Traces of paleo-earthquakes and tsunamis along the eastern Nankai Trough and Sagami Trough, Pacific coast of central Japan*

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Overview

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Great earthquakes of M8 and above and accompanying tsunamis have repeatedly occurred in the Nankai and Sagami Trough regions. These events have caused severe damage to the coastal areas close to the troughs. As part of the response to the 2011 off the Pacific Coast of Tohoku Earthquake (or the Great East Japan Earthquake) and tsunami, the Cabinet office of the central Japanese Government proposed new guidelines for assessing the risk of similar earthquakes and tsunamis affecting the Nankai and Sagami Trough regions. These new guidelines call for the largest possible class of earthquake and tsunami to be taken into account even if the probability of such an event is low. Large earthquakes and tsunamis in this region would affect an area with high concentrations of population and industrial infrastructure. As a result of these changes, the last 2 years have seen a high public awareness of disaster mitigation measures in the region. One of the results has been that some local governments have begun upgrading their existing disaster prevention infrastructure, such as raising the height of existing dikes and reinforcing refuges to help protect the population in the case of future great earthquake and tsunami events.

Paleoseismological studies have been carried out in the Nankai and Sagami Trough regions to help establish the recurrence history of great earthquakes and tsunamis. The sources of information are both historical documents and tsunami deposits. However, our present level of knowledge remains insufficient to be able to confidently reconstruct the size and recurrence intervals of past earthquakes and tsunamis. This information is key to developing predictive models for the timing and size of future events as well as formulating disaster prevention measures, and there is a need for more studies.

In this excursion, we will visit historical sites that preserve evidence for past natural disasters and geological sites that preserve records of seismic-related uplift and great tsunamis. We will also observe the current state of tsunami disaster mitigation measures, such as the plan for tsunami evacuation, in Shizuoka Prefecture. Through this excursion, we also hope to offer the participants an opportunity to discuss the significance of geological information in paleoseismology, to assess its importance in informing and guiding plans for disaster mitigation and to explore likely future trends in the field of paleoseismology.

Keywords

Nankai Trough, Sagami Trough, paleoearthquake, tsunami, tsunami deposit, emerged shoreline, earthquake disaster countermeasures

1: 25,000-scale topographic maps

Araimachi, Hamamatsu, Iwata, Fukuroi, Kakezuka, Omaezaki, Tateyama, Mera, Shirahama, Chikura.

Excursion details

Sep. 16

- 8 : 00 Leave Kagoshima-chuo Station (travel by Shinkansen Mizuho)
- 11 : 44 Arrive at Shin-Osaka Station
- 11 : 53 Leave Shin-Osaka Station (travel by Shinkansen Kodama)
- 13 : 47 Arrive at Hamamatsu Station
- 14 : 20 Leave Hamamatsu Station (travel by charter bus)
- Stops 1 and 2, overnight in Hamamatsu

Sep. 17

- 8 : 30 Leave Hamamatsu (travel by charter bus) → Stops 3–9
- 16 : 20 Arrive at Shizuoka Station
- 16 : 48 Leave Shizuoka Station
- 18 : 17 Arrive at Tokyo Station, overnight in Tokyo

Sep. 18

- 8 : 30 Leave Tokyo Station (travel by charter bus)
- 10 : 30 Arrive at Tateyama → Stops 10–14
- 15 : 00 Leave Tateyama
- 17 : 20 Arrive at Narita Airport (finish of field trip)

Locations of field trip stops

- Stop 1 (34°40'47.3"N, 137°30'55.5"E) Shirasuka, Kosai City, Shizuoka Pref.
- Stop 2 (34°41'40.8"N, 137°33'40.7"E) Arai, Kosai City, Shizuoka Pref.
- Stop 3 (34°41'30.0"N, 137°53'32.0"E) Toyohama, Iwata City, Shizuoka Pref.
- Stop 4 (34°41'08.0"N, 137°58'16.0"E) Yokosuka Castle. Kakegawa City, Shizuoka Pref.
- Stop 5 (34°40'37.9"N, 137°57'36.9"E) Nakashinden, Fukuroi City, Shizuoka Pref.
- Stop 6 (34°40'50.5"N, 137°55'56.5"E) Asaba-minami, Fukuroi City, Shizuoka Pref.
- Stop 7 (34°40'45.0"N, 137°55'05.0"E) Minato, Fukuroi City, Shizuoka Pref.
- Stop 8 (34°36'59.5"N, 138°10'21.9"E) Shin-kango, Omaezaki City, Shizuoka Pref.
- Stop 9 (34°35'45.0"N, 138°13'32.6"E) Cape Omaezaki, Shizuoka Pref.
- Stop 10 (34°58'15.0"N, 139°49'14.2"E) Koyatsu, Tateyama City, Chiba Pref.
- Stop 11 (34°58'25.5"N, 139°47'46.2"E) Kembutsu coast, Tateyama City, Chiba Pref.
- Stop 12 (34°55'35.4"N, 139°50'42.7"E) Tomoe River, Tateyama City, Chiba Pref.
- Stop 13 (34°55'29.3"N, 139°51'11.5"E) Tomoe River, Tateyama City, Chiba Pref.
- Stop 14 (34°55'23.0"N, 139°54'16.7"E) Shirahama, Minami-boso City, Chiba Pref.

Introduction

In this excursion we will visit localities in two separate areas: alluvial lowland along the Shizuoka coast facing the eastern Nankai Trough, and southern Boso coast facing the Sagami Trough. These troughs lie along a plate boundary where the Philippine Sea plate subducts beneath the Honshu arc. Since the announcement by the Central Disaster Management Council of the Cabinet Office [URL1] that disaster mitigation policy should consider the greatest possible classes of earthquake and tsunami along the Nankai Trough, paleoseismological studies in this area have attracted increasing attention from both scientists and the general public. The potential seismogenic rupture zone covers almost the entire Nankai Trough and would result in an estimated Mw 9.1 earthquake; much larger than the former estimates used in disaster planning [URL2]. Japanese historical documents cover the past 1300 years and there are several records of great tsunami-related earthquakes that were generated in the Nankai Trough—referred to as the Nankai and Tokai-Tonankai earthquakes. However, none of these historical events was an M9-class mega earthquake.

