

Sedimentary features of AD1741 tsunami deposit and some older event deposits in the narrow lowlands along the eastern margin of the Japan Sea, northern Hiyama District, Hokkaido, Japan

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Abstract

Deposits of the AD1741 Oshima-Ohshima tsunami and some other events were identified by pit excavations in two narrow coastal lowlands along the eastern margin of the Japan Sea, northern Hiogo District, Hokkaido, Japan. The AD1741 tsunami deposits were consisted of volcanic-ash sand grains derived from the AD1640 Ko-d tephra, and were characterized by landward thinning bed geometry, landward paleocurrent, normal grading, erosional base with rip-up clasts, and higher ratio of marine diatoms. In the Kumaishi-Ayukawa lowland, well-preserved out-flow layer indicates that the tsunami entered through the river mouth reached the terrace cliffs and returned along the river. Whereas the tsunami deposits in the Hirahama lowland lack return flow layer and were overlain by marsh muds, suggesting that the tsunami overtopped the coastal sand dunes and seawater ponded the vast lowland for a period. The sand grains of AD1741 tsunami deposits in Hirahama were not much rounded compared with those in the Kumaishi-Ayukawa, which probably reflected sediment source from tephra fell on the sand dunes and inland. We also recognized event deposits younger than AD1741 of flash flood origins in both lowlands. In addition, two older event deposits (672–561 cal yBP and 2333–1999 cal yBP) existed in Hirahama, that were consisted of rounded pebbles to cobbles similar with present beach gravels. Although such gravelly event deposits may be formed by storm surge or tsunami, the details of their origins are currently unclear.

INTRODUCTION

In the northern part of the eastern margin of the Japan Sea (EMJS), southwest Hokkaido is situated in the E-W compressional stress field caused by the interaction between the North Pacific and Eurasian plates (Wei and Seno, 1998; Okamura, 2000, 2010; Okamura et al., 2005). Consequently, large tsunamis have occurred around this area over the last 300 years: AD1993 Hokkaido Nansei-Oki (tsunami magnitude: *Mt* 8.1), AD1983 Nihonkai-Chubu (*Mt* 8.1), AD1940 Shakotanhantou-Oki (*Mt* 7.7), AD1792 Shiribeshi (*Mt* not clear), and AD1741 Oshima-Ohshima (*Mt* 8.4) (Abe, 1999; Fig. 1A). Among these modern and historical tsunamis, the AD1993 Hokkaido Nansei-oki tsunami (referred to as 'AD1993 tsunami') widely inundated the lowlands along the Japan Sea in southwestern Hokkaido (Tsuji et al., 1994; Ganzawa et al., 1995). Furthermore, the AD1741 tsunami caused by the collapse of the Oshima-Ohshima eruption (Tsuji et al., 2002; Satake, 2007) had the largest tsunami magnitude along the coast of the EMJS. Historical records of the AD1741 tsunami well documented great damage to southwest Hokkaido (Tsuji et al., 2002).

Sedimentary facies of the AD1993 tsunami deposits have been reported as modern analogs used to interpret regional paleotsunami characteristics (e.g., Nishimura and Miyaji, 1995; Sato et al., 1995; Nanayama et al., 2000; Nanayama and Shigeno, 2006; Nanayama, 2008; Ganzey et al., 2017). In addition, several studies have tried to describe the facies of AD1741 tsunami deposits to reveal the depositional processes by the tsunami of landslide origin (Nishimura et al., 1999, 2000; Nanayama et al., 2017).

After the AD2011 tsunami triggered by the Tohoku-Oki earthquake, intensive tsunami deposit surveys were conducted along the Japan Sea in Hokkaido (Hokkaido Research Organization, 2015). As a result,

historical and prehistorical tsunami deposits, including the AD1741 tsunami, have been recognized in the coastal lowlands of the southern Hiyama District and Okushiri Island (Fig. 1B; Hokkaido Research Organization, 2015; Kase et al., 2016; Kawakami et al., 2017a, 2017b; Takashimizu et al., 2020).

STUDY AREAS

Hirahama lowland

The Hirahama lowland, Setana-chou, Hokkaido, is located in narrow coastal zone at the front of terrace of marine isotope stage (MIS) 5e (Koike and Machida, eds., 2001; Figs. 1B, C, and 2A). The terrace cliff of 30 m in height is located at 150 m distance from the present coastline (Fig. 1C). A small valley dissecting the terrace cliff presents 150 m away from the excavated site to the southeast (Fig. 1C). On the beach in front of the excavation sites, rounded, flat pebbles-cobbles of Neogene volcanic rocks and well-sorted medium to coarse sands are distributed (Fig. 2B).

Although the lowland is almost flat and gently inclined to the seaward, a topographic step with a relative height of ca. 1.2 m runs parallel to the shoreline in the center of the lowland (Fig. 2A) and the landward side of the step forms a low-lying terrace. The lowland was previously used as a field but is now a wasteland. The AD1993 tsunami of 6.6–6.7 m wave height (Ganzawa et al., 1995; Watanabe, 1998) inundated there. The excavation locations were placed on a line perpendicular to the coastline, 60 to 100 m distance from the present coast at 4–6 m elevation (Figs. 1C and 2A), as crossing the topographic step.

Kumaishi-Ayukawa lowland

The Kumaishi-Ayukawa lowland, ca. 700 m wide and 2 km long, is formed at the right bank to the mouth of the Ken-ichigawa River, Yakumo-chou, Hokkaido (Figs. 1B, D, and 2C). The river deposits are consisted of coarse-grained clastics, and gravelly bars are formed (Fig. 2D). The coastline shows delta form, and coastal dunes of several meters high are developed (Fig. 1D). Moderately sorted sub-angular coarse to very coarse sands are distributed in the present beach (Fig. 2E).

The excavation sites were located behind the coastal dunes at ca. 3 m elevation, ca. 200 to 220 m away from the present coastline and 1.1 km from the river course (channel) (Figs. 1D and 2C). The locations were previously used as a field but is now a wasteland. A small waterway, the Ayudomarigawa River, traverses at the seaward of the sites and meets the Ken-ichigawa River (Fig. 1D). On the other hand, a fluvial terrace of MIS2 —at a relative height of 7–10 m (10–13 m ground elevation)— is formed at the landward side of the excavation sites (Fig. 1D; Koike and Machida, eds., 2001).

The lowland was not inundated by the AD1993 tsunami which had a height of 2.43 m at the Kumaishi Port (Watanabe, 1998; Fig. 1B) located 1.5 km northwest of the excavation site; while Tsuji et al. (2002) have reported that the height of the AD1741 tsunami was ca. 13 m and ca. 12 m in the Nezaki and Ainuma areas, respectively, that are located 2.6 km northwest and 7 km southeast of the excavation sites.

METHODS

Field survey

Several event deposits were found in both lowlands, which will be detailed later in this paper. Before the pit excavation, small-diameter predictive excavations were conducted using a hand corer (sample length: 50 cm, diameter: 5 cm). We selected pit sites where organic sediments developed immediately below the ground surface, potentially suitable for preserving tsunami deposits.

Three pits were excavated orthogonal to the coast of the Hirahama lowland (Fig. 2A). The three pits were named Pits 1 to 3 to reflect the distance from the sea to land, as shown in Fig. 2A. A topographic step of 1.2 m relative height was situated between Pits 2 and 3 (Fig. 2A). The sizes (length × width × depth) of Pits 1 to 3 are as follows:

- Pit 1; ca. 18 m × ca. 2 m × ca. 1.5 m,
- Pit 2; ca. 8.5 m × ca. 2 m × ca. 2 m,
- Pit 3; ca. 3 m × ca. 2 m × ca. 3.5 m.

In the Kumaishi-Ayukawa lowland, eight pits, Pits 4 to 11, were excavated parallel and orthogonal to the coastline (Fig. 2C). Their sizes (length × width × depth) were as follows:

- Pit 4; ca. 1.5 m × ca. 1.5 m × ca. 2.0 m,
- Pit 5; ca. 2.0 m × ca. 1.5 m × ca. 1.7 m,
- Pit 6; ca. 2.5 m × ca. 1.5 m × ca. 1.3 m,
- Pit 7; ca. 9.5 m × ca. 1.5 m × ca. 1.7 m,
- Pit 8; ca. 2.0 m × ca. 1.0 cm × ca. 1.0 m,
- Pit 9; ca. 1.5 m × ca. 2.0 m × ca. 0.6 m,
- Pit 10; ca. 1.5 m × ca. 2.0 m × ca. 0.8 m,
- Pit 11; ca. 1.5 m × ca. 3.0 m × ca. 1.0 m.

Grain size analysis

Laboratory grain size analysis to compare sandy event deposits with river and beach sands, candidates for being the source of sandy event deposits, was performed using a Beckman Coulter LS-230 (Beckman Coulter Inc., Brea, CA, USA) at the Research Institute of Energy, Environmental and Geology, Hokkaido Research Organization (HRO), Japan. The sampling locations are shown in Fig. 1C and D. In the Hirahama lowland, the river sands were not analyzed because of the absence of a major river neighboring the pit sites. Event deposit samples were collected directly from the pit walls. Particles larger than 2 mm

in diameter exceeded the measuring range of the instrument, they were removed using a sieve when preparing the samples.

Clastic compositions and roundness

The clastic compositions and roundness of the sandy event deposits were compared with those of river and/or beach sands. The sampling locations on the beach and river sands are shown in Fig. 1C and D. Thin sections were prepared by Earth Science Co., Ltd. (Sapporo, Japan) and Nippon Light Metal Co., Ltd. (Tokyo, Japan). The modal compositions of the sand grains were measured using the traditional point-counting method with a polarizing microscope (approximately 300 points per thin section). Based on the geological distributions surrounding the pit sites (Ishida, 1981; Sawamura and Hata, 1981), crystal grains and rock fragments were classified as follows: quartz (Qz), K-feldspar (K-f), plagioclase (Pl), amphibole (Amp), orthopyroxene (Opx), clinopyroxene (Cpx), biotite (Bi), opaque mineral (Op), other crystal grain (Otc), pumice (Pm), Neogene volcanic rock (Ngv), Neogene sedimentary rock (Ngs), granitic rock (Gr), Mesozoic rock (Mz), and other rock fragments (Otr). The roundness of the clastic particles was qualitatively compared using photographs from a polarizing microscope.

Chemical analyses of volcanic glasses

The chemical compositions of volcanic glasses in tephra beds and pumice grains in event deposits were analyzed and compared with those of known tephra and Pliocene tuffs (Tate Formation; Sawamura and Hata, 1981) distributed around the study areas. The analysis used energy-dispersive X-ray spectroscopy (EDS; JEOL JED-2300, JEOL JSM-6510 scanning electron microscope, JEOL Ltd., Tokyo, Japan) at HRO. Almost 10 particles were selected for the measurements. The setting conditions for the EDS analyses were as follows: acceleration voltage, 15 kV; measurement time, 30 s; count rate, 10 kcps; range, ca. 2 μm $\times$ 2 μm ; data correction, ZAF method.

Diatoms

Diatom species assemblages were analyzed to identify the contribution of seawater to the transportation of event deposits. Samples were collected from sandy event deposits, organic clays, and silts above and below the event deposits. The analyses were performed by Earth Science Co., Ltd., following the procedures described by Akiba et al. (1982). First, 0.5–20 g samples were placed in a 100-cc beaker, and the mud sediments were separated using hot water and a microspatula. Subsequently, ~ 0.5 cc suspensions were used for thin sections. The diatoms were identified in up to 300 individuals following Hustedt (1930), Akiba (1986), Witkowski et al. (2000), Nigorikawa and Hasegawa (2002), Sawai and Nagumo (2003), Watanabe (2005), and Kobayashi et al. (2006). The following six groups were classified according to species assemblages: (1) marine water, (2) brackish water, (3) brackish–fresh water, (4) fresh water, (5) indistinct, and (6) extinct species.

Anisotropy of magnetic susceptibility

Anisotropy of magnetic susceptibility (AMS) was conducted to estimate the paleocurrent directions of the parallel-laminated sandy event deposits. Samples were collected in a fixed direction from pit walls in the Kumaishi-Ayukawa lowland using ca. 7 cc plastic cubes. Ten samples were measured for each horizon, totaling 80 samples (eight horizons). The analysis was performed using an Agico MFK1-FA (Advanced Geoscience Instruments Company, Brno, Czech Republic) at Niigata University, Japan. The magnetic north's deviating angle (9.4°) was corrected to true north. The Agico Anisoft program (Version 5) was configured to show lower hemisphere projection figures. The declination direction of Kmin was considered a proxy for the tilt direction of the grain fabric, reflecting the paleocurrent direction (Shibuya et al., 2014).

Fabric of gravelly event deposits

The gravel fabrics (long-axis and maximum tilt directions) were measured to estimate the paleocurrent directions of the gravelly event deposits. Rose diagrams were drawn based on these results. They were excluded from the measurements because measuring the tilt direction in spherical gravel is difficult.

Radiocarbon dating

Radiocarbon dating was conducted using accelerator mass spectrometry (Institute of Accelerator Analysis, Ltd., Kanagawa, Japan) to determine the ages of the event deposits. Organic sediments (bulk samples) above and below the event deposits and carbonized wood pieces in the event deposits were used as dating samples. Furthermore, complementary radiocarbon dating was conducted using organic sediments (bulk samples) from normal background deposits. The INTCAL20 (Reimer et al., 2020) and OxCal v4.4.2 programs were used to calculate the calibrated ages. The calibrated ages were shown as a range of 2 σ (95% confidence interval).

