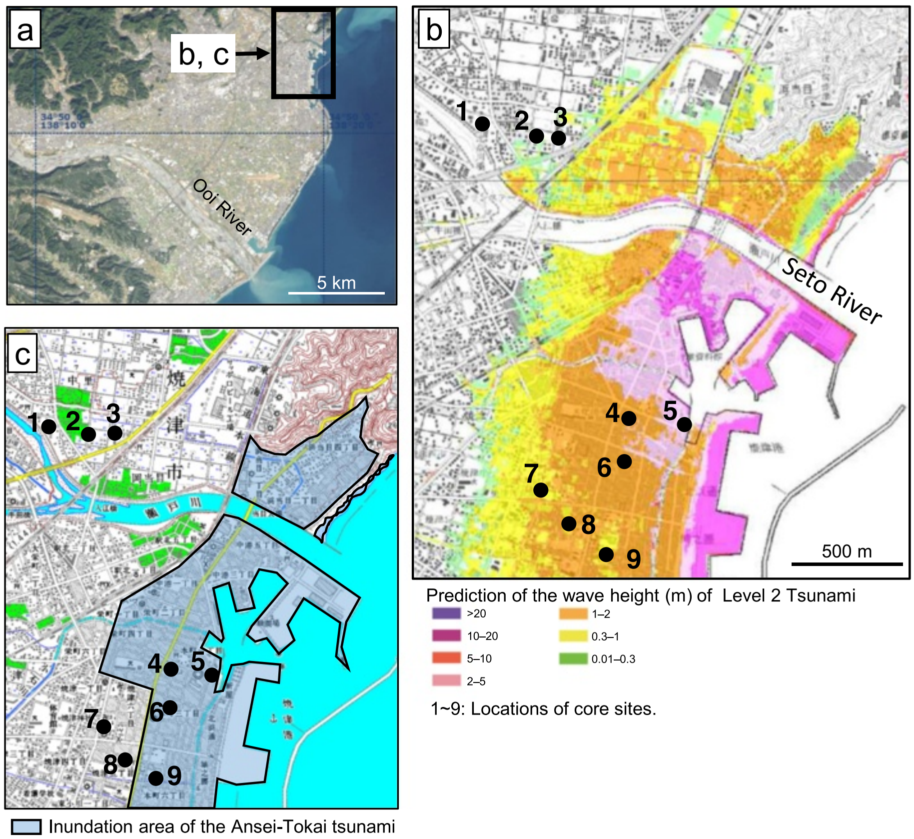

Fig. 12 Location map of the study area. **a** Aerial photograph of the study area (source: website of Geospatial Information Authority of Japan, http://maps.gsi.go.jp/#12/34.817186/138.330059) **b** Prediction of the height of a level 2 tsunami on the Yaizu Plain, after Kitamura et al. (2015a) and Shizuoka Prefectural Government (2013). **c** Inundation area of the Ansei-Tokai tsunami, after Shizuoka Prefectural Government (2011)

of the sand sheet caused an abrupt paleoenvironmental change along the coastline, in which the area evolved from a semi-open brackish coastal environment to a freshwater peaty marsh due to closure of a tidal inlet. Fujiwara (2013) noted that the tsunami was not an extremely large tsunami, as inferred from a reconstruction of the past coastal geomorphology.

Lake Hamana

Lake Hamana is connected to the Pacific Ocean via the Imakire tidal channel (Fig. 3). It is commonly accepted that the 1498 Meio tsunami breached the sand ridges that separated Lake Hamana from Enshu-nada and created the Imakire channel (Tsuji 1979; Shizuoka Prefecture 1996; Fujiwara et al. 2013). The wave heights of the Hoei and Ansei-Tokai tsunamis around Imakire are estimated to have been 3 and 5.6 m, respectively (Fig. 3). In this area, the predicted wave heights for a Level 2 tsunami are 13–15 m (Fig. 15).