The 1703 and 1923 Kanto earthquakes have been explained in terms of a megathrust seismic cycle along the Sagami Trough (e.g., Matsuda et al., 1978; Nyst et al., 2006; Namegaya et al., 2011). Both earthquakes resulted in significant uplift events recorded in the formation of prominent marine terraces. These two earthquakes were also associated with large tsunamis along the southern Kanto coast and are among the worst historically documented natural disasters in Japan. It is estimated that more than 100,000 people died as a result of the 1923 event. Although the recorded history of earthquakes in the Kanto region goes back to the 9th century, the recurrence history of Kanto earthquakes before the 1703 event remains unclear.

In order to assess the appropriateness of the recently revised much larger estimates of possible earthquakes in the Nankai Trough area, it is important to examine whether previously undocumented mega earthquakes have occurred over geological time. Paleoseismological studies including studies of tsunami deposits are also vital to extend the time coverage of the earthquake and tsunami records beyond the historical documents and to make reliable estimates of long-term recurrence intervals of the plate boundary earthquakes based on their recurrence history.

In this excursion, we will observe natural records of the Tokai-Tonankai and Kanto earthquakes, including

emerged coastal geomorphology, tsunami deposits and historical monuments damaged by earthquakes and tsunamis. We will also visit the tsunami evacuation facilities that were constructed in 2012 and 2013 as a response to the new government guidelines that call for the greatest feasible classes of earthquake and tsunami to be taken into consideration.

Earthquake and tsunami history along the Nankai and Sagami Troughs

1. Nankai Trough

The Nankai Trough extends from off the east of Kyushu to central Japan (Fig. 1). Its eastern end is known as the Suruga Trough. The excursion course is located on the Pacific coast facing the eastern Nankai Trough. A history of the known tsunami-inducing great earthquakes (M~8) that have occurred in this area is shown in Fig. 2. Earthquakes that occurred in the region from the western Nankai Trough (rupture zones A and B) are known as Nankai earthquakes and those generated in the region from the eastern Nankai Trough (rupture zones of C, D and E) are known as Tokai or Tonankai earthquakes. Solid lines and dotted lines show the suggested rupture zone for each earthquake estimated from analyses of historical documents. Dotted lines indicate that there is considerable uncertainty in the estimation of the source area. There is evidence for a total of eight large Nankai earthquakes since the 7th century. There is also evidence for a total of 6 large Tokai earthquakes since the 11th century. Tokai and Nankai earthquakes typically occur very close in time and may occur simultaneously. The 1707 Hōei earthquake (M8.6) is regarded as a multi-segment earthquake caused by rupturing of all the zones A to D and possibly part of zone E. Despite its relatively low seismic intensity, the Keicho earthquake of 1605 was accompanied by a large tsunami, and is referred to as a tsunami earthquake (e.g., Ishibashi and Satake, 1998). Vertical lines in figure 2 indicate locations of archaeological data, such as traces of liquefaction and ground cracking, suggesting the occurrence of strong ground shaking near the Nankai Trough (e.g., Sangawa, 2001). The length of each line indicates the estimate error in the age. These archaeological data indicate the existence of other great paleo-Tokai and Nankai earthquakes that were not recorded in contemporary historical documents. It seems likely that the Nankai and Tokai earthquakes are linked in most cases and have a recurrence interval of 90 to 250 years.

One of the drawbacks with archaeological data is that they nearly always include significant errors in the age estimates: 50 years or more is common. In addition,

Fig. 1. Topographic and bathymetric map using data from JTOPO30 of the Marine Information Research Center, Japan Hydrographic Association. Numbers refer to Stop locations.

Fig. 2. Historical earthquakes that have occurred along the Nankai Trough. Modified from Sangawa (2001, 2007) and Ishibashi (1999).

earthquakes due to movement on inland faults can also be the source of strong ground shaking and induce liquefaction. Therefore, it is important to integrate historical, archaeological and geological data, such as tsunami deposits to establish a reliable reconstruction for the history of the Tokai and Nankai earthquakes. Studies of

the tsunami deposits aimed at reconstructing the earthquake cycle along the Nankai Trough have been conducted in the region since the early 1990's and a review of the results of the paleotsunami research is given in Komatsubara and Fujiwara (2007).

Fig. 3. Location map showing details of the route of the excursion on the Enshu-nada coast. Sources: Esri, DeLorme, NAVTEC, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster, NL, Ordnance Survey, Esri Japan, METI, ESRI China (Hong Kong), swisstopo, and the GIS User Community.

2. Sagami Trough

The 1703 and 1923 Kanto earthquakes have been explained as separate events in the same megathrust seismic cycle along the Sagami Trough (e.g., Matsuda et al., 1978; Nyst et al., 2006). In the Kanto region there is a good historical record that can be used to reconstruct ancient seismicity. The record is less complete in other parts of Japan and the history of pre-17th plate boundary earthquakes in the Sagami trough region is still unclear.

The 1703 and 1923 Kanto earthquakes both caused large surface uplift and generated tsunamis along the southern Kanto coast. The uplift events formed prominent marine terraces. These features can be used to study recurring interplate seismicity of the region and have been the subject of many studies (e.g., Sugimura and Naruse, 1954; Matsuda et al., 1974, 1978; Shishikura, 2003). Using the re-leveling data of benchmarks, Miyabe (1931) proposed that the maximum uplift in 1923 was ~2 m at the tip of the Boso Peninsula. The position of the paleo-shoreline before the 1703 earthquake has been deduced from historical maps and documents, and from topographic evidence such as the elevations of

wave-cut benches (e.g., Matsuda et al., 1974; Shishikura, 2003). For the 1703 event, Shishikura (2003) estimated ~6 m of uplift at the southern tip of the Boso peninsula. This estimate takes into account interseismic subsidence.