RESULTS FROM THE HIRAHAMA LOWLAND

Normal deposits

Unit 1 (beach)

Description

Unit 1, at least 80 cm thick, mainly consists of well-sorted, very coarse to medium sands with minor pebbles. This unit was observed only at the base of Pit 3. Distinct parallel laminations developed (Fig. 3C), and planar (low-angle) stratifications inclined seaward by several degrees were locally observed. A small number of flat rounded cobbles existed in the lowest part of the unit (Fig. 3C), resembling those of modern beach gravel (Fig. 2B). This unit is overlain by Unit 2 (Fig. 3C).

Interpretation

The parallel- and planar-stratified well-sorted medium sands indicate deposition in the upper foreshore environment (Clifton, 1981). These beds are formed under an upper-flow regime when breaking waves cause swash and backwash flows on the beach surface (Clifton, 1969; Reinson, 1984; Aagaard and Hughes, 2006; Masselink and Puleo, 2006). The similarity of the flattened gravel in the unit with the gravel observed on the present beach supports this interpretation.

Unit 2 (aeolian dune)

Description

Unit 2 mainly consists of well-sorted medium sands (Figs. 3A, C, 4A, B, and C) several to 70 cm thick. This unit appeared in the lowest part of Pits 1 and 2 (Figs. 3A and 4A) and covered Unit 1 at Pit 3 (Fig. 3C). A small number of rounded, flat-shaped pebbles to cobbles were observed in the uppermost part of this unit at the seaward end of Pit 1 (Fig. 4A). Although distinct sedimentary structures such as stratification, grading, and erosional surfaces were not recognized, the B-Tm and blackish soil layers intercalated in sands showed mounded beddings. On the upper side, Unit 2 was overlain by the blackish soils of Unit 3 via a nearly flat boundary (Figs. 3A, C, and 4A). The top of Unit 2 was positioned at an elevation of approximately 3 m in Pits 1 and 2, whereas it reached ca. 4.5 m in Pit 3, located on the landward side of the topographic step (Fig. 5).

Interpretation

The preserved mound-like beddings of B-Tm and blackish soil layers show dune topography and well-sorted medium sands are interpreted to have been deposited in aeolian dune environments (Brookfield, 1992). Flat but rounded pebbles and cobbles were inferred to be deposits washed up on the backshore to dunes by large storms. As discussed later, the discrepancy in the elevation of the top surface of the units between Pits 2 and 3 suggests coastal uplift.

Unit 3 (vegetated dune)

Description

Unit 3 consisted of ~ 35 cm thick, blackish, or dark brownish sandy soil (Figs. 3A, C, and 4A). Blackish soils covered Unit 2 (dune sand) with a flat contact surface. The unit was overlain by the Ko-d tephra in Pit 1 (Fig. 4A) and by Unit 4 in Pits 2 and 3 (Fig. 3A, C). Notably, two cobbly event layers of different ages (Th-3a and Th-3b, described later) are intercalated into this unit (Figs. 3C and 4A).

Interpretation

Accumulation of blackish sandy soils, rich in organic materials known as “Kurosuna”, indicates a cessation of growth of coastal dunes due to decreased sand supply and progress of vegetation

(Toyoshima and Akagi, 1965; Endo, 1969). The development of “Kurosuna” over a wide area of Japan is thought to have been controlled by climatic effects (Endo, 1984). Based on the sedimentary ages of the Kurosuna, it is divided into the old Kurosuna (ca. 3000–2000 years ago) and the new Kurosuna (about 1700–1000 years ago and after about 800 years ago) (Endo, 1984). The formation ages of Unit 3 (see details later) differ between Pit 3 and Pits 1–2, which correspond to the old and new Kurosuna, respectively.

Unit 4 (coastal marsh or pond)

Description

Unit 4, approximately 40–130 cm thick, consists of silty sand, sandy silt, and organic clay. The unit was observed in Pits 2 and 3 and covered the blackish soil of Unit 3 (Fig. 3A, C). Patch-like Ko-d volcanic ash was detected in Pit 2 (Fig. 3B). Bioturbation by the plant roots was slightly more intense (Fig. 3B, C). This unit also contained carbonized wood pieces approximately 4 cm in length.

Four coarse-grained layers were encased between the blackish soils (Unit 3) and muddy deposits (Unit 4), suggesting unusually rapid deposition of coarse-grained clastics in quiescent sedimentary environments. Two of the four layers were sandy, whereas the others were gravelly. These four layers were identified as event deposits. Based on the stratigraphic relationship of Ko-d and B-Tm tephra layers and radiocarbon dating (see details below), four event deposits in order from the latest were named Th-1, Th-2, Th-3a, and Th-3b (Figs. 3–5; Table 2).

Table
2
Kase
et al.

Description

Th-1 was intercalated in the organic clays of Unit 4 in Pit 2 (Fig. 3A, B), located 86–90 m inland from the present coastline at ca. 4.3 m of elevation. The deposits were poorly sorted angular pebble-sized gravel 5–10 cm thick, showing a thinning and fining seaward trend (Fig. 3A, B). The angular gravels were mainly composed of diatomaceous siltstones resembling the rocks outcropping on the terrace cliff, which are different from the Neogene volcanic rocks of beach gravel (Figs. 2B, 3A, and B).

Interpretation

The angular and monomict gravels imply a neighboring local source. The seaward thinning and fining trends suggest that small-scale flash floods transported clastic rocks. Because Neogene diatomaceous siltstones constitute the hill slope behind the lowlands (Pliocene Makomanai Formation; Yoshii et al., 1973), the provenance of Th-1 is a terraced cliff.

Th-2 (AD1741 tsunami deposits)

Description

Th-2 was a 5–15 cm thick sandy layer found in Pit 2 (at ca. 80–94 m inland from the present coastline and 3.9 m elevation), which was erosively overlying Ko-d tephra and overlain by the organic clays of Unit 4 with a sharp contact surface (Fig. 3A, B). The sand grains consisted of well-sorted fine-to-coarse sands of volcanic ash origin (Fig. 3B). The erosional base of Th-2 deepens landward, reaching Unit 4 below Ko-d. The erosion depth was 10 cm, indicating landward flow (Fig. 3A, B). Rip-up clasts of organic clays and Ko-d tephra were found above the erosional surface of the flat plate or spherical shapes up to 14 cm in length (Fig. 3B). Parallel- and ripple cross-laminations by concentrated heavy minerals were observed locally (Fig. 3B), showing northward paleocurrents.

The mode of grain size distribution of Th-2 was ϕ 2.6–2.7, finer than beach sand (ϕ 1.8) (Fig. 6). In addition, Th-2 contained muddy components and poorly sorted (σ_1 : 1.75–1.91) compared with beach sand (σ_1 : 0.32), and weak normal grading was recognized. The modal composition showed that Th-2 was mainly comprised of no much rounded felsic and mafic minerals of phenocryst origin and pumice fragments, which was different from the beach sands dominated by well-rounded Neogene volcanic rock fragments with minor mafic minerals (Figs. 7A, 8A, and B). The EDS analysis suggested that most Th-2 grains originated from the Ko-d tephra (Fig. 9; Additional file 1).

Marine–brackish diatoms were more abundant in Th-2 (31% in HIM-1 and 17% in HIM-2) than in the normal deposit (10% in HIM-3) (Fig. 10A; Additional file 2). Conversely, freshwater to brackish–freshwater species were more abundant in the normal deposits (80% in HIM-3) than in the Th-2 deposits (53% in HIM-1, 70% in HIM-2).

Radiocarbon dating showed that the sedimentary age of Th-2 was 290–21 cal yBP. Organic clay at least 50 cm thick accumulated between the ground surface and Th-2, whereas only several centimeters existed between Th-2 and Ko-d (Fig. 3A, B). Therefore, the age of Th-2 was close to that of AD1640 and was correlated with the AD1741 tsunami. The location of the shoreline at the time of an event is important when considering the origin of event deposits (i.e., storm surges and waves or tsunamis) (e.g. Sawai, 2012). Although the positions of the shoreline in Hirahama during the deposition of Th-2 are unknown, it was not significantly different from the present day because the Ko-d tephra is well preserved at the seaward end of Pit 1 (Fig. 4A). Th-2 is the only event deposit of landward flows preserved above Ko-d, strongly implying an AD1741 tsunami origin rather than storm surges of a higher frequency (six events/100 years; Nanayama et al., 2000).

Th-3 (run-up gravel by storm surges or tsunamis)

Description

Th-3 was identified in Pits 1 and 3 but not in Pit 2. Because radiocarbon dating showed that the beds in Pits 1 and 3 were deposited at different ages, they were described separately as Th-3a in Pit 1 and Th-3b in Pit 3 (Fig. 5).

Th-3b was approximately 40 cm thick and consisted of matrix-supported pebbles to cobbles (5–14 cm and maximum 20 cm in diameter) and a blackish soil matrix (Fig. 3C). The gravels were well-rounded and flat-shaped (Fig. 3C). Because of the small size of Pit 3, the lateral changes in the facies were unknown. Th-3b was positioned 100 m inland from the coastline, up to 4.9 m in elevation. Although the gravel fabric showed that the direction of the a-axis tended to be orthogonal to the coastline (northeast-southwest), the dominant direction of tilting could not be determined because the number of measurements was insufficient (Fig. 11).

The radiocarbon ages of the organic sediments above and below Th-3a were 668–561 cal yBP and 672–563 cal yBP, respectively (Table 3). These ages were consistent with the stratigraphy: older than AD1640 Ko-d and younger than AD946 B-Tm tephras. The radiocarbon ages of the organic sediments above and below Th-3b were 2146–1999 cal yBP and 2333–2151 cal yBP, respectively (Table 3), which are older than those of Th-3a.

Table
3
Kase
et al.

Interpretation

Accumulated beach gravels inland in coastal areas are usually attributed to high-energy events, such as tsunamis or large storms (e.g. Etienne and Paris, 2010). Although the distance from the coastline is unknown when Th-3a was deposited, storm surges were probably able to emplace beach gravel up to the place 3.4 m elevation and several tens of meters distance, considering that the known large storm waves at the Hirahama coast exceeded 5 m high and inundated more than 60 m (Shigeno and Nanayama, 2016). The gravels of Th-3b were positioned higher than Th-3a (up to 4.9 m elevation) and inland; however, the age of Th-3b was old, and its elevation was likely affected by the uplifting of the coast after deposition, as will be discussed in the Discussion chapter. Hence, Th-3b was deposited at a lower altitude and a shorter distance from the shoreline than at present. The blackish soil matrix indicated a deceleration in dune growth, resulting in gravel accumulation. A landward coarsening trend may have formed because unusual storm surges pushed and rolled larger clasts behind the dune crest (e.g. Etienne and Paris, 2010).

However, the possibility of tsunamis remains. The depositional ages of Th-3a and Th-3b are close to those of the 12th century and the 2.4–2.6 ka tsunami events known in adjacent areas, respectively (Kawakami et al., 2017a). However, it is difficult to provide a definitive interpretation because coastal lowlands facing open seas can be affected by both tsunamis and storm surges or waves. The sedimentological characteristics of the gravelly event deposits formed by these two events are similar,

especially when they are formed at low elevations and close to coastlines that can easily be inundated by storm washover (e.g. Etienne and Paris, 2010).

RESULTS FROM THE KUMAISHI-AYUKAWA LOWLAND

Normal deposits

Two sedimentary/stratigraphic units (Units 5 and 6) were identified, excluding the uppermost cultivated soils (5–30 cm thick; Figs. 12 and 13; Table 1). Ko-d tephra 4–10 cm thick can be traced to excavated Pits 4–11 (Figs. 12–14; Additional file 1).

Table
1
Kase
et al.

Unit 5 (fluvial gravel bar)

Description

Unit 5, 15–100 cm thick or more, consists of clast-supported and poorly sorted pebbles to cobbles filled by a very coarse to coarse sand matrix. Weakly rounded pebbles and cobbles resembled those of the gravel bars of the Ken-ichigawa River (Figs. 2C and 13C). This unit was found in the basal parts of Pits 4, 5, 6, 7, and 11 (Figs. 12 and 13), and the top of this unit was positioned higher in the northwest (Pit 8, furthest from the Ken-ichigawa River) (Figs. 13A, C, and 14).

Interpretation

This unit is characterized by clast-supported and poorly sorted pebbles to cobbles that resemble those constituting the gravel bars of the adjacent Ken-ichigawa River. Therefore, it is interpreted that the gravel bars were formed in a fluvial environment (Miall, 1992).

Unit 6 (flood plain)

Description

Unit 6, more than 15–30 cm thick, consists of structureless brown to brownish-gray silts and brownish organic clays (Figs. 7A, B, E, 8A, and B). Coarse-grained sand and gravelly deposits were not observed. Plant roots were present (Figs. 7A, B, E, 8A, and B).

Event deposits

Two distinct coarse-grained layers were recognized above the gravel bar deposits (Unit 5) and in the floodplain muddy deposits (Unit 6) (Figs. 12 and 13), which were distinguished from the normal deposits. These two layers were named Ku-1 and Ku-2 from the younger stratigraphic layer (Figs. 12, 13, and 14; Table 2).

Ku-1 (flash flood deposits)

Description

Ku-1 was a 2–5 cm thick, poorly sorted, very coarse sand layer containing granules and minor pebbles, which were overlying silts and covered by organic clays (Unit 6) (Fig. 12A, B). The distribution of Ku-1 reached at least 220–240 m inland from the present coastline and ca. 2.5–2.7 m above mean sea level (amsl). Although lateral changes in the grain size were not observed, a landward thickening trend was observed (Fig. 14). No sedimentary structures such as grading, laminations, or erosional bases were observed. Carbonized wood pieces are contained in Pit 6.