Tsuji et al. (1998) collected sediment cores from Lake Hamana near Imakire (Fig. 15) and reported five event beds. The upper three beds were interpreted to represent the 1707 Hoei, 1605 Keicho, and 1498 Meio tsunamis. The depositional ages of the lower two beds were estimated to be 3354–3242 cal BP and 3873–3726 cal BP (Fig. 14) (calibrated by Komatsubara et al. 2006).

Figure 14 shows the distribution of prehistorical tsunami deposits in the coastal area of Shizuoka Prefecture. Given the existence of suitable geologic records for the time since 4000 years BP, this study discusses whether a Level 2 tsunami occurred during the past 4000 years.

Kitamura and Kobayashi (2014b) showed that the possible tsunami deposit T1 (3565–3486 cal BP) on the Oya lowland may correlate to tsunami deposit T-IV (3670–3540 to 3500–3360 cal BP) on the Shimizu Plain, whereas tsunami deposits corresponding to T-I, T-II, and T-III on the Shimizu Plain have not been identified on the Oya lowland. Given the uncertainty of the ages of tsunami deposits, Kitamura and Kobayashi (2014b) proposed that the above two event beds (T1 and T-IV) may be correlated to the tsunami deposit (3400–3300 cal BP) found in the horizon immediately below the Kawagodaira Pumice in the Rokken-gawa lowland (Fujiwara et al. 2013). Thus, Kitamura and Kobayashi (2014a) named this event the