Around the coast of the Sagami Bay, the tsunamis of 1703 and 1923 generally had similar heights of about 5 m, although the 1703 tsunami waves were locally considerably higher. Along the Kujukuri coast of eastern Boso Peninsula, the 1703 tsunami travelled about 3 km inland from the present coast and wave heights are estimated to have been several times those of the 1923 tsunami (e.g., Koyama, 1987). These tsunamis had devastating effects on the southern Kanto coast (e.g., Hatori, 1976). Shimazaki et al. (2011) conducted an excavation survey in the tidal area of southern Miura Peninsula and documented evidence for coastal uplift and three separate tsunami deposit horizons of historical age. These geological data suggest the occurrence of Kanto earthquakes in 1923, 1703 and 1293 AD, respectively.

There is a good record of paleo-Kanto earthquakes both in Holocene emerged coastal landforms, such as marine terraces and sea caves, and tsunami deposits.

Fig. 4. Map showing the locations of Stops 1 and 2 (A) and a photograph showing the main structure of the Arai Checkpoint at Stop 2 (B). (A) Population migration of the villages following the 1707 Hoei tsunami and the relocation history of the Arai Checkpoint. Excavation sites of historical tsunami deposits are also shown in this figure (see text). Base maps: 1:25,000-scale topographic maps “Araimachi” and “Hamamatsu”.

These geological features form a valuable source of information to help establish earthquake recurrence interval in the region. These emerged coastal landforms cover the last 7300-year history of the plate boundary earthquakes in this area and the accumulated uplift in this period reaches ~30 m at the southern portion of the Boso Peninsula. Studies of the paleo-tsunami deposits in this area have been conducted since the 1990s and are reviewed by Fujiwara (2012).

Stops on the Enshu-nada coast

In this part of the excursion, we will visit both historical monuments and geological sites along Enshu-nada coast that record information on historical earthquakes (Fig. 3). Historical documents record a total by six major tsunami events that have affected the Enshu-nada coastal plain since the 1096 Eicho earthquake. Tsunami deposits attributed to the 1498 Meio, 1605 Keicho, 1707 Hoei and 1854 Ansei Tokai earthquakes have been identified in the sedimentological record in the western Enshu-nada coastal plain (e.g. Kumagai, 1999; Komatsubara et al., 2008). Historical tsunami deposits were also reported from the excavation sites in the Otagawa lowland, middle Enshu-nada coast (Fujiwara et al., 2012a, b).

Stop 1 Population migration following the 1707 Hoei tsunami

[Map] 1:25,000-scale topographic map “Araimachi”.

[Location] $34^{\circ}40'47.3''\text{N}$, $137^{\circ}30'55.5''\text{E}$

[Description] There are several examples of population migration following the 1707 Hoei tsunami along the

Enshu-nada coast. The historic post-town of Shirasuka located on the old Tokaido road and Nagaya Village are two examples where large-scale migration took place (Fig. 4A). According to historical documents and oral tradition, these villages were originally located at Motomachi and Nagaya-motoyashiki, respectively both of which lie on the landward slope of a beach ridge with a height of approximately 5 m. These two settlements were severely damaged by the Hoei tsunami and they subsequently relocated to areas overlying Middle Pleistocene Terraces with a height of approximately 70 m.

Tsunami deposits attributed to the 1605 Keicho and 1707 Hoei earthquakes have been reported from the site of the Nagaya-motoyashiki ruins (Takada et al., 2002). Fujiwara et al. (2006) and Komatsubara et al. (2008) conducted an excavation survey using a Geoslicer in the back marsh near the ruins and reported washover sand beds (Fig. 5). Based on AMS radiocarbon ages and historical investigations, these sand beds have been correlated with both historical earthquakes (1498 Meio, 1605 Keicho, 1707 Hoei and 1854 Ansei Tokai) and storm surges (1680 and 1699) (Komatsubara et al., 2008).

Stop 2 Arai Checkpoint and historical tsunamis

[Map] 1:25,000-scale topographic maps “Araimachi” and “Hamamatsu”

[Location] $34^{\circ}41'40.8''\text{N}$, $137^{\circ}33'40.7''\text{E}$

[Description] The Arai Checkpoint (Arai Sekisho) (Fig. 4) is the only remaining example of a series of security checkpoints that were established along the Tokaido road by the Tokugawa Shogunate. In the Edo period the Tokaido road connected the capital of Edo (present To-

Fig. 5. Historical tsunami and storm deposits obtained from Geoslicer cores near the Nagaya-Motoyashiki ruins. Modified from Fujiwara et al. (2006) and Komatsubara et al. (2008).

kyo) with Kyoto. The checkpoint was strategically positioned at the narrow channel (Imakire—see below) between Lake Hamana and the Pacific Ocean. In the Edo Era the checkpoint was repeatedly damaged by earthquakes, tsunamis and typhoons and each time it was relocated and rebuilt (Fig. 4A).