Grain size distribution showed polymodal peaks like the river sand and different from the well-sorted beach sands (Fig. 6). However, the diameter of first mode (ϕ 0.4) was coarser than measured river sand (ϕ 1.1). The modal composition of Ku-1 (Ngv: 31%, Gr: 23%, Qz: 17%, Pl: 11%) was similar to those of the river sand (Ngv: 41%, Gr: 22%, Qz: 10%, Pl: 10%) and beach sand (Ngv: 27%, Gr: 28%, Qz: 17%, Pl: 18%) (Fig. 7B), whereas the angular grain shape of Ku-1 (Fig. 8E) was similar to that of the river sand (Fig. 8C) rather than the rounded beach sands (Fig. 8D).

Diatom analysis indicated that 91% of the diatoms in Ku-1 were freshwater species, and only 1% were marine–brackish (Fig. 10B; Additional file 2). This result is like that of Unit 6 (freshwater species: 87%; marine–brackish water species: 0%).

Radiocarbon dating obtained from carbonized wood pieces in Ku-1 showed 261–28 cal yBP (Table 3), which was younger than the fall age of the Ko-d tephra (AD1640) and consistent with the actual stratigraphy.

Interpretation

Ku-1 was embedded within silt and organic clay with clear boundaries, showing a thickening landward trend. Although the paleocurrent directions are unknown, the sand grains of Ku-1 showed very poorly sorted features and angular grain shapes closely resembling river sands, differing from those of beach sands. Additionally, inland thickening is a common feature of flood deposits (e.g. Bristow et al., 1999). Therefore, Ku-1 is a deposit formed due to flood events. The diatom assemblage of Ku-1 was almost the same as that of Unit 6 (floodplain), which supports deposition under river flooding. According to radiocarbon dating, the sedimentary age of Ku-1 is 261–28 cal yBP. Although flood events are not known

in the adjacent areas (Hokkaido Research Organization, 2015), the sedimentary age of Ku-1 is close to that of Th-1 on the Hirahama lowland. Therefore, they may have been formed during the same event.

Ku-2 (AD1741 tsunami deposits)

Description:

Layer A: Layer A consisted of a lower sandy part (30–45 cm thick, very coarse-to-fine volcanic-ash sand) and an upper silty part (3–5 cm thick structureless volcanic-ash silts), which showed a thinning landward trend. Convolutions were locally recognized at the boundary between the sandy and silty parts (Fig. 12C). Layer A overlays the Ko-d tephra and is covered by Layer B, which has a sharp, erosive contact surface (Fig. 12C). The basal part consists of poorly sorted reverse grading sands containing scattered granular grains. In contrast, the main part of the layer consists of well-sorted homogeneous sands.

The modes (first mode) of the grain-size distributions (Ku-2-A1–A6) were ϕ 1.8–2.0 finer than those of the beach and river sands (Fig. 6). The modal composition of the crystal grains was poor in Qz and rich in Pm, which is different from both river and beach sands (Fig. 7B). The chemical composition of the volcanic glass shards showed a Ko-d tephra origin (Fig. 9; Additional file 1).

No diatoms were obtained from Layer A (KUM-3-01–02; Fig. 10B).

Layer B: Layer B was 10–30 cm thick and comprised well-sorted fine- to medium-grained volcanic-ash sands and overlying volcanic-ash silts of approximately 2 cm in thickness (see section Pit 4 in Fig. 14). The boundaries above and below the layer were sharp, and the layer was thicker at the most seaward site (Pit 4) and slightly thinner inland (Fig. 14). Layer B exhibited an erosional surface (Fig. 12C, D). In particular, Layer B eroded Layer A at a maximum depth of 15 cm in Pit 7 (Fig. 13A). Several rip-up clasts derived from Layer A were observed on the erosional base. Parallel laminations of concentrated heavy minerals developed in the lower part (Fig. 12A, D). In contrast, ripple cross-laminations were observed in the upper part. These laminations show landward (northwestward) paleocurrent directions (Fig. 14). The scouring (flute marks) found in Pit 7 indicated ENE-WSW current directions (64° – 244° ; Fig. 13B), which are consistent with the paleocurrent directions obtained by cross-laminations. The AMS showed northwest to north paleocurrent directions (landward directions) (Fig. 16; Additional file 3). The mode of grain-size distribution was ϕ 1.1 in the lower part and ϕ 2.0 in the upper part, respectively (Fig. 6).

The modal composition of the crystal grains was poor in Qz, like Layer A, rich in Opx and Pm, different from the river and beach sands (Fig. 7B). Abundant Opx, Cpx, and Pm were moderately rounded, and the rock fragments were well rounded (Fig. 8G). The chemical composition of the volcanic glass shards is consistent with that of the Ko-d tephra (Fig. 9; Additional file 1).

The results of the diatom analysis showed proportions of marine–brackish water diatoms and freshwater diatoms of 15% and 56%, respectively (Fig. 10B), which was a higher ratio of marine–brackish water

diatoms than in Layer C and above normal deposits.

Layer C: Layer C comprises well-sorted fine to medium volcanic-ash sands (5–20 cm thick) and overlying volcanic-ash silt (1–3 cm thick). This layer had an erosive contact surface with Layer B and was overlain by the silts of Unit 6 (Figs. 12D and 13A). A slightly normal grading structure and concentration of heavy minerals were present in the lower part, similar to those of Layer B (Fig. 12D). Landward thinning was observed, but grain size did not change laterally (Fig. 14). The mode of grain-size distribution was ϕ 1.1–1.2, similar to the base of Layer B (Fig. 6). Distinct ripple cross- and parallel laminations were observed (Figs. 12A, D, and 13B), which indicate south to southeast (seaward) flows (264°; Pit 5, 160°; Pit 7, 195°; Pit 11), except for the north flow in Pit 6 (350°; Fig. 14). The AMS analysis suggested a southwestward paleocurrent, roughly consistent with the laminations (Fig. 16).

Interpretation

The modal composition of Ku-2 showed that sand grains were mostly sourced from Ko-d tephra, similar to Th-2 on the Hirahama lowland. However, the crystal grains of Ku-2 (at least Layers B and C) are rounded, and well-rounded fragments of Neogene rocks and granite and their crystal grains (Qz, K-f, Amp, and Bi) coexist (Fig. 8G, H). This implies that these grains were distributed on the seafloor. The results of the diatom analysis, that is, the higher proportion of marine–brackish water diatom species in Layer B than those of the flood plain (Unit 6) and flood deposits (Ku-1), also show the contributions of seawater for transport (Fig. 10B). The paleocurrent directions obtained from Layer B indicate landward flow (Figs. 14 and 16). In contrast, the paleocurrent direction of Layer C showed a seaward flow opposite to that of Layer B (Figs. 14 and 16). The run-up and return flows of the tsunami can explain the change in the paleocurrent direction. The thickness change of Layer B of the landward thinning is a common feature of tsunami deposits formed by run-up flow (e.g. Nanayama et al., 2000).

The origin of Layer A is unclear. The succession of reverse-graded sands and the overlying homogeneous sands and silts can be interpreted as the deposition of tsunami decay and stagnation (mud drape), respectively (Fujiwara and Kamataki, 2007). In this case, Layers B and C were deposits of the second wave of the tsunami. However, rip-up clasts derived from Layer A were recognized above the erosive base of Layer B, indicating a certain time interval between the two layers. In addition, the convolutions formed under water-saturated conditions were eroded by Layer B (Fig. 12C), and flute marks were developed at the base of Layer B (Fig. 13B). Thus, Layer A was formed before the deposition of Layer B and by another event that preceded the tsunami (e.g., a flood event immediately after the deposition of Ko-d, such as a lahar).

The sedimentary age of Ku-2 is after AD1640 (Ko-d) and before 261–28 cal yBP. As the 15–30 cm-thick floodplain silts of Unit 6 existed between Ku-1 and Ku-2, the sedimentary age of Ku-2 ranged from a few decades to 100 years older than Ku-1. Furthermore, as historical records of the AD1741 tsunami showed inundation at excavated sites (Tsuji et al., 2002), the origin of Ku-2 (at least Layers B and C) must have been the AD1741 tsunami rather than a storm surge or wave.

DISCUSSION

During the past 100 years, large storm events have occurred around this area in AD1936, AD1941, AD1952, AD1954 (Toyamaru Typhoon), AD1959 (Miyakojima Typhoons), and AD1980 (Nanayama et al., 2000). Although large storms have frequently occurred, only the AD1959 storm deposits have been identified below the AD1993 tsunami deposits by trench surveys around small riverbanks in the Hirahama lowland (Nanayama et al., 2000; Shigeno and Nanayama, 2016). In this case, the run-up flow of the storm inundated the lowlands through a small river channel. The deposits, up to 40 cm thick, were poorly sorted sands due to a mixing of beach and river sands and were distributed in a quite narrow zone along the river bank (length: ≈ 15 m, width: ≈ 5 m, altitude: ≈ 3 m, and distance from the present shoreline: 60–75 m) (Shigeno and Nanayama, 2016). In our study, only one event layer was recognized at the shallow stratigraphic level in both the Hirahama and Kumaishi-Ayukawa lowlands, interpreted as flash flood deposits sourced from the landward side. Although the flood event(s) could correspond to one of the above large storms during the 20th century, the stratigraphic records imply that even a large storm surge or high wave cannot transport sand widely to the inland areas behind the coastal dunes in the Hirahama and Kumaishi-Ayukawa lowlands.

The reliable tsunami deposits identified in the Hirahama and Kumaishi-Ayukawa lowlands were of the AD1741 tsunami origin. The Th-2 sand layer in Hirahama presents tsunami-genic characteristics, such as a landward paleocurrent, erosive base with rip-up clasts, normal grading, and marine diatoms, all consistent with the general characteristics of tsunami deposits (e.g. Goto and Sugawara, 2021); this supposed depositional age undoubtedly suggests a historical tsunami of AD1741 Oshima-Oshima. Although the historical record of inundation at the Hirahama lowland by the AD1741 tsunami was uncertain (Tsuji et al., 2002), the site is currently the northern-end locality traceable to the AD1741 tsunami deposits. The composition of the sand grains showed that the major source of clastics was Ko-d tephra. The grains were not very rounded (Fig. 8B), implying that the Ko-d tephra covering the ground surface of the Hirahama coast (i.e. coastal sand dunes and inland) was eroded and redeposited by the tsunami. Conversely, most sand grains of Layers B and C of Ku-2 in the Kumaishi-Ayukawa lowland were rounded (Fig. 8G, H). Their grain-size distribution was ϕ 1.0–2.0, generally consistent with the mode of beach sands along the Hirahama coast (Shigeno and Nanayama, 2016); this suggests that the beach surface of Kumaishi-Ayukawa coasts was covered by Ko-d tephra or sand grains derived from the tephra even a hundred year after the AD1640 eruption. As in this study, when reworked tephra that fell on the sand dunes and inland is the source of clastics, sandy clastic particles are not necessarily circularly polished, which should be considered when identifying tsunami deposits. There is an example of an event deposit composed of volcanic-ash sand of possible tsunami origin with almost unrounded, although the source of tephra is unknown (Kase et al., 2022).

Deposits of the AD1741 tsunami were previously reported on the Ayukawa coast near the excavated site of this study (Fig. 1B), where the tsunami deposits were confined to a narrow trough between coastal dunes (Nishimura et al., 2000; Nanayama et al., 2017). In Ayukawa coast, the distance from the present coastline to the terrace cliffs is ca. 50–90 m, and flat lowland has been limitedly developed behind the

dunes. They identified a single succession consisting of a lower unit formed by the inflow and an upper unit formed by the outflow. The facies of Layers B and C of Ku-2 in the Kumaishi-Ayukawa lowland are consistent with previous results. The inundated seawater blocked by the terrace cliffs behind the excavated site returned seaward along the adjacent Ayudomari-gawa River (Fig. 1D). Th-2 in the Hirahama lowland lacks a unit of outflow, indicating that the inundated seawater-surmounted coastal dunes reached the coastal marsh. The flat lowlands were flooded for some time, similar to the vast coastal lowlands facing the Pacific coast during the AD2011 Tohoku tsunami (Takashimizu et al., 2012). The high content of marine- to brackish-water diatom species in Unit 4 above Th-2 (Fig. 10A) supports this interpretation. Takashimizu et al. (2013) reported that the 17th century tsunami deposits in Iburi lowland, Hokkaido, consist only of in-flow deposits, which is considered to be the damming of the return flow by high coastal sand dune topography. The waveform characteristics, such as tsunami period and amplitude, and topographic factors that inhibit the return flow, such as coastal dune and vast lowland behind, are considered to have a significant influence on the tsunami behavior and the depositional process of the tsunami deposits.

The AD1741 tsunami sand layer in southern Hiyama, Ootobe-chou, was identified 1000 m inland from the shoreline in the floodplain of the Himekawa River (Hokkaido Research Organization, 2015; Kawakami et al., 2017a). These deposits consist of a normal-graded single layer, probably formed by run-up flow. The modal composition of these deposits showed sands resembling neighboring beach sands, poor in grains sourced from the Ko-d tephra (Hokkaido Research Organization, 2015). The characteristic compositions of Th-2 and Ku-2, rich in grains from Ko-d and different from the modern beach sands, could reflect that the northern Hiyama area was located on the axis of the ashfall of Ko-d tephra (northwest of Mt. Hokkaido Komagatake; Fig. 1B; Katsui et al., 1989).

Gravelly event deposits (Th-3a and Th-3b) older than AD1741 have been identified in the Hirahama lowlands, although their origins are uncertain. The stratigraphic section of Units 1–4 showed a regressive trend from the beach to the backmarsh. The section in Pit 3 shows an older age and is located at a higher elevation compared to the section in Pits 1 and 2 (Fig. 5). In addition, there was a topographic step between Pits 2 and 3 (Figs. 2A and 5). Thus, the inland side of the step was tectonically uplifted (i.e., earthquake-induced). Although the age of the uplifting event could not be determined, there is possibilities that the event deposits Th-3a and/or 3b was formed by coastal earthquake(s) and associated tsunamis. However, these gravelly deposits appear in a certain environment (blackish sandy soils of Unit 3) above coastal dunes (Unit 2) and are presently considered run-up gravels by storm surges.