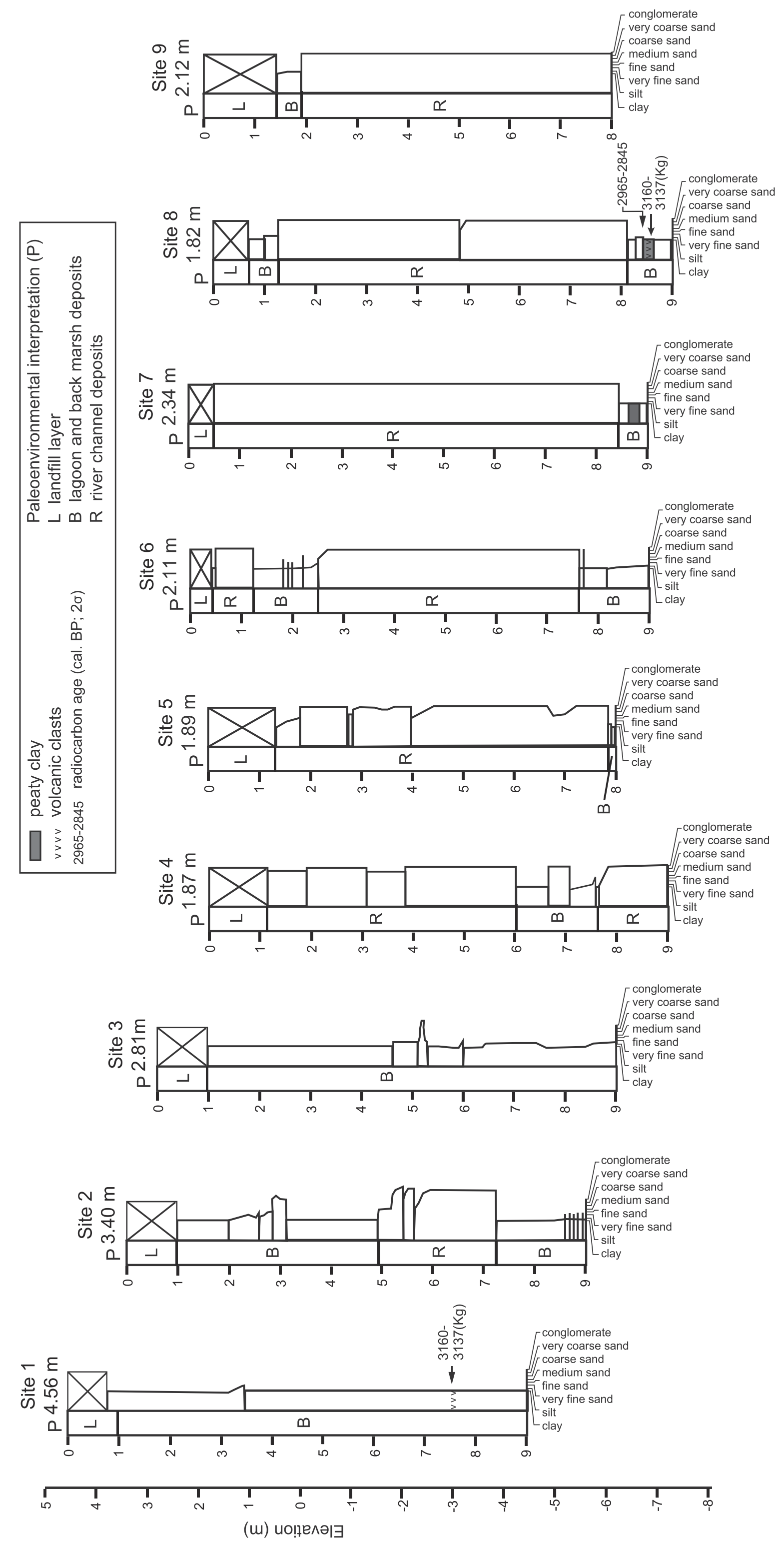

Fig. 13 Columnar sections of study sites on the Yaizu Plain, after Kitamura et al. (2015a)