The Arai Checkpoint was established in 1601AD near Moto-arai, and was the start of the section of the Tokaido route that crossed to Maisaka via the Imakire channel. Due to damage by a typhoon in 1699, the checkpoint was moved several hundred meters northwest at the beginning of the 18th century. It was also damaged by the 1707 Hoei earthquake and tsunami and was moved again northwest to its present position. During the 1854 Ansei Tokai earthquake, many of its structures collapsed due to the strong ground shaking, but after the earthquake these were rebuilt at the same site. The checkpoint was abandoned in 1869 following the Meiji Restoration. It was designated as a national historical site in 1921 and as a special historical site in 1955. There is a small museum located next to the Arai Checkpoint, which we will also visit. Tsunami deposits correlated with the 1498 Meio, 1605 Keicho and 1707 Hoei earthquakes have also been reported from the Go-

ten-ato ruins near the Arai Checkpoint (Fig. 4A) (Kumagai, 1999). Before 1634 AD, these buildings were used as a rest area for the Tokugawa Shogun.

On our way to Stop 3, we will cross over the tidal channel at the mouth of the Lake Hamana. A local tradition says that until the 1498 Meio tsunami, the coastal ridge completely separated Lake Hamana from the Pacific Ocean. The Meio tsunami is thought to have breached the ridge to form a new tidal channel connecting the lake with the ocean (Tsuji, 1979; Shizuoka Prefecture, 1996). The name of the tidal channel, Imakire, reflects this history (in Japanese ima means just now and kire means breached). Formation of the Imakire channel and the related relocation of the coastal villages are discussed by Fujiwara et al. (2013).

Stop 3 Meio tsunami deposit in the Otagawa lowland

[Map] 1:25,000-scale topographic map "Iwata"

[Location] 34°41'30.0"N, 137°53'32.0"E

[Description] The Otagawa lowland is a strand plain facing the Enshu-nada coast (Fig. 3). It contains three major beach ridges, which formed in the last 7,000 years (Watanabe, 1995) (Fig. 6A). The present course of the

Fig. 6. (A) Map showing the locations of Stops 3–7. (B) An old map showing part of the landscape in the 1640s around Stop 4. Base maps: 1:25,000-scale topographic maps “Iwata”, “Fukuroi”, and “Kakezuka”.

Otagawa River is artificial and formed by excavation at the beginning of the 1600s. Based on old maps and geomorphological features such as natural levee systems, before the 17th century the lowland was characterized by small meandering streams.

At Stop 3, the 1498 Meio tsunami deposit can be observed along the bank of the Otagawa River where they are intercalated in the muddy flood plain sequence (mainly clay and silt beds) (Fig. 7B). The Meio tsunami deposit consists of alternations of laminated very fine sand and silt sheets with a total thickness of ~20 cm. The very fine-grained nature of the tsunami deposits at this location reflects the original location of Stop 3: about 2.5 km inland from the Meio coast line. Current ripples in the tsunami deposit show mainly landward water currents, and are an important diagnostics to differentiate the tsunami deposit from river flood deposits. The tsunami deposit consists of sand and silt sheets several cm thick with a light greenish gray or yellowish gray color. Each layer shows normal grading and is covered by a clay layer (mud drape), representing deposition from a waning process of sediment flow. The multiply layered structure of the tsunami deposit records the repeated occurrence of sediment flows: repeated tsuna-

mi run-up and return flows.

The Meio tsunami deposit was first discovered as a result of excavation related to river improvement and the study of archaeological sites. The excavated faces were mainly exposed in a coast-normal cross section up to 4 m-deep that cut through the Otagawa lowland (Fig. 7A). The total length of the cross-section is about 1 km; this covers a line 2.2–3.2 km from the present coastline. In this geological cross-section, the Meio tsunami deposit shows both a landward-fining trend and a landward-thinning trend. The age estimate of this tsunami deposit is based on AMS radiocarbon ages of charcoal and historical investigations (Fujiwara et al., 2012a, b). A total of four tsunami deposits that formed after the 7th century have been reported from the above-mentioned cross-section (Fujiwara et al., 2012a, b). However, as a result of the riverbank works, the three older tsunami deposits that underlie the Meio tsunami deposit are now below the river water level.

Stop 4 Yokosuka Castle (including remains of a port uplifted during the 1707 Hōei earthquake)

[Map] 1:25,000-scale topographic maps “Fukuroi”,

Fig. 7. Photographs showing the excavated face with (A) intercalated tsunami deposits and (B) the 1498 Meio tsunami deposit. The photographs were taken in September, 2011 (A) and in February, 2012 (B).

“Kakezuka”.

[Location] 34°41′08.0″ N, 137°58′16.0″ E

[Description] Stop 4 is the ruins of the Yokosuka Castle located in the eastern margin of the Otagawa lowland (Fig. 6A). The castle was constructed in 1578 on Ieyasu Tokugawa’s instructions. It was the main town of the Yokosuka area during the Tokugawa shogunate of the Edo period. Historical investigations suggest that the uplift of this area mainly occurred during the 1707 Hoei earthquake (M8.6).

An old map made in the 1640s shows an inlet connecting the Pacific Ocean with the Yokosuka castle, which is referred to as Yokosuka-minato (Yokosuka-port) (Fig. 6B). A document from the same period describing the effect of the Hoei earthquake on this area, reports that the uplift of the port followed strong ground shaking and parts of the original sea floor emerged to become new land. By comparing maps of the 1640s with those of the present day, it is easy to recognize the outline of the former Yokosuka port. The former port area is nowadays used mainly as paddy field and has an elevation of 1.0 to 1.5 m. This observation is in good agreement with the uplift reported in the historical documents. Excavation of the paddy field and paleo-environmental analyses revealed the upper surface of tidal deposits that were formed before the Hoei earthquake now

has an elevation of 1.4 m (Fujiwara et al., 2007, 2009). This area is located near the hinge line of the crustal deformation during the 1854 earthquake (Ishibashi, 1981) and the maximum uplift associated with the Hoei earthquake is estimated to be 1.4 m.

Stop 5 Nakashinden inochi-yama (Flood evacuation mounds)

[Map] 1:25,000-scale topographic map “Fukuroi”.