SUMMARY AND CONCLUSION

We conducted pit excavations to find tsunami deposits in two narrow coastal lowlands along the EMJS, northern Hiyama District, Hokkaido, Japan. The results are as follows:

1. Four (Th-1, Th-2, Th-3a, and Th-3b) and two (Ku-1 and Layers A–C of Ku-2) event deposits were found in the Hirahama and Kumaishi-Ayukawa lowlands, respectively. Radiocarbon dating and

tephrochronology constrained sedimentary ages of Th-1 to after Th-2, Th-2 to 290–21 cal yBP, Th-3a to 672–561 cal yBP, Th-3b to 2333–1999 cal yBP, Ku-1 to 261–28 cal yBP, and Ku-2 to between Ku-1 and AD1640 Ko-d tephra.

2. Th-2 and Layers B–C of Ku-2 were formed by the AD1741 Oshima-Ohshima tsunami. Th-2 and Layer B were formed by run-up flow, that were characterized by thinning inland, landward paleocurrent, normal grading, erosional base with rip-up clasts, and higher ratio of marine diatoms. Whereas Layer C showed thinning seaward and seaward paleocurrent, indicating deposition under return flows. Layer A was likely formed by another event, such as a lahar, occurred immediately after deposition of Ko-d tephra.
3. Well-preserved coupled layers of run-up and return flows in the Kumaishi-Ayukawa lowland indicated that the AD1741 tsunami entered through the river mouth reached the terrace cliffs and returned along the river. Whereas Th-2 in the Hirahama lowland lack return flow layer and was overlain by coastal marsh muds, suggesting that the tsunami overtopped the coastal sand dunes and seawater ponded the vast lowland for a period.
4. The sand grains of AD1741 deposits were derived from the Ko-d tephra. The sand grains of Th-2 were not much rounded compared with those in Ku-2, which probably reflected sediment source from tephra fell on the sand dunes and inland.
5. Th-1 and Ku-1 were of flash flood origins. Considering sedimentary ages and distribution distance, they may have been formed by the contemporaneous flood events.
6. Th-3a and Th-3b consisted of rounded pebbles to cobbles similar with present beach gravels. Th-3a pinched out inland and showed landward paleocurrent, indicating deposition by storm surge or tsunami. The origin of Th-3b is currently unclear.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

Not applicable

Competing interests

There are no competing interests in relation with the present research.

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Authors' contributions

YK, GK, and AU contributed to writing the main part of the paper. YK, GK, KN, AU, and HK conducted the geological surveys. YT analyzed the anisotropy of magnetic susceptibility.

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Tables

Tables are available in the Supplementary Files section.

Figures

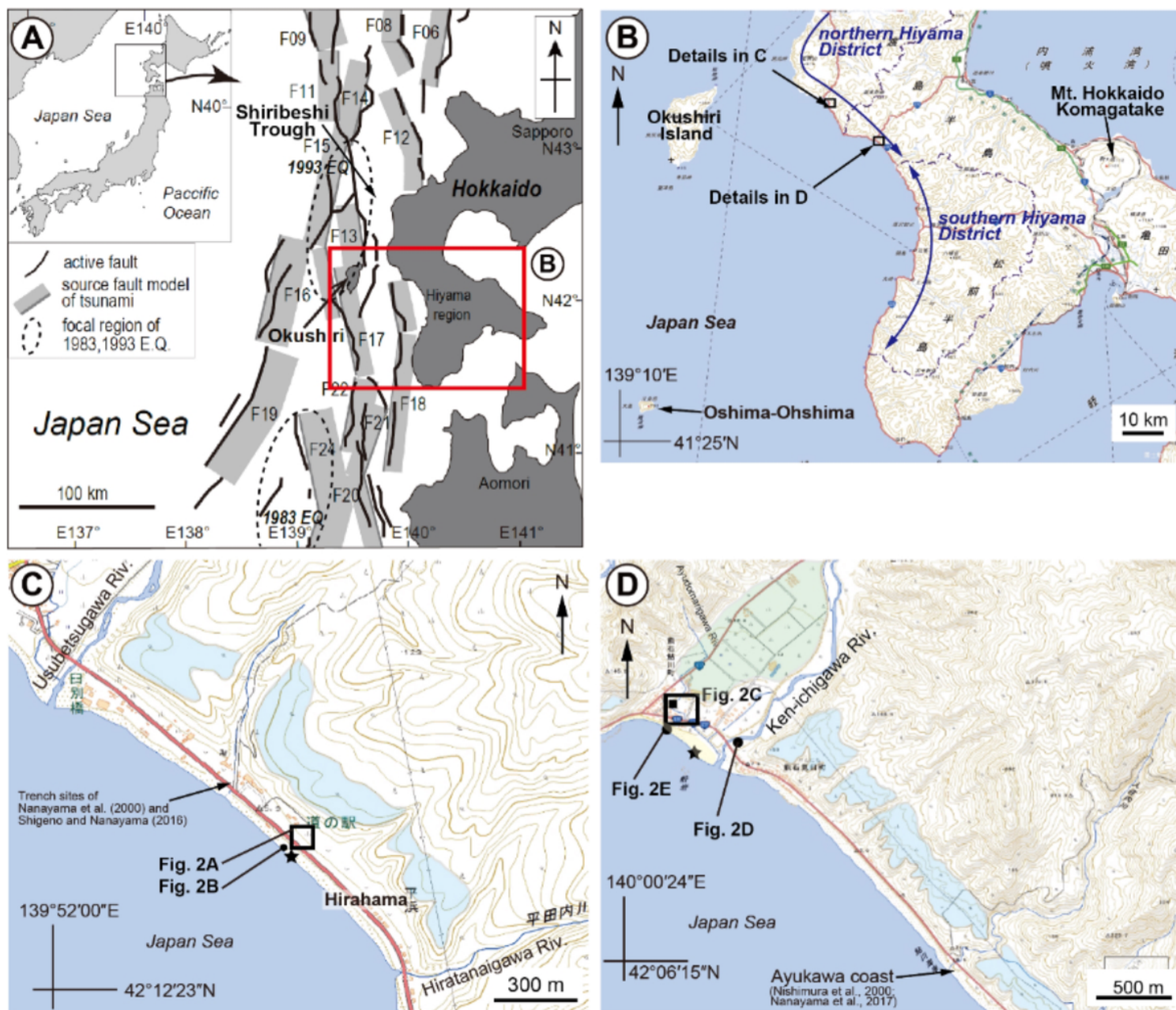


Figure 1

(A) Plate-tectonic framework and distribution of active faults along the eastern margin of the Japan Sea. Localities of faults are based on the Committee the Technical Investigation on Large-Scale Earthquakes in the Japan Sea (2014). (B) Close-up view of a part of (A), showing the study area. (C) Topographic map of the Hirahama lowland. (D) Topographic map of the Kumaishi-Ayukawa lowland. Contour lines of (C) and (D) are spaced 10 m apart. The stars and rectangles indicate the sampling locations of beach and river sands, respectively. The black circles indicate where the photographs were taken in Fig. 2. Light blue and light green colors indicate Marine Isotope Stage (MIS) 5e marine and MIS 2 fluvial terraces, respectively. The topographic map was derived from a Digital Map 1:25,000 (Map Image) published by the Geospatial Information Authority of Japan (GSI).

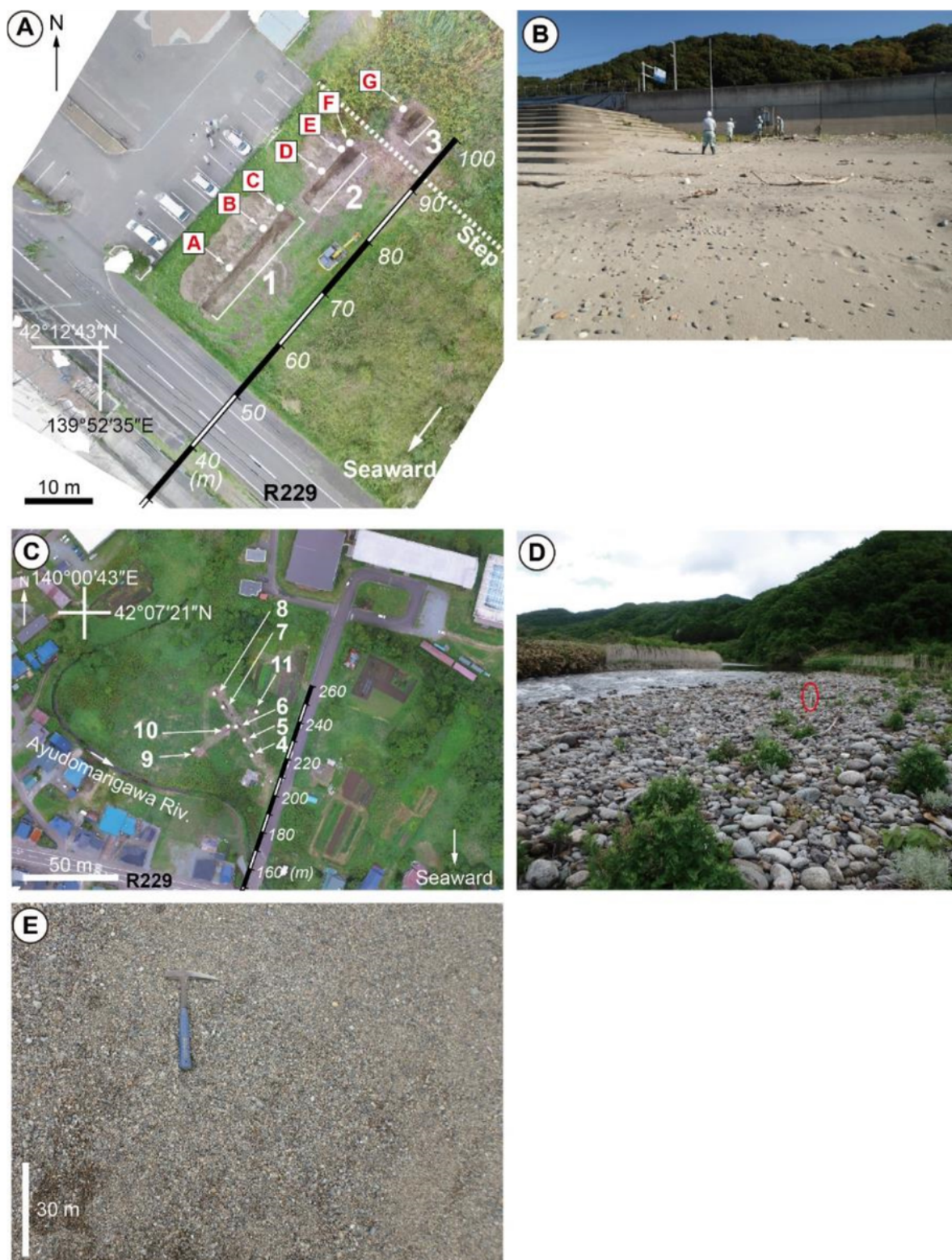


Figure 2

(A) Orthophotograph of the Hirahama lowland obtained with an Unmanned Aerial Vehicle (UAV) showing the pit localities (Pits 1–3). The white dashed line shows a topographical step, where ca. 1.2 m is the relative height of ground level between Pits 2 and 3. White circles with red letters show the localities of columnar sections in Fig. 5. Italic letters indicate the distance from the present shoreline. (B) Photograph of the coast in front of the survey sites ($42^{\circ}12'41''\text{N}$, $139^{\circ}52'37''\text{E}$) showing the distribution of well-sorted

medium sand with rounded pebbles and cobbles. The locality is shown in Fig. 1C. (C) Orthophotograph of the Kumaishi-Ayukawa lowland was obtained with an UAV showing pit locations (Pits 4–11). White circles and italic letters indicate the localities of columnar sections in Fig. 14 and the distance from the present shoreline, respectively. (D) Photograph of the gravel bar in the Ken-ichigawa River ($42^{\circ}7'10''\text{N}$, $140^{\circ}1'3''\text{E}$). The red circle indicates the 5 m scale. The locality is shown in Fig. 1D. (E) Photograph of the beach sand in front of the survey sites ($42^{\circ}7'5''\text{N}$, $140^{\circ}0'55''\text{E}$). The locality is shown in Fig. 1D.