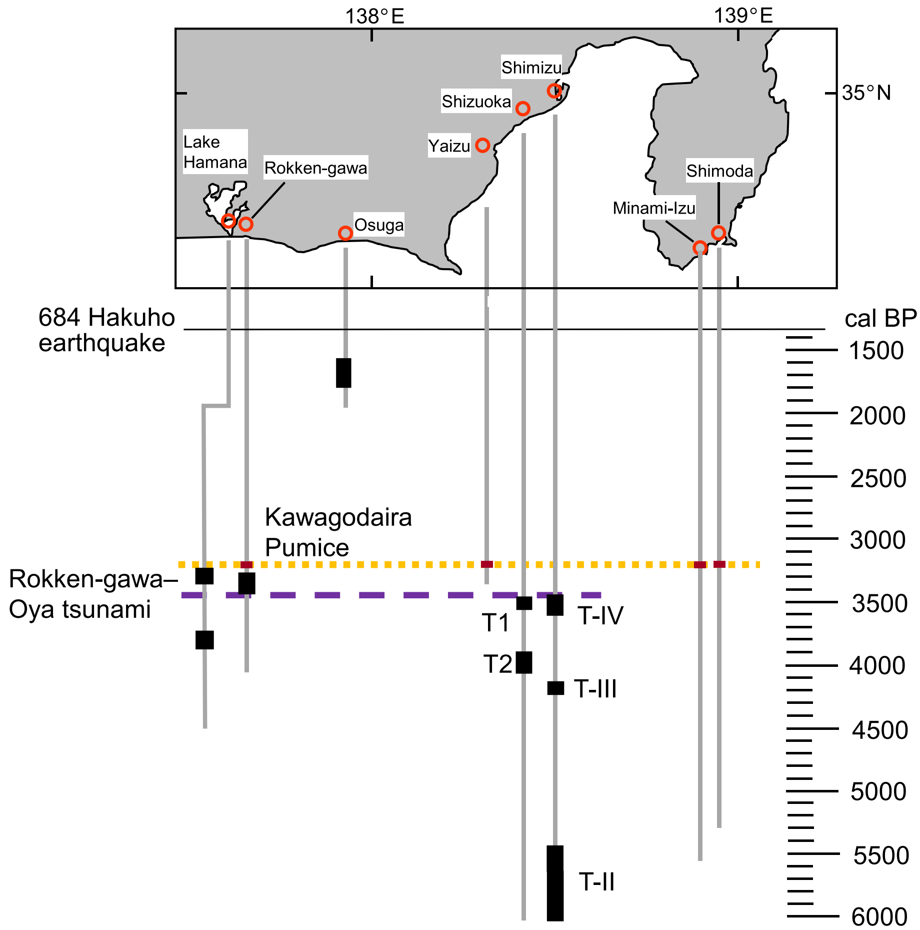

Fig. 14 Ages of prehistorical tsunami deposits in Shizuoka Prefecture reported in previous studies. Shimoda: Kitamura and Kobayashi (2014a), Minami-Izu: Kitamura et al. (2013b) and Kitamura and Kawate (2015), Shimizu: Kitamura and Kobayashi (2014b), Shizuoka: Kitamura et al. (2013b), Yaizu: Kitamura et al. (2015a), Osuga: Uchida (2002), Rokken-gawa: Fujiwara et al. (2013), Lake Hamana: Tsuji et al. (1998)

Rokken-gawa–Oya tsunami. The tsunami deposit at Lake Hamana, dated at 3354–3242 cal BP, may also have been caused by the Rokken-gawa–Oya tsunami. As noted above, the possible tsunami deposit T1 on the Oya lowland was linked to an earthquake that caused abrupt uplift of the lowland. Thus, the Rokken-gawa–Oya tsunami was caused by ruptures along megathrusts in the Suruga and/or Nankai troughs, and is the only prehistorical tsunami that may correspond to model cases 1, 6, and 8 of a Level 2 tsunami.

As noted above, the Tohoku-oki sandy tsunami deposit is distributed along the 900 km long coastal area between southwestern Hokkaido and the northern Boso Peninsula (Fig. 1; Table 1). The Jogan sandy tsunami deposit also occurs along at least 230-km of coast between the Sanriku coast and Fukushima Prefecture (Fig. 1; Table 1). In contrast, the length of the coastal area in Shizuoka Prefecture is only 200 km. Comparing the distribution of the Tohoku-oki and Jogan sandy tsunami deposits, it is expected that sandy tsunami deposits and tsunami boulders from a Level 2 tsunami would be distributed over coastal areas in Shizuoka Prefecture. Thus, if the Rokken-gawa–Oya tsunami was a Level 2 tsunami, sandy tsunami deposits and tsunami boulders should be present on the Yaizu Plain and the southern Izu Peninsula.

Beach ridges up to 5 m high protect the lowland from the open sea in both the Yaizu Plain and the coastal lowlands of the southern Izu Peninsula (Tsuchi and Takahashi 1972; Kitamura et al. 2013a; Kitamura and Kawate 2015). The foreshore, backshore, and beach ridge deposits in these areas consist mainly of sandy sediment. It is therefore likely that the source of the sandy tsunami deposits of the Rokken-gawa–Oya tsunami was the Yaizu Plain and the southern Izu Peninsula.

The Kawagodaira Pumice was found from back-marsh clayey deposits at sites 1 and 8 on the Yaizu Plain (Fig. 13). The clayey deposits below the pumice are 1.5 m thick at site 1 and 0.5 m thick at site 8. The absence of sandy tsunami deposits can be explained in