[Location] 34°40′37.9″ N, 137°57′36.9″ E

[Description] Due to its low altitude, the Otagawa lowland is prone to floods, and numerous such disasters have affected area in the past. A particularly destructive typhoon struck this area on 28 September 1680; it is classified as some of the worst typhoon damage during the 260 year-history of the Edo period. According to old documents, large storm surges and waves generated by the typhoon swept away the turrets of the Yokosuka castle and destroyed around 6000 other houses. It is said that around 300 people drowned in this disaster. Following this typhoon, under the guidance of technicians from the feudal government, the survivors constructed earth mounds that could be used for flood evacuation. These mounds helped save numerous lives in the following years.

In recognition of this history, people began to refer to the mounds as “Inochi-yama” (inochi=lifesaving, yama=mound). Two inochi-yama are still in existence in this area. One is Nakashinden inochi-yama (Fig. 8A). It is a rectangular mound with dimensions of 30.5×27 m at the base and a height of 5 m. The mound has a flat top surface with an area of 68 m². Ono inochi-yama is oval in shape with basal dimensions of 24×27 m and a height of 3.7 m (6.7 m in elevation). This mound has a flat top with a surface area of 136 m².

Stop 6 Tsunami evacuation tower in the Asaba-minami area

[Map] 1:25,000-scale topographic map “Fukuroi”.

[Location] 34°40′50.5″ N, 137°55′56.5″ E

[Description] Following the recent Cabinet office’s reappraisal of the largest possible class of earthquake and tsunami along the Nankai Trough [URL3, 4] that needs to be planned for, local governments of regions facing the trough are actively promoting the construction of new tsunami evacuation facilities. At Stops 6 and 7 we will visit two types of tsunami evacuation facilities constructed in Otagawa lowland.

At Stop 6, 1.3 km inland from the coast, we will visit a tsunami evacuation tower constructed in 2012 (Fig. 8B). It is a steel frame tower with a height of 10 m

Fig. 8. Photographs showing: (A) the Nakashinden Inochi-yama (flood evacuation mound) constructed in Edo Era, and (B and C) the tsunami evacuation tower and tsunami evacuation mound in Fukuroi City. The new tsunami evacuation tower and mound were constructed following the 2011 Tohoku-oki tsunami.

(12 m in elevation). It has an accommodation area of 160 m², enough for 270 people.

Stop 7 Minato inochi-yama (Heisei no inochi-yama)

[Map] 1:25,000-scale topographic map “Fukuroi”.

[Location] 34°40′45.0″N, 137°55′05.0″E

[Description] At this stop we will visit a large tsunami evacuation mound constructed in December 2013 (Heisei 25 in Japanese year number) (Fig. 8C). The mound is located 1.3 km inland from the present coast. It is an oval-shaped soil mound mixed with cement, which has a site area of 6400 m². The top of the mound is 7.2 m high (10.0 m in elevation) and can accommodate around 1300 evacuees.

Stop 8 Holocene marine terraces at the Cape Omaezaki

[Map] 1:25,000-scale topographic map “Omaezaki”.

[Location] 34°36′59.5″N, 138°10′21.9″E

[Description] A flight of Late Pleistocene and Holocene marine terraces characterize the Cape Omaezaki at the eastern end of the Enshu-nada coast (Fig. 9). Four Holo-

cene marine terraces around Stop 8 provide evidence of recurrent millennium-scale seismic uplift events (Azuma et al., 2005). From higher to lower levels these terraces are referred to as Shin-kango I to IV (Fujiwara et al., 2010) (Fig. 9). They are covered by thick aeolian sand beds. Fujiwara et al. (2010) used sediment core analyses and ¹⁴C age determinations to reconstruct the uplift history of these terraces.

Coastal uplift events can be identified by the displacement of beach deposits such as foreshore deposits, which represent the intertidal swash zone of a wave-dominated sandy coast (Fujiwara et al., 2010). Three levels of former beach deposits were identified at the levels of 6.4–6.9 m, ~3.2 m and 0.4–1.6 m for the Shin-kango I, II, and III terraces, respectively (Fig. 9B). The former sea level of the highest terrace is still unclear. The estimated emergence ages of the younger three terraces are around 3020–2880 BC, 370–190 BC, and somewhat older than 1300–1370 AD. The Hamaoka nuclear power station, which is now out of operation following a request from the government as a result of the 2011 Tohoku-oki earthquake, can be seen to the west of

Fig. 9. Late Pleistocene and Holocene marine terraces in the Omaezaki area. (A) Topographic classification modified from Sugiyama et al. (1988) and Azuma et al. (2005). (B) Former sea level (upper limit of beach deposits) projected onto a schematic cross-section of the Shin-kango area. Modified from Fujiwara et al. (2010). (C) Classification of Holocene marine terraces and location map of drill cores. Modified from Fujiwara et al. (2010). Base map: 1:25,000-scale topographic map "Omaezaki".

Stop 8.

Stop 9 Late Pleistocene marine terrace around Cape Omaezaki

[Map] 1:25,000-scale topographic map "Omaezaki".

[Location] 34°35'45.0"N, 138°13'32.6"E

[Description] A Late Pleistocene marine terrace distributed around the Cape Omaezaki is known as Omaezaki Terrace (Fig. 9A) and has an estimated emergence age of around 80 ka (Marine Isotope Stage 5a) (e.g., Sugiyama et al., 1987; Koike and Machida, 2001; Azuma et al., 2005). The terrace is tilted towards the southwest and has an elevation that decreases from 48 m to 25 m from NE to SW (Azuma et al., 2005). An average uplift rate of 0.8 m/ 1000 years can be calculated for the Omaezaki terrace (Azuma et al., 2005) based on its emergence age and the paleo sea level during MIS 5a (–18 m: Chappell and Shackleton, 1986).