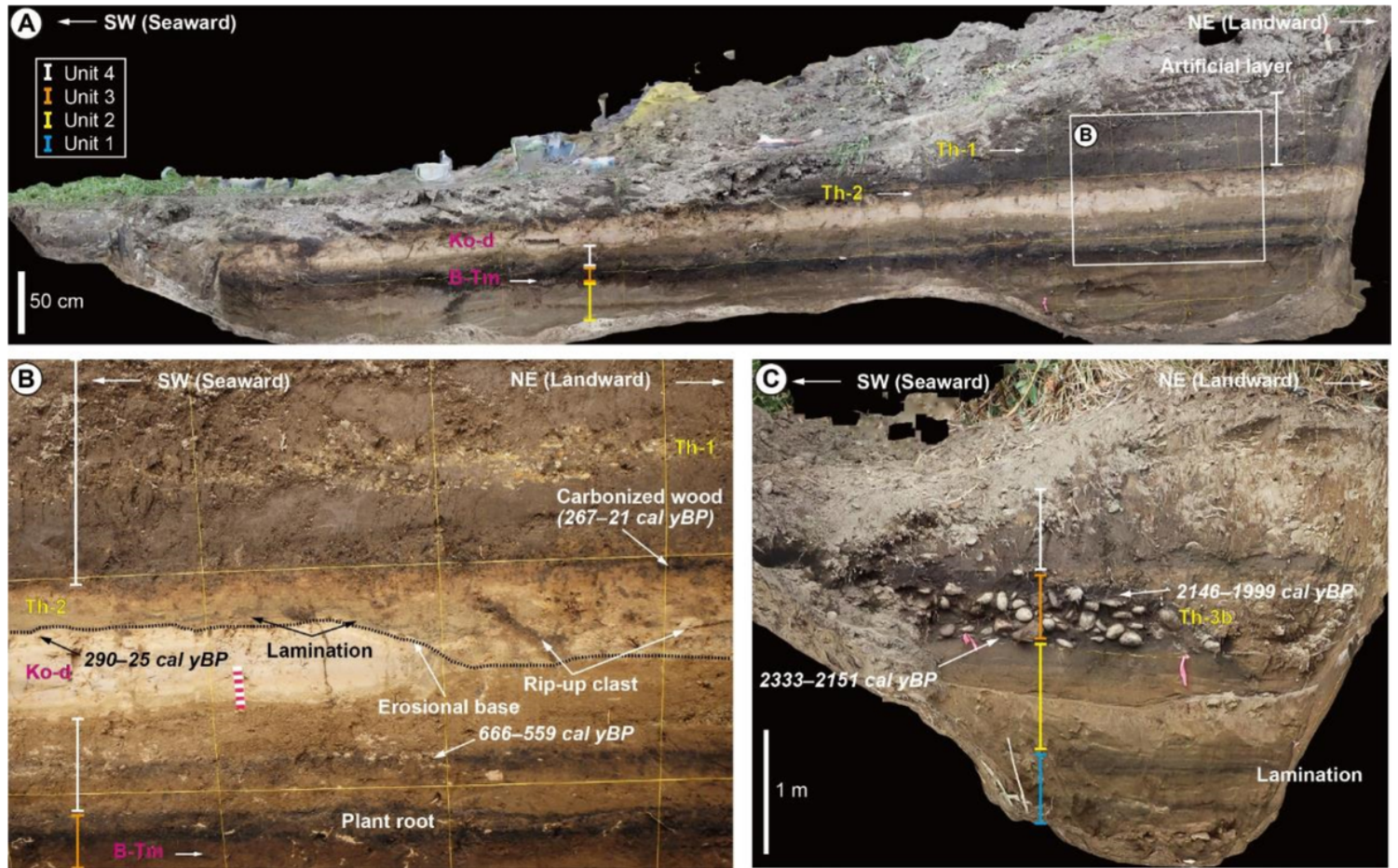


Figure 3

(A) Photograph of the Northeast-Southwest (landward-seaward) cross section of Pit 2. Th-1 and Th-2 were interbedded within organic clays (Unit 4). (B) Close-up view of a part of (A). Th-1 and Th-2 comprised poorly sorted angular pebbles and well-sorted fine- to coarse-sand, respectively. Th-2 showed laminations and erosional bases, suggesting landward paleocurrent directions, and contained rip-up clasts. Scale is 10 cm. (C) Photograph of the Northeast-Southwest (landward-seaward) cross-section of Pit 3. Th-3b, embedded in blackish sandy soils (Unit 3), comprises well-rounded flat pebbles and cobbles. Italicized texts indicate carbon-14 dating results. Th-1, Th-2, and Th-3b: event deposits. Ko-d: AD1640 Hokkaido Komagatake volcanic ash. B-Tm: AD946 Baitoushan-Tomakomai volcanic ash. Units 1–4: normal deposits.

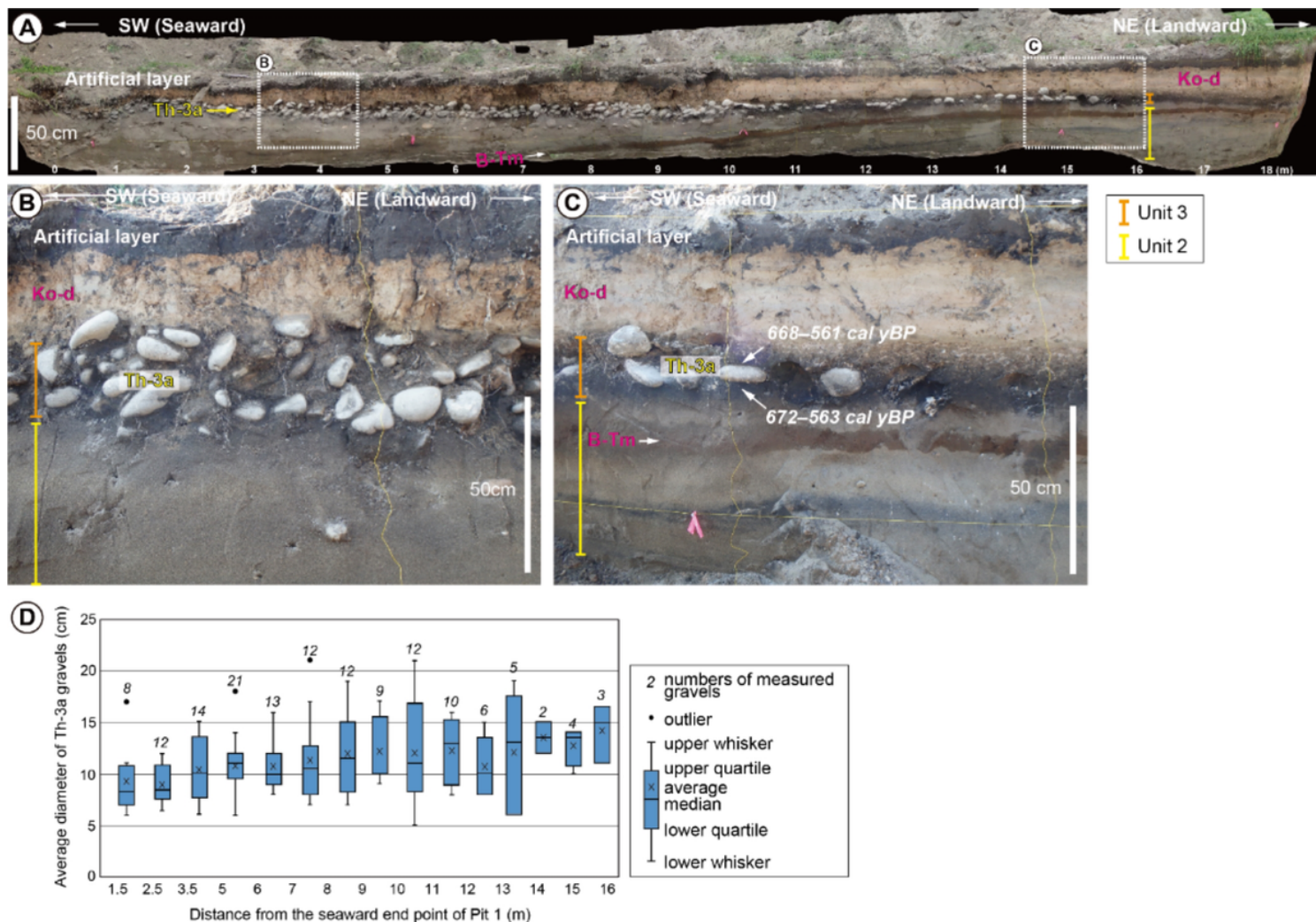


Figure 4

(A) Photograph of the Northeast-Southwest (landward-seaward) cross section of Pit 1. Th-3a, embedded in blackish sandy soils (Unit 3), comprises well-rounded flat pebble- to cobble-sized gravels. The numbers at the bottom of the figure indicate the distance from the seaward end point of Pit 1. (B, C) Close-up views of a part of (A). Italicized texts indicate carbon-14 dating results. (D) Box plot showing diameters of gravels of Th-3a versus distances from the most landward side of Pit 1. Th-3a: event deposit. Ko-d: AD1640 Hokkaido Komagatake volcanic ash. B-Tm: AD946 Baitoushan-Tomakomai volcanic ash. Units 2–3: normal deposits.

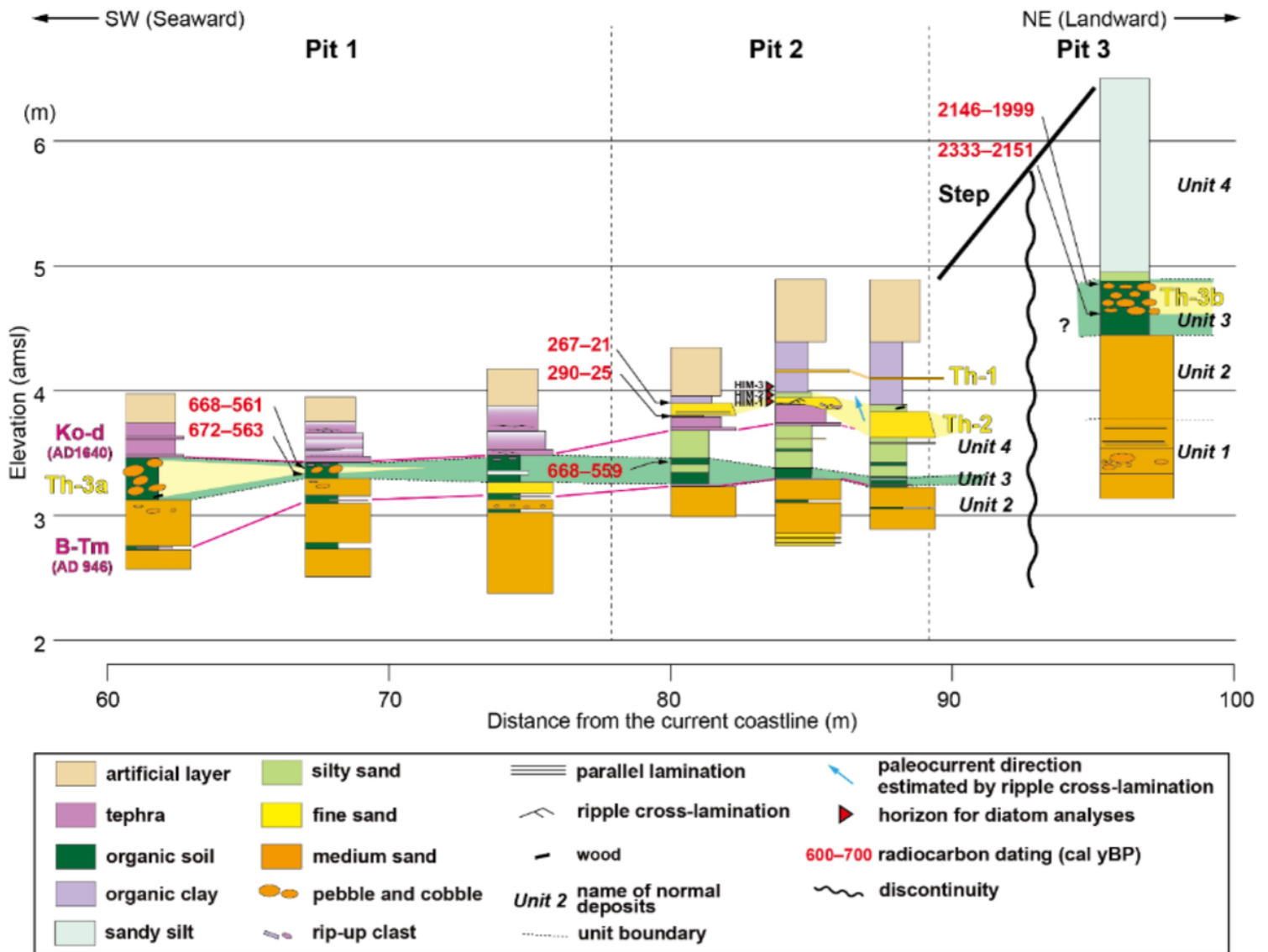


Figure 5

Vertical logs recognized in the Hirahama lowland. Based on tephra stratigraphy and radiocarbon dating, Th-1–Th-2, Th-3a, and Th-3b are recognized in Pit 2, Pit 1, and Pit 3, respectively. Arrows of paleocurrents indicate 0° in the upward direction and northward. Th-1, Th-2, Th-3a, and Th-3b: event deposits. Ko-d: AD1640 Hokkaido Komagatake volcanic ash. B-Tm: AD946 Baitoushan-Tomakomai volcanic ash.