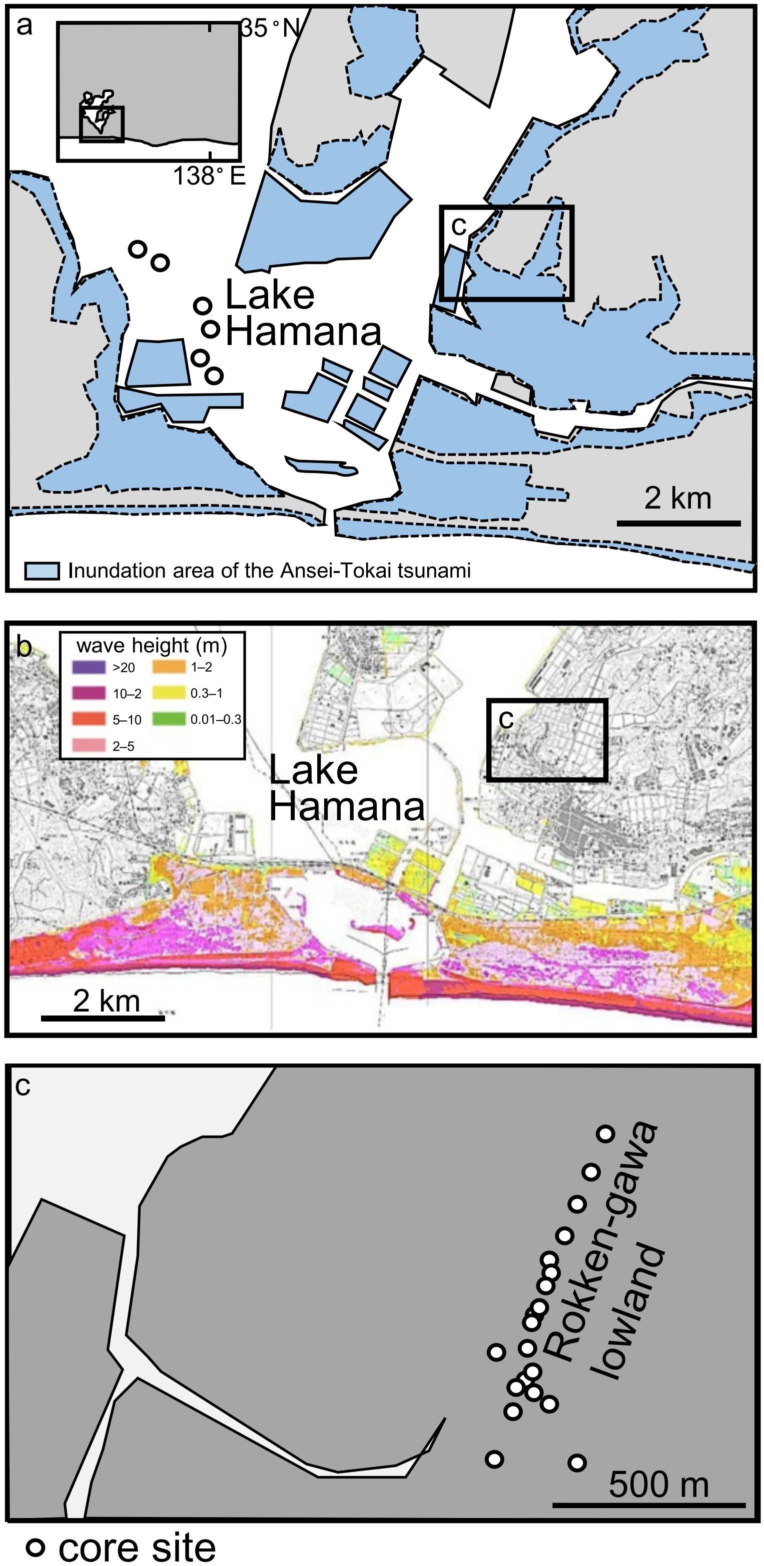

Fig. 15 Locations of core sites. **a** Core sites at Lake Hamana (Tsuji et al. 1998) and the inundation area of the Ansei-Tokai tsunami, after Shizuoka Prefectural Government (2011). **b** Prediction of the height of a level 2 tsunami around Lake Hamana, after Shizuoka Prefectural Government (2013). **c** Core sites in the Rokken-gawa lowland (Fujiwara et al. 2013)

two ways. First, the depositional ages of the clayey deposits may be younger than the occurrence of the Rokken-gawa–Oya tsunami. Second, sites 1 and 8 may be located outside the inundation area of the Rokken-gawa–Oya tsunami. As the Yaizu Plain has subsided during the past 3200 years (Kitamura et al. 2015a), the paleo-coastline may have been located offshore of the present-day shoreline, thus explaining why sandy tsunami deposits are absent from cored sediments from the Yaizu Plain.