After leaving Stop 9, we will travel first to Shizuoka station and then onto Tokyo on the Shinkansen super express (also known as the bullet train). Shortly after leaving Shizuoka, the train will cross the Fujikawa River, which closely corresponds to the plate boundary between the Eurasian and Philippine Sea plates (Fig. 3). The boundary zone is referred to as the Fujikawa-kako

fault zone (The Research Group for Active Faults of Japan, 1991). From the Fujikawa River crossing we will also be able to observe Mt. Fuji (3776 m), the highest mountain in Japan, from the left side of the train. The imposing size and elegant looks of this basaltic strato-volcano have made it known throughout the world as a symbol of Japan. Mt. Fuji and the surrounding area was added to the UNESCO World Heritage List as an important Cultural Site on June 22nd, 2013.

The formation of Mt. Fuji is related to the subduction of both the Philippine Sea and Pacific plates beneath the Japanese Islands. Mt. Fuji is part of the volcanic arc associated with the subduction of the Pacific plate. Its location corresponds to the point at which the volcanic front related to the Pacific plate subduction intersects the convergent plate boundary between the Philippine Sea plate and SW Japan (Kaizuka, 1990). The original volcanic edifice of Mt. Fuji started to form more than 100 ka; however the present beautiful stratovolcano was mainly constructed as a result of repeated eruptions throughout the last 11,000 years (Uesugi, 2003). The last eruption of Mt. Fuji occurred on its southeastern slope at the end of 1707 AD. The eruption started just 49 days after the Hoei earthquake (16, December, 1707) and ended 31, December 1707. The plinian eruption se-

Fig. 10. Map showing the route of the excursion on the southern Boso Peninsula with the estimated position of the former shore line at ca. 7300 cal BP.

verely damaged the adjacent villages and caused ash fall reaching several cm thick even in the streets of Edo (Tokyo) almost 100 kilometers away. The eruption is rated 5 on the Volcanic Explosivity Index. A flank volcano, Mt. Hoei (2,693 m), and three volcanic vents formed during the Hoei eruption can all probably be seen from the train window.

Stops on the southern Boso Peninsula

The southern part of the Boso Peninsula is located directly above the fault rupture zone of the 1923 and 1703 Kanto earthquakes. During these earthquakes, large coastal uplift and tsunami were reported in this area. Our excursion includes examining emerged wave cut benches recording uplift after the 1923 and 1703 Kanto earthquakes and Holocene tsunami deposits exposed along a river cliff. If there is sufficient time, we will visit a remarkable outcrop exhibiting the Pliocene submarine landslide deposits. The ages and locations of tsunami deposits reported from the Kanto region including

the southern Boso Peninsula and Miura Peninsula are reviewed in Fujiwara (2012).

Stop 10 Holocene emerged coral reef around the Numa area

[Map] 1:25,000-scale topographic map “Tateyama”.

[Location] 34°58′15.0″N, 139°49′14.2″E

[Description] Tateyama, near Tokyo (35°N lat.), is the site of the world’s most northern occurrence of living hermatypic corals and is also the site of a substantial outcrop of Holocene fossil corals with a radiocarbon dates of around 7300 cal BP (Figs. 11A, 11B). The alluvial sediments including the fossil corals are known as the Numa beds. These form a dominantly shallow inner bay sequence yielding abundant fossils such as corals (e.g., Yabe and Sugiyama, 1931; Ma, 1934; Hamada, 1963; Veron, 1992), molluscs (e.g., Yokoyama, 1904, 1924; Yabe, 1922; Nomura, 1932; Matsushima, 1979, 1984) and microfossils (e.g., Frydl, 1982).

The fossil coral reef is sporadically distributed along

Fig. 11. Location map and explanation of photographs for Stops 10 and 11. (A) Location map modified from the 1:25,000-scale topographic map of “Tateyama”. (B) Emerged Holocene coral reef at Stop 10. (C) Emerged wave-cut benches recording uplift after the 1923 and 1703 Kanto earthquakes at Stop 11.

the southern coast of the Paleo-Tateyama bay. The reef has an E–W range of 6 km (Matsushima, 2006) and yields about 80 fossil hermatypic corals (Hamada, 1963). These fossil corals flourished on the sea floor with a water depth of around 10 m (Matsushima, 2006). They now lie distributed at elevations of 10 m or more, showing there has been significant subsequent uplift. The height of the top surface of the fossil coral reef seen at Stop 11 is around 15–16 m (Matsushima, 2006). Based on a comparison between the fossils documented in the Numa beds and extant Japanese fauna, Veron

Fig. 12. Location map and explanation photographs for Stops 12 and 13. (A) Location map modified from the 1:25,000-scale topographic map “Mera”. (B) T2.2 tsunami deposit at Stop 12. (C) Tsunami deposits intercalated with the muddy bay sequence observed at Stop 13. (D) T2.2 tsunami deposit consisting of the HCS sand sheets observed at Stop 13.

(1992) estimated the mean sea-surface temperature during the formation of the Numa fossil coral reef was $\sim 2^{\circ}\text{C}$ warmer than at present. One part of the Numa beds has been designated as a natural monument of Chiba Prefecture.

Stop 11 Geomorphology of emerged coastline uplifted during the 1707 Genroku and 1923 Taisho Kanto earthquakes

[Map] 1:25,000-scale topographic map "Tateyama".

[Location] $34^{\circ}58'25.5''\text{N}$, $139^{\circ}47'46.2''\text{E}$

[Description] At this stop we will observe a good exposure of wave-cut benches that were uplifted as a result of the 1703 Genroku (M8.2) and 1923 Taisho (M7.9) Kanto earthquakes (Figs. 11A, 11C). The elevations of the upper surfaces are ~ 4.5 m for the Genroku terrace and 1.5 m for the Taisho bench (Shishikura, 2003). The Genroku terrace is wider than the 1923 bench and shows more than twice the uplift. These features reflect the greater magnitude of the 1703 earthquake compared to the 1923 earthquake (e.g., Matsuda et al., 1974, 1978; Shishikura, 2003).