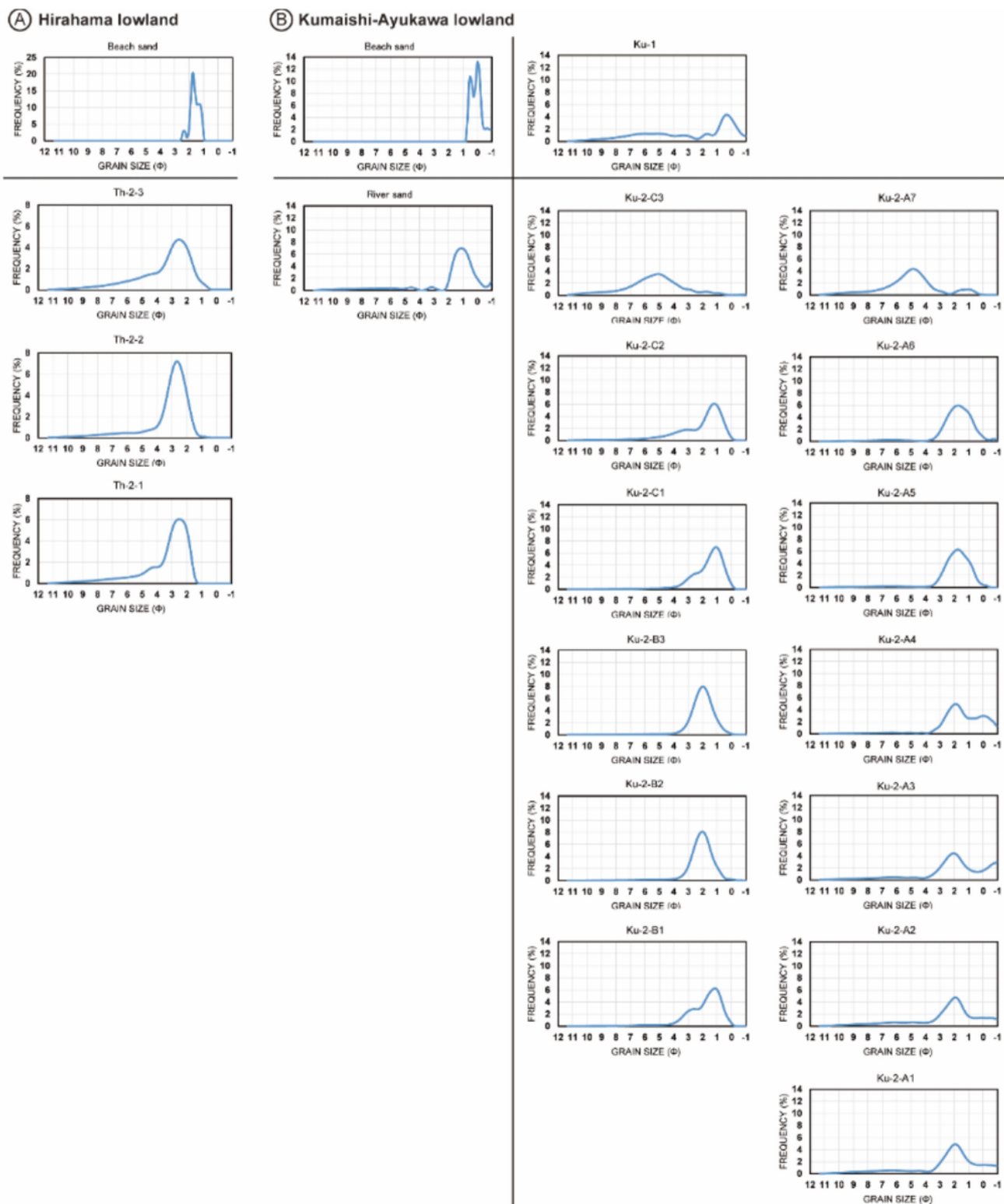


Figure 6

Grain size distribution of event deposits, beach sands, and river sands. (A) Hirahama lowland. (B) Kumaishi-Ayukawa lowland. The stratigraphic horizons of the samples analyzed are shown in Figs. 5 and 14. Th-2, Ku-1, and Ku-2: event deposits.

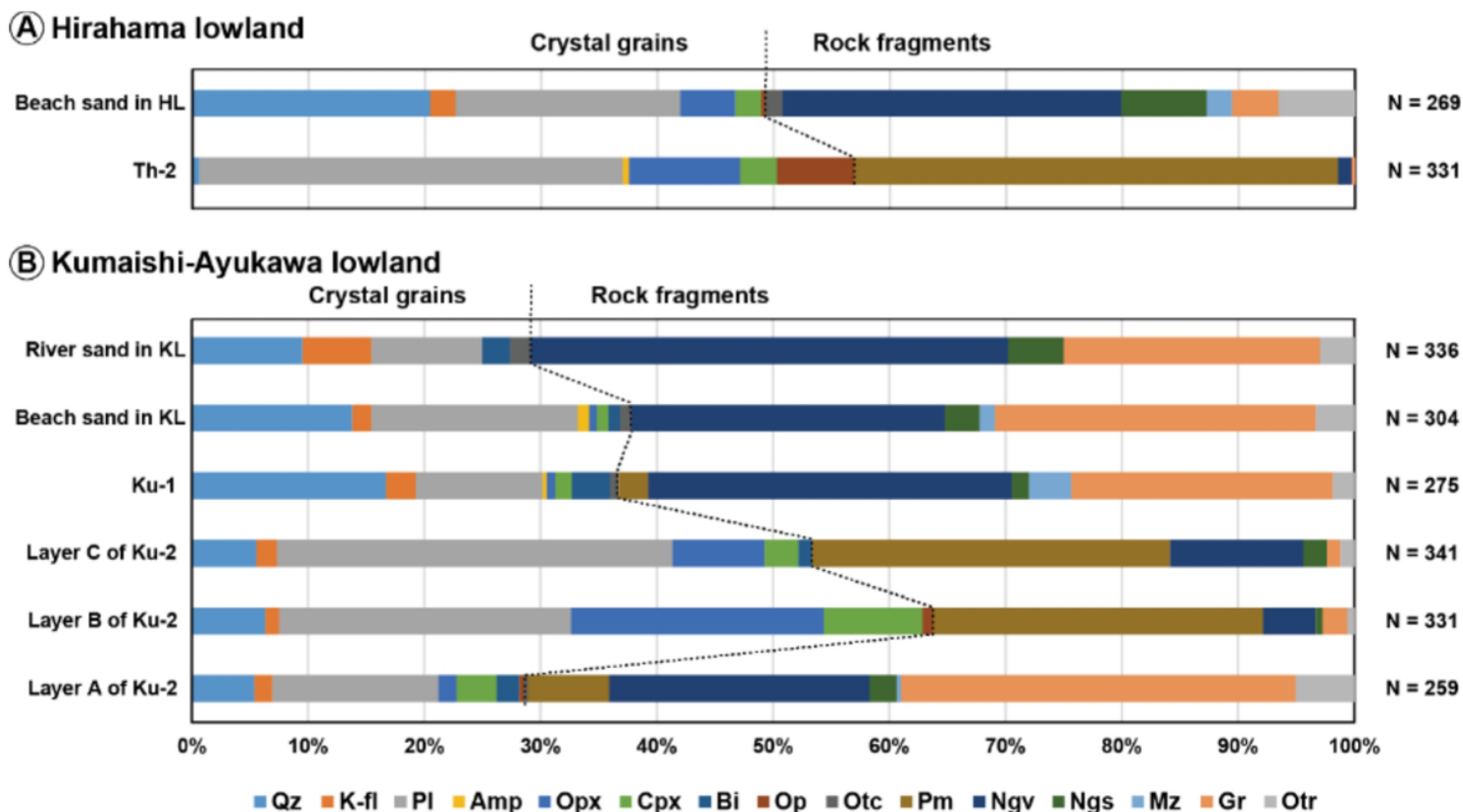


Figure 7

Modal composition of the sandy event deposits compared to neighboring beach and river sands. The sampling locations of the beach and river sands are shown in Fig. 1C and D. Qz: quartz, K-fl: K-feldspar, Pl: plagioclase, Amp: amphibole, Opx: orthopyroxene, Cpx: clinopyroxene, Bt: biotite, Op: opaque minerals, Otc, other crystal grains, Pm: pumice, Ngv: Neogene volcanic rock fragment, Ngs: Neogene sedimentary rock fragment, Mz: Mesozoic basement rock fragment, Gr: Granitic rock fragment, Otr: other rock fragments. N: number of point counts. Th-2, Ku-1, and Ku-2: event deposits. HL: Hirahama lowland. KL: Kumaishi-Ayukawa lowland.

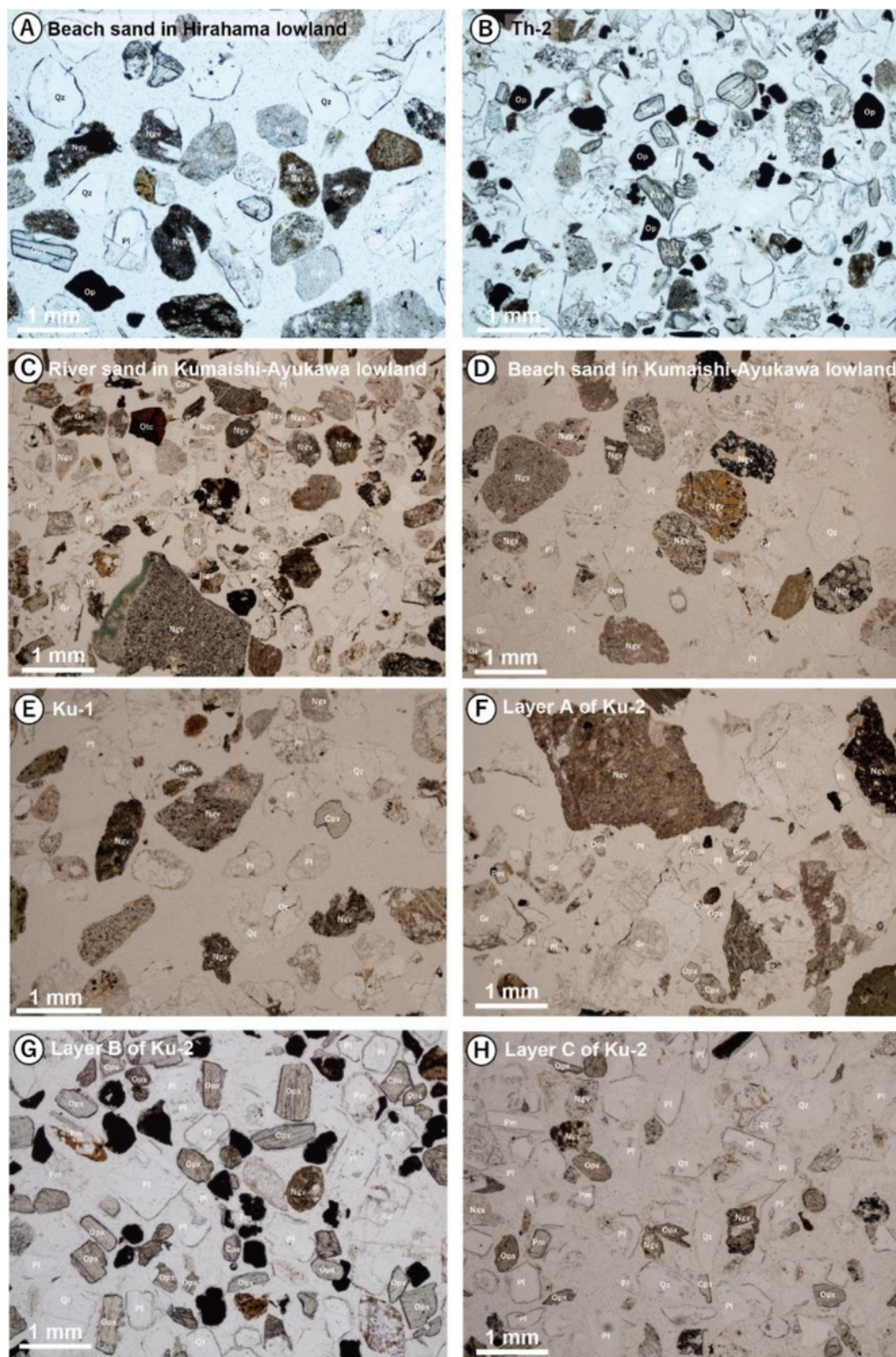


Figure 8

Photomicrographs (open-nicol) of (A) beach sand in the Hirahama lowland, (B) Th-2, (C) river sand in the Kumaishi-Ayukawa lowland, (D) beach sand in the Kumaishi-Ayukawa lowland, (E) Ku-1, (F) Layer A of Ku-2, (F) Layer B of Ku-2, and (G) Layer C of Ku-2. Th-2, Ku-1, and Ku-2: event deposits. Qz: quartz, Pl: plagioclase, Amp: amphibole, Opx: orthopyroxene, Cpx: clinopyroxene, Otc, other crystal grains, Pm:

pumice, Ngv: Neogene volcanic rock fragment, Ngs: Neogene sedimentary rock fragment Gr: Granitic rock fragment.

