The Tohoku Tsunami of 11 March 2011: The Key Event to Understanding Tsunami Sedimentation on the Coasts of Closed Bays of the Lesser Kuril Islands

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Abstract—The Tohoku tsunami of 11 March 2011 manifested in the region of the South Kuril Islands, although, as a rule, the run-up heights in this region did not exceed 3 m. In closed bays that were covered with ice before the tsunami, the eroding capacity of tsunami waves was aggravated by the ice fragments they carried. Here, mud sheets formed, reaching up to 106 m inland. The 2012 studies have shown well-preserved tsunami deposits, evident 1.5 years after the event. A comparative analysis of tsunami deposits from the periphery and from the near-field area close to the tsunami source was performed; this was important for understanding the deposition mechanism during the event, as it had different strengths on different shores. The difference in run-up heights determined the considerable differences in erosion, sedimentation, distribution of tsunami deposits, the formation of sedimentary structures, grain-size composition, and diatom and foraminifera assemblages. The sources of the material also varied significantly from each other: the material came from offshore in closed bays located in the tsunami source periphery, while in the near-field region close to the epicenter, the most active erosion occurred in the inundation area. In the latter area, the main sources of sand were beaches and dunes, while soil erosion was the source of mud. Studies of the Tohoku tsunami on the coasts of the Lesser Kuril Islands demonstrated that mud layers in the sections of coastal lowlands in closed bays could contain preserved detailed geological records of paleotsunamis, even those