Four large marine terraces are present around the southern Boso Peninsula, which emerged around 7200 cal BP, 5000 cal BP, 3000 cal BP and in 1703AD (Sugimura and Naruse, 1954; Nakata et al., 1980; Fujiwara et al., 1999). The oldest terrace reaches 30 m in elevation. Three to four smaller marine terraces (benches) with 1–2 m height differences can also be observed between the main terraces (Kayane and Yoshikawa, 1986). Distribution of these marine terraces along the southern Boso coast is illustrated in Kawakami and Shishikura (2006). Main terraces and smaller terraces are thought to be related to the Georoku- and Taisho-type earthquakes, respectively (e.g., Matsuda et al., 1974, 1978; Kayane and Yoshikawa, 1986; Shishikura and Miyachi, 2001). Based on the ages and elevations of the terraces, recurrence intervals of 2000–2700 years and ~ 400 years can be estimated for the Genroku- and Taisho-type earthquakes, respectively (Shishikura, 2003).

Stop 12 Tsunami conglomerate formed in the mid Holocene bay mouth area

[Map] 1:25,000-scale topographic map "Mera".

[Location] $34^{\circ}55'35.4''\text{N}$, $139^{\circ}50'42.7''\text{E}$

[Description] Numerous drowned valleys can be observed along the coast of the Boso Peninsula; these formed during the Holocene transgression—also known as the Jomon transgression (Fig. 10). The Paleo-tomoe Bay is one example of these drowned valleys (Fig.

12A). During the maximum transgressive stage ~ 7300 cal BP, this valley was 2.6 km in length and 0.3–0.6 km-wide. The water depth in that period is estimated to have been around 15 m (Fujiwara et al., 2000). Subsequent uplift has revealed a cross-section through the former inner bay sequence now well exposed in river cliffs. The Paleo-tomoe bay was sheltered from the open sea by the narrow-opening of the mouth of the bay, and dominantly muddy sediments were deposited on the bay floor indicating low wave energy conditions. Rock reefs were also locally present in the bay area. At least seven separate tsunami deposits consisting of sand or gravel beds have been reported from the muddy inner bay sequence deposited between 8500 cal BP and 6900 cal BP (Fujiwara et al., 1999, 2003b; Fujiwara and Kamataki, 2007) (Fig. 13).

One of the tsunami deposits, referred to as T2.2, (Fujiwara and Kamataki, 2007; Fujiwara et al., 2003b) is well exposed along the river cliff around the Stop 12 (Fig. 12B). The T2.2 tsunami deposit is about 1 m thick and consists mainly of gravel with lesser amounts of molluscan shells. It overlies the bay mud sediments with a sharp erosional surface. Stop 12 lies close to the mouth of the bay and the rocky coast around the bay was the source of the coarse clastic material that makes up most of the T2.2 tsunami deposit at this location. Clasts of the conglomerate show a range of different sizes, are generally well rounded and exhibit numerous cavities formed by boring molluscs. Boring molluscs mainly inhabit the inter-tidal zone and it is most likely that the cavity-rich rocks were derived from the inter-tidal rocky coast just beyond muddy bay floor (with a depth of ~ 15 m) and carried to their present location by the tsunami. The T2.2 tsunami deposit can be traced until Stop 13—about 800 m inland from Stop 12—and shows an overall landward-fining trend, suggesting the dominant sediment transport was by tsunami run up (Fig. 13). Molluscan fossils from the tsunami deposit show varying degrees of mechanical breakage but are generally well preserved with only minor abrasion. The fossils comprise a mixed assemblage of species derived from various habitats, such as rocky coast, sandy substrate and muddy substrate. In detail, the T2.2 tsunami deposit is composed of a stack of multiple sand and gravel layers. Each layer has an erosion base and commonly exhibits inverse grading in its lower part and normal grading in its upper part. This structure suggests that each layer formed under a waning flow.

At Stop 12, the left-hand side of the outcrop corresponds to the southern coast of the Paleo-tomoe bay. Pebble and boulder imbrication within the different sed-

Fig. 13. Columnar sections of Paleo-Tomoe Bay. Modified from Fujiwara and Kamataki (2007).

imentary layers of the outcrop indicates both leftward (landward) and rightward (seaward) current directions. In many cases, a sediment layer showing a landward current alternates with a sediment layer showing a seaward current (Fujiwara and Kamataki, 2007). This structure reflects the repeated occurrence of tsunami run-up and return-flow in the closed bay.

The T2.2 tsunami deposit consists mainly of a fine-grained lower part (gravelly sand beds) overlain by the coarsest beds (pebble to boulder size conglomerate). These beds are overlain by finer-grained and relatively thinly bedded sands that grade into a muddy uppermost part with intercalated debris-rich layers. This succession of sediments reflects the change in the size and strength of the tsunami wave with time (Fujiwara and Kamataki, 2007). The lower part corresponds to relatively small waves in the early stage of the tsunami. The middle part corresponds to the large wave group at the peak of the tsunami. The uppermost sandy and muddy layers record the waning stage of the tsunami and subsequent sinking of debris derived from the tsunami. Radiocarbon ages of the fossil oyster shells that grew on the tsunami deposit suggest a depositional age for the T2.2 tsunami deposit of ca. 7500 cal BP.

Stop 13 Tsunami deposits formed in the bay center

[Map] 1:25,000-scale topographic map "Tateyama".