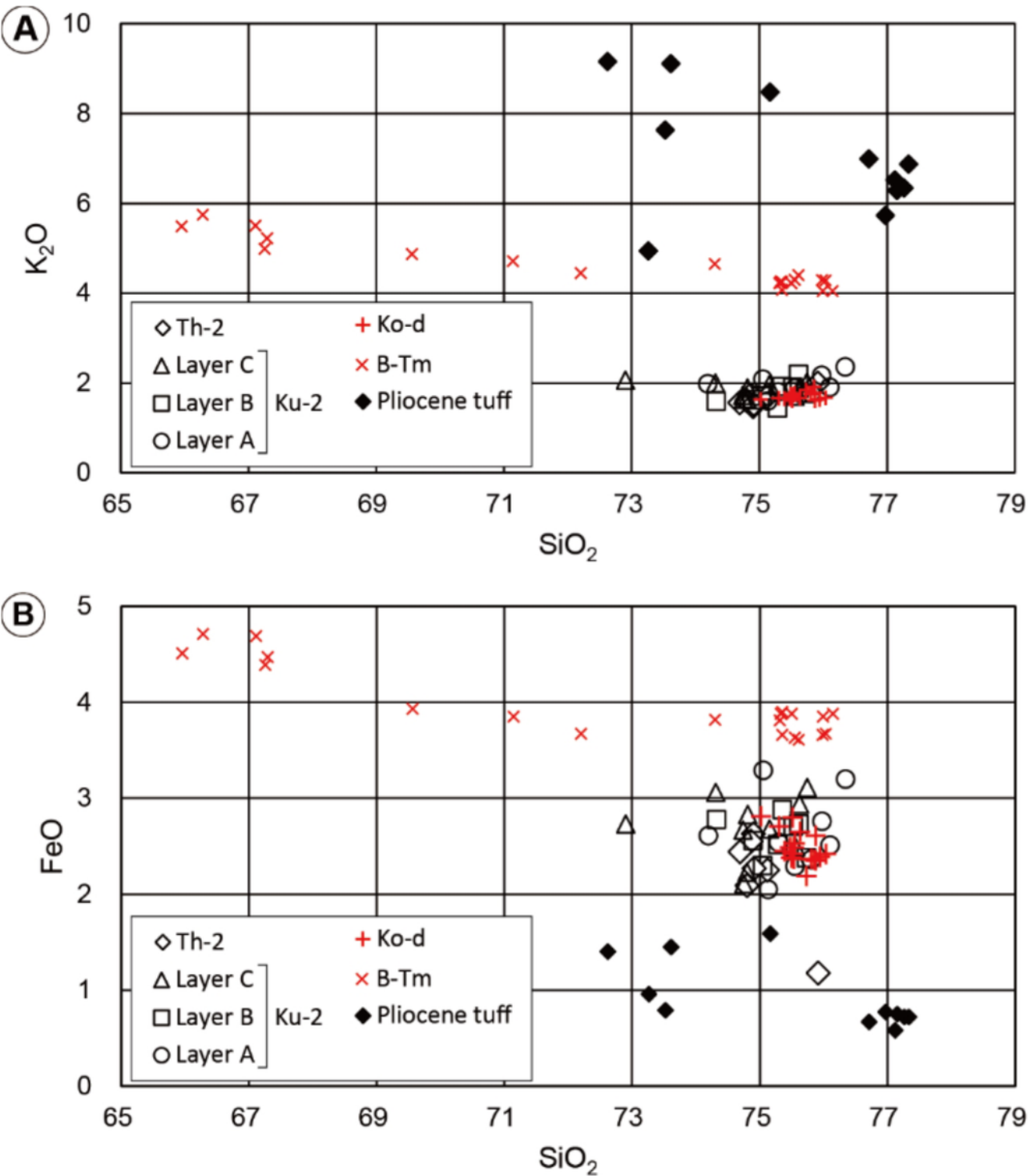
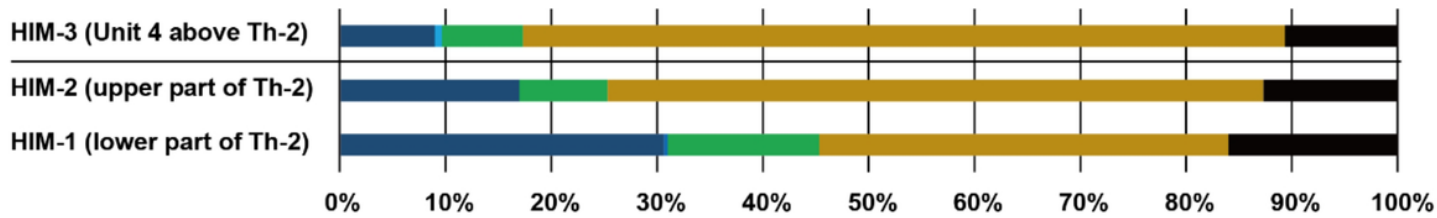


Figure 9

Harker diagrams of (A) SiO_2 – K_2O and (B) SiO_2 – FeO for volcanic glass shards in Th-2, Layers A–C of Ku-2, Ko-d, B-Tm, and Pliocene tuffs. Th-2 and Ku-2: event deposits. Ko-d: AD1640 Hokkaido Komagatake

volcanic ash. B-Tm: AD946 Baitoushan-Tomakomai volcanic ash.

A Hiraehama lowland



B Kumaishi-Ayukawa lowland

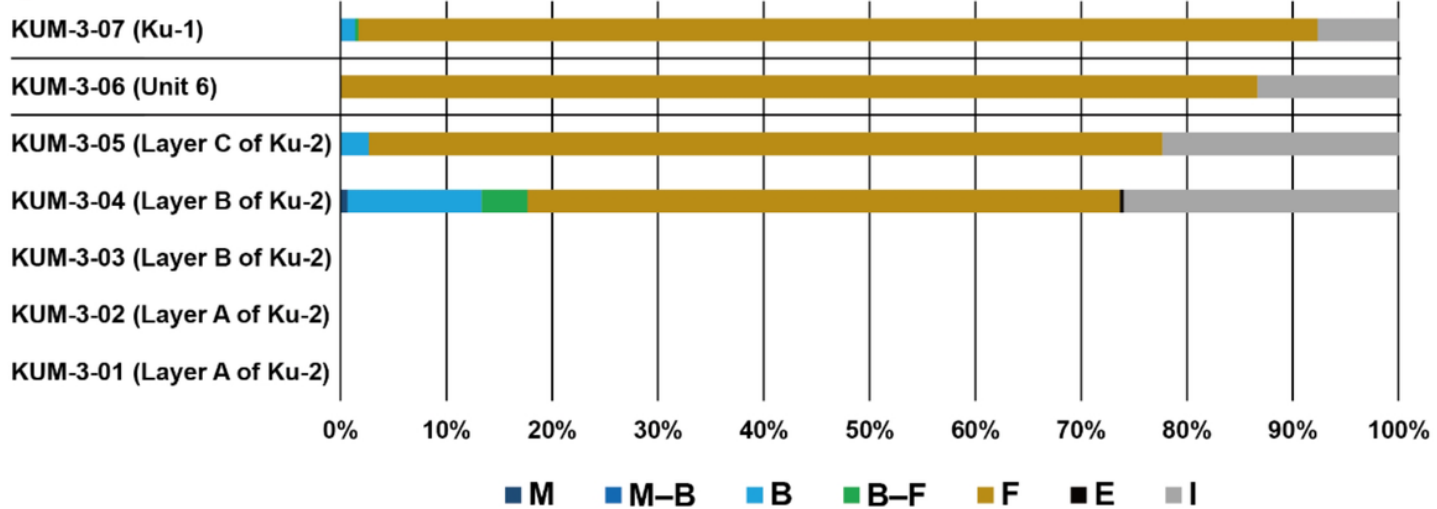


Figure 10

Composition of diatom valves in the event and normal deposits. The stratigraphic horizons of the samples analyzed are shown in Figs. 5 and 14. Th-2, Ku-1, and Ku-2: event deposits. Unit 4 and Unit 6: normal deposits.

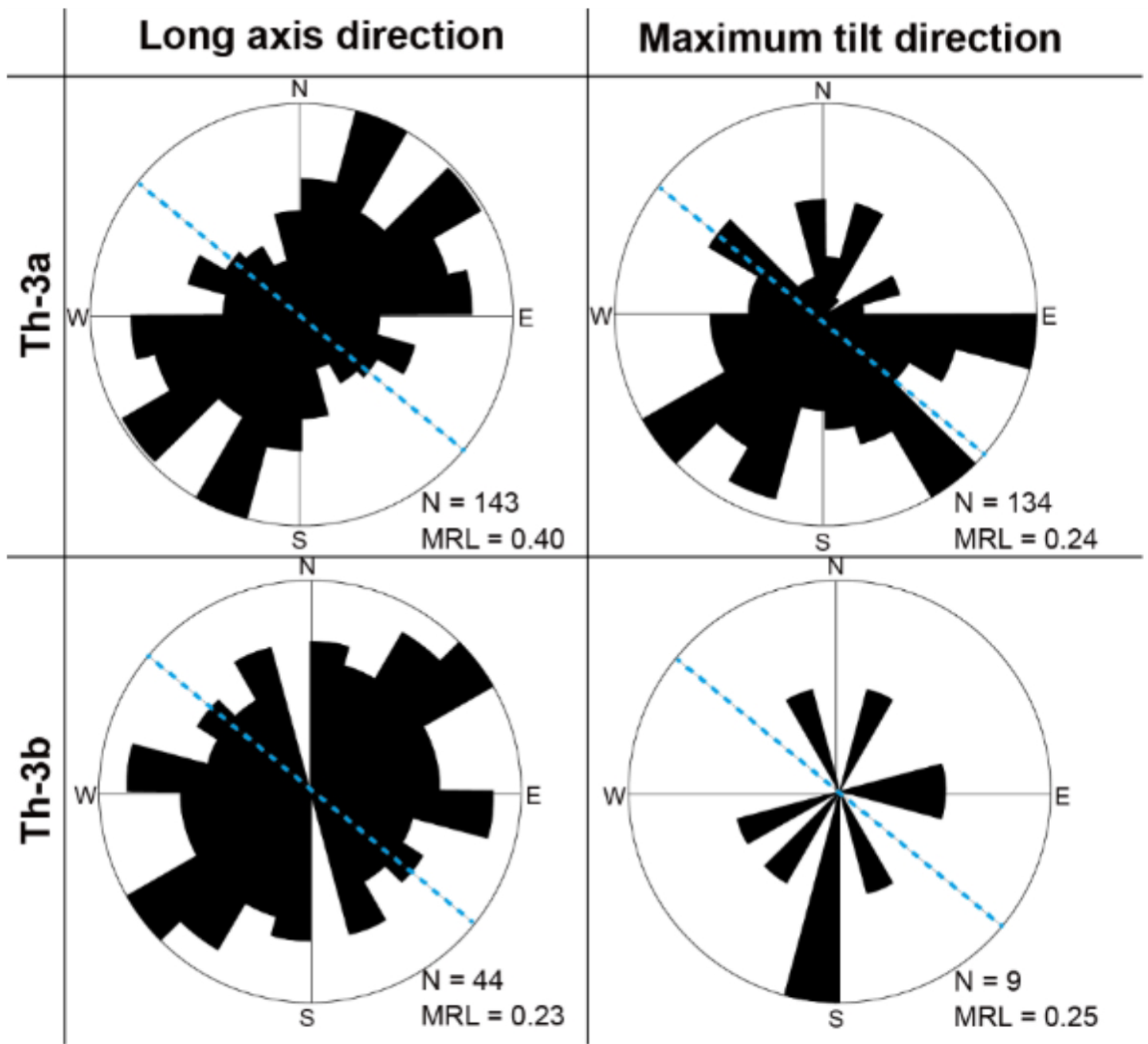


Figure 11

Rose diagrams showing the directions of the longest axis and the maximum tilt of Th-3a and Th-3b. Blue dashed lines with figures show coastline directions. Th-3a and Th-3b: event deposits. N: number of measurements. MRL: mean resultant length of vectors.

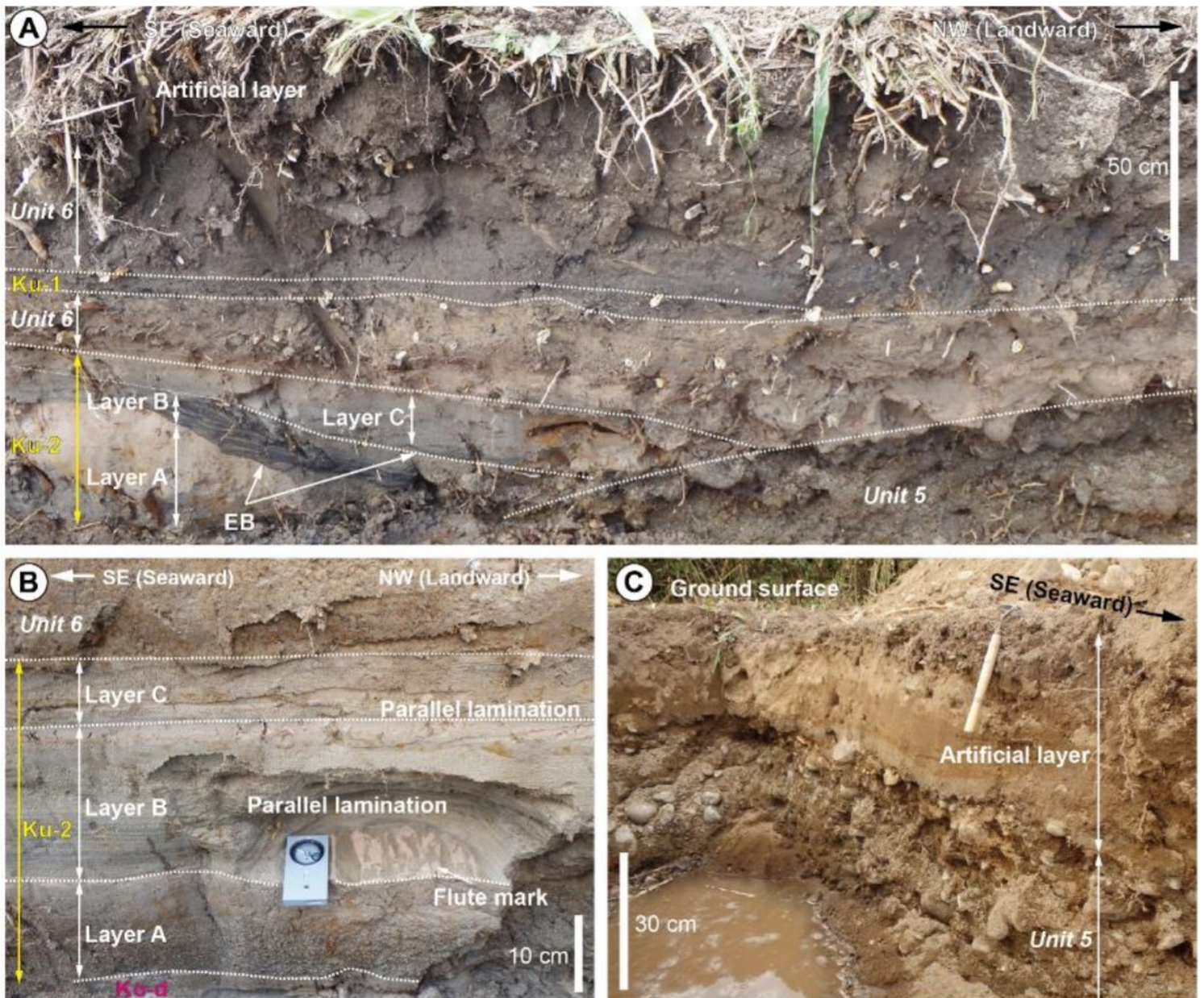


Figure 13

(A) Photograph of the Northwest-Southeast cross-section of Pit 7. Ku-1 is embedded in silts and organic clays (Unit 6). In Ku-2, Layer B shows an erosional base on Layer A. Laminations on the erosional base of Unit B show landward paleocurrent directions. Ripple cross-laminations of Layer C show seaward directions. (B) Close-up view of the boundaries between Layers A and B. Flute marks are recognized on the boundaries, showing northeast-southwest paleocurrent directions. (C) Photograph of the Northwest-Southeast cross-section of Pit 8. The fluvial gravel bar (Unit 5) is recognized. EB: erosional base. Ku-1 and Ku-2: event deposits. Ko-d: AD1640 Hokkaido Komagatake volcanic ash. Unit 5 and Unit 6: normal deposits.

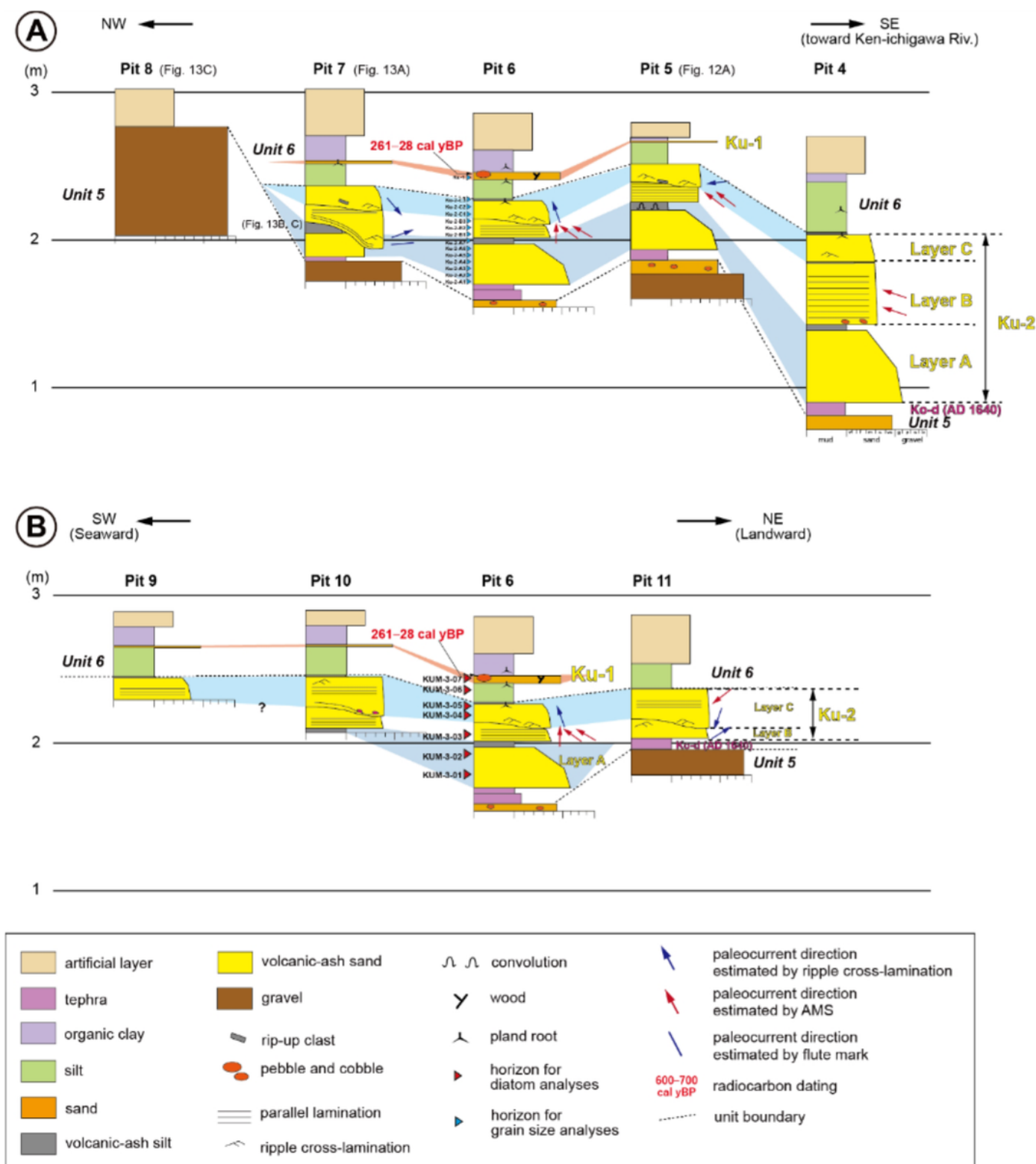


Figure 14

Vertical logs recognized in the Kumaishi-Ayukawa lowland. Based on Ko-d volcanic ash, radiocarbon dating, and succession of normal deposits, Ku-1 and Ku-2 could be well traceable in the survey area. Arrows of paleocurrents indicate 0° in the upward direction and northward. Ku-1 and Ku-2: event deposits. Ko-d: AD1640 Hokkaido Komagatake volcanic ash. Lateral distances are not to scale.

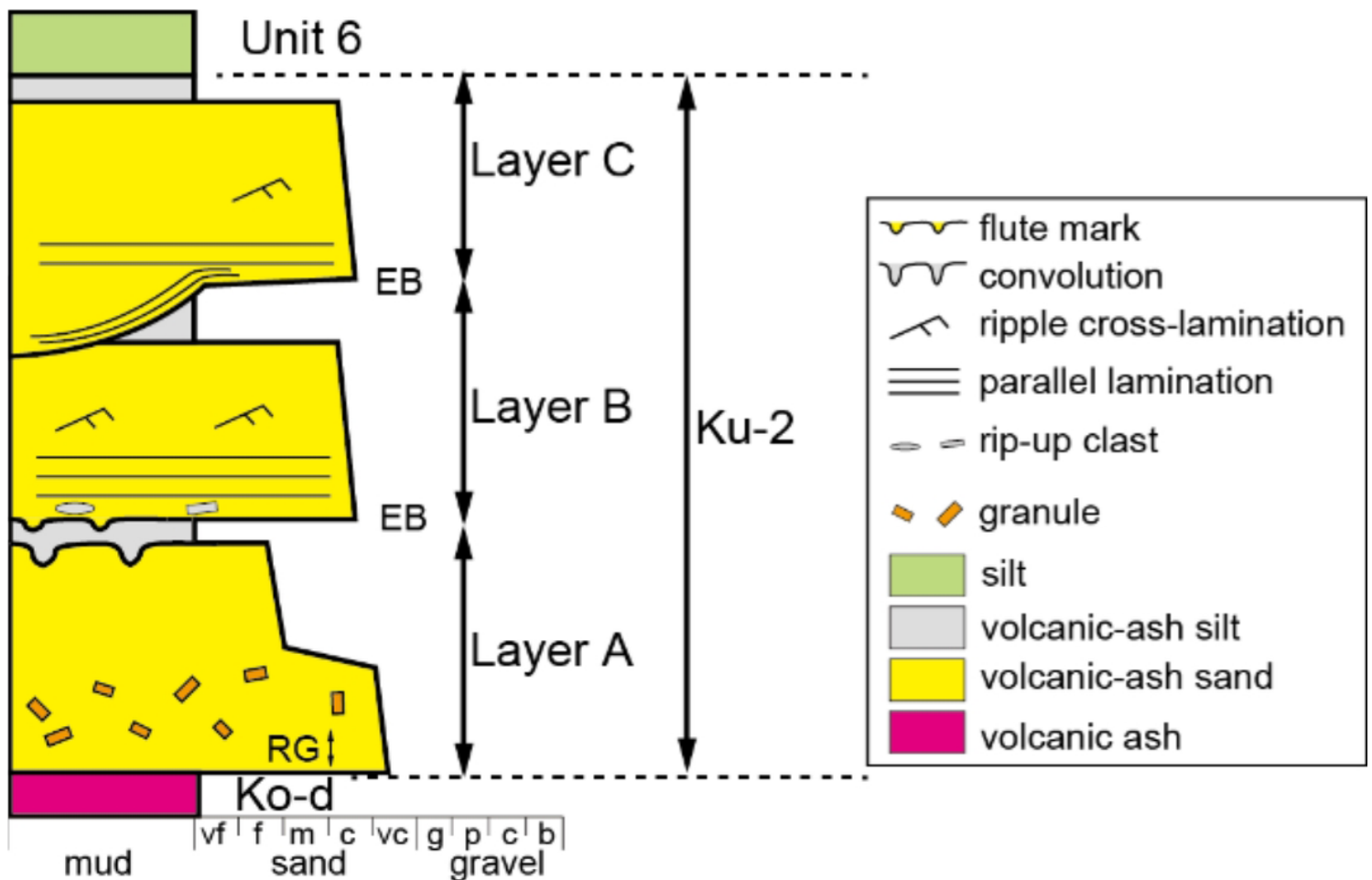


Figure 15

Schematic succession of Ku-2 recognized in the Kumaishi-Ayukawa lowland. EB: erosional base. RG: reversed grading. Ku-2: event deposits. Ko-d: AD1640 Hokkaido Komagatake volcanic ash. Not to scale.

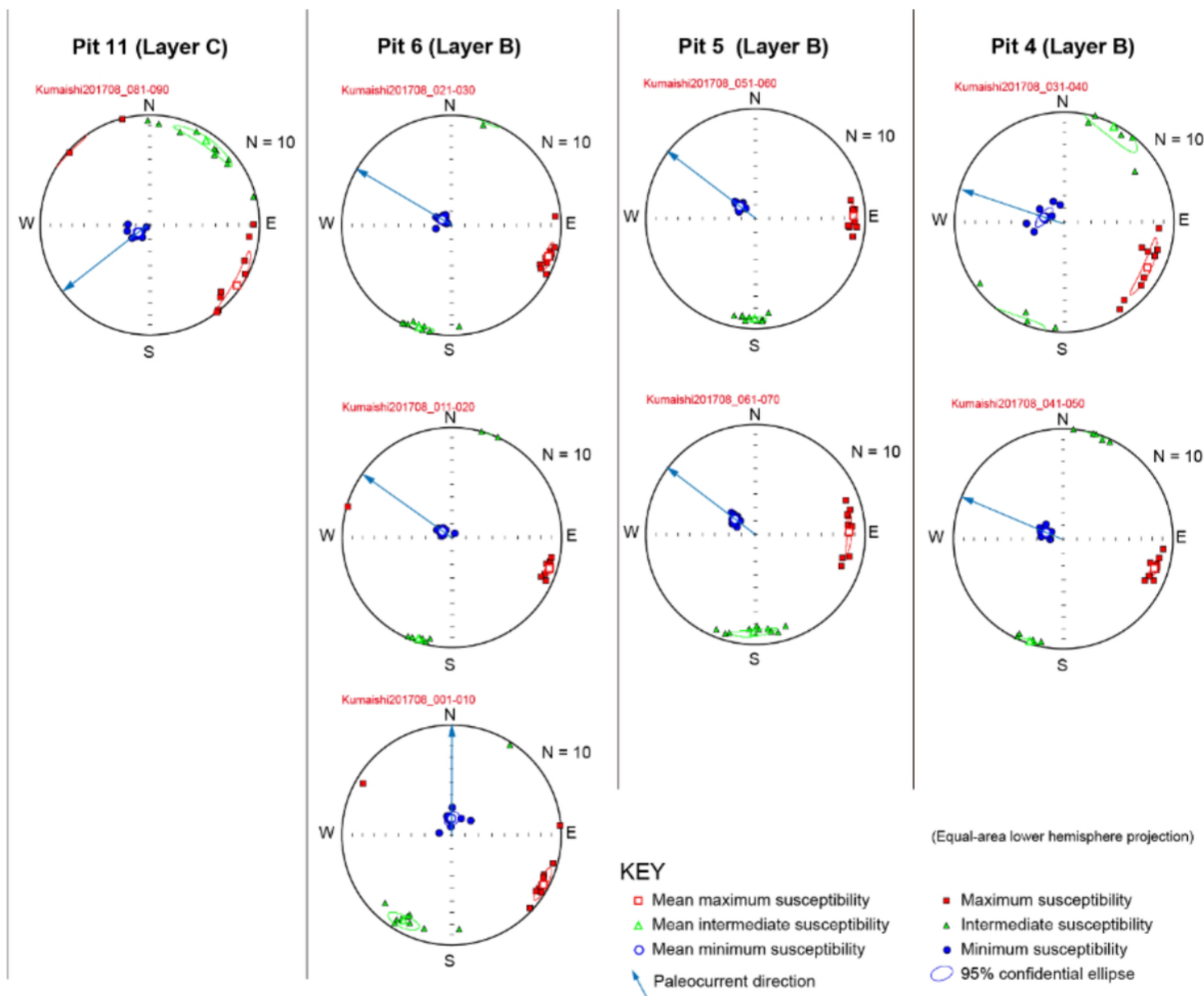


Figure 16

Magnetic fabric of Ku-2. Kmax, Kint, and Kmin data are plotted on equal-area lower-hemisphere projections. Red texts indicate sample names. N = the number of samples. Ku-2: event deposit.

Supplementary Files

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