In model cases 1, 6, and 8 (Figs. 4 and 5), the mean tsunami wave heights at Shimoda and Minami-izu are 15 m. The coastal area has experienced four co-seismic uplift events since 1256–950 BC; consequently, the total uplift has been at least 3.40 m (Kitamura et al. 2015b). In addition, the depositional succession represents a regressive phase (Kitamura and Kobayashi 2014a). These observations indicate that the paleo-coastline was located inland of the present-day shoreline. Thus, the areas from which sedimentary cores were obtained were more sensitive to tsunamis in the past than at the present day.

As noted above, the thickness of the 2011 tsunami deposit increases concomitantly with increasing flow depth, and the thickness reached its peak value when the flow depth was 4–5 m. At depths greater than 5 m, almost no deposition occurred. Instead, erosion of surface sediments exceeded deposition from the tsunami. Site 8 at Shimoda and site K1 at Minami-izu are located in a back marsh within the inundation area of a Level 2 tsunami (Fig. 6). The tsunami wave heights of the former and latter are predicted to be 5–10 and 10–20 m, respectively (Fig. 6). However, neither tsunami deposits nor severe erosional contacts were recognized in the back-marsh deposits at these two sites. In addition, tsunami deposits cannot be found from deposits below the Kawagodaira Pumice at two sites (site 5 at Shimoda and site 1 at Minami-izu) (Figs. 7 and 8). Moreover, although a tsunami boulder moved by the Ansei-Tokai tsunami occurs in the coastal lowland around Nabeta Bay, older tsunami boulders cannot be recognized in the area in which the tsunami wave height of a Level 2 tsunami is estimated to exceed 20 m (Fig. 6). In summary, the Rokken-gawa-Oya tsunami is not regarded as a Level 2 tsunami because the tsunami did not leave either a deposit or an erosional surface on the southern Izu Peninsula. This view is consistent with the interpretation of Fujiwara (2013) of the magnitude of paleo-tsunamis in the Rokken-gawa lowland.

The occurrence of the Rokken-gawa–Oya tsunami deposit on the Oya lowland may be explained in two ways. First, the paleo-coastline was located on the site of a present-day landside. According to Kitamura et al. (2013b), the paleo-coastline may be located at Site 7, which is 300 m from the present-day shoreline. Second, an increase in tsunami wave height was caused by submarine landslides associated with earthquake shaking, as occurred in the 1929 Grand Banks (Fine et al. 2005) and 2009 Suruga Bay (Baba et al. 2012) events. A magnitude 6.4 earthquake took place in Suruga Bay off the Yaizu plain in 2009 (Aoi et al. 2010). Baba et al. (2012) reported that this earthquake caused a submarine mass movement in the foreset slope, as inferred from the discovery of an escarpment (450 m wide and 10–15 m deep) located ~5 km off the coast. In addition, Baba et al. (2012) documented an increase in tsunami wave height caused by a submarine landslide, on the basis of a numerical simulation. The foreset slope of the fan delta of the Abe River off the Shizuoka plain (Nemoto et al. 1988) has a high potential for submarine landslides.

Conclusions

In summary, there is no geologic evidence of a Level 2 tsunami having occurred in the coastal area of Shizuoka Prefecture during the past 4000 years.

Competing interests

The author declares that he has no competing interests.

Authors' contributions

AK conceived, designed, and carried out the study and wrote the manuscript.

Authors' information

AK is a professor in the Institute of Geosciences and the Center for Integrated Research and Education of Natural Hazards, Shizuoka University. He is an expert in paleontology, sedimentology, and Quaternary geology.

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