[Location] 34°55'29.3"N, 139°51'11.5"E

[Description] Stop 13 is located about 800 m inland from the Stop 12 (Fig. 12A). Here we can observe good exposure of multiple tsunami deposits in a 4 m-high outcrop, which consist of silt beds deposited in the central part of the Paleo-tomoe Bay (Figs. 12C, 13). The tsunami deposits are composed of loosely packed sand beds and because these are easily eroded by river action, they show up as depressions or grooves in the outcrop, which mainly consists of more erosion resistant silt beds. Five discrete tsunami deposits are exposed at this outcrop. An additional two tsunami deposits are hidden in the vegetation above the outcrop. These tsunami deposits overlie the bay muds with sharp erosion surfaces and are mainly composed of laminated fine to coarse-grained sand beds. They include abundant molluscan fossils and some gravels and are up to 30 cm in thickness. As Stop 13 is about 1 km inland from the bay mouth, the tsunami deposits are dominantly fine-grained. These tsunami deposits consist of a stack of sand layers, which are all less than 10 cm-thick and show a fining-upward sequence and are covered with a mud drape. The sand layers commonly display hummocky cross-stratification (HCS; e.g., Harms et al.,

1975) with a wavelength of several tens of cm (Fig. 12D).

In general, HCS is considered to be formed under a combination of unidirectional and oscillatory flow (combined flow) that is generated by the action of large storm waves. Each HCS sand sheet reflects a waning process of a combined flow. The presence of multiply-layered HCS sand beds suggests the repeated occurrence of combined flow. However, storm waves cannot grow large in small bays such as the Paleo-tomoe bay. They should be too small to form HCS on the bay floor with a depth of ~15 m. One explanation is that the multiply-layered HCS sand beds on the bay floor formed by the action of large tsunami wave trains with long wave periods, on the order of 10 minutes.

Similar to the T2.2 tsunami deposit at Stop 12, the tsunami deposits at Stop 13 can be classified into four parts: a fine-grained lower part, a coarse-grained middle part, and an upper part showing a fining upward domain with a muddy uppermost part that locally contains high concentrations of debris. Depositional ages of the tsunami deposits were estimated from the radiocarbon ages of autochthonous molluscan shells; T2 (8100–8050 cal BP), T2.1 (7700–7600 cal BP), T2.2 (7500–7400 cal BP), T3 (7300–7200 cal BP), and T3.1~T3.2 (7100–6900 cal BP) (Fig. 13). Based on the petrographic and petrologic analyses, Kotake et al. (2006) suggested that the existence of the Kikai-Akahoya tephra (K-Ah; ca. 7300 cal BP; Machida and Arai, 2003) in the mud interval above the T3.1 tsunami deposit. Probable cause of the contradiction between the stratigraphic position and radiocarbon ages is local reservoir effect of the fossil marine molluscan shells.

Analyses of macro and micro fossil assemblages were also conducted on some of these tsunami deposits: mollusca (Fujiwara et al., 2003a), foraminifera (Abe et al., 2004; Uchida et al., 2004, 2007, 2010) and ostracode (Sasaki et al., 2007). Foraminiferal assemblages in the tsunami deposits characteristically show extremely high planktonic to total species ratios (P/T ratios), with values of 40–66%. This contrasts with the underlying bay muds that generally show P/T values of only 5–16% (Abe et al., 2004). The P/T ratio generally increases toward the open sea and the high P/T ratios in the tsunami deposits suggest the tsunami transported foraminifers from seafloor with a depth of 100 m or more to the inner bay area.

Stop 14 Early Pleistocene submarine landslide deposit in the Hata Formation

[Map] 1:25,000-scale topographic maps "Shirahama"

Fig. 14. (A) Map showing the location of Stop 14. (B) Photograph of the outcrop exhibiting an Early Pleistocene submarine landslide deposit. Base maps: 1:25,000-scale topographic maps “Shirahama” and “Chikura”.

and “Chikura”.

[Location] 34°55′23.0″N, 139°54′16.7″E

[Description] At Stop 14 we will observe an excellent exposure of an Early Pleistocene submarine landslide deposit, which has been preserved for public viewing (Figs. 14A, 14B). The outcrop was discovered during road construction and exposes the Upper Pliocene to Pleistocene Hata Formation. Details of this outcrop have been described by Yamamoto et al. (2007). According to these workers, the outcrop shows a liquefied sediment flow deposit, which formed associated with an earthquake that occurred 2 Ma. The thickness of the liquefied sediment flow deposit reaches 20 m. The outcrop shows a section through the sediment body parallel to the slip direction and provides valuable insight into the internal structure of earthquake-induced submarine landslide deposits.

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* in Japanese with English abstract.

** in Japanese.

English translation from the original written in Japanese

和文概要

南海トラフや相模トラフでは、大きな津波を伴う巨大地震(M8クラス)が過去に繰り返し発生し、沿岸の地域に被害を及ぼしてきた。2011年東北地方太平洋沖地震を受けて国の地震・津波の想定が見直され、「最大クラスの巨大地震・津波」が公表された。その結果、一部の自治体などでは巨大津波を想定した防災・減災対策も進みつつある。この地域では巨大地震と津波の履歴解明のために、歴史記録の解読とともに津波堆積物の調査研究が進められてきた。しかし、過去の地震・津波の規模や再来間隔を解明して、将来発生する地震・津波の規模や時期などを予測し、防災対策に役立てるにはまだ情報が不足しており、さらなる研究が必要である。本巡検では、東海地震や関東地震の痕跡を伝える建物や地層・地形を巡る。また、自治体等による防災対策の状況を視察する。これらを通じて、古地震・津波に関する研究の意義と、今後の方向性について議論する機会としたい。

科学論文では、学説の検証可能性を保証することが重要です。そのため、地質学雑誌掲載論文には、重要な証拠となった試料がどこで得られたかを示しているものがあります。言うまでもないことですが、見学や採取を行う場合、各自の責任において地権者や関係官庁への連絡と許可の取得の必要があることにご注意下さい。詳しくは、次のページをご覧ください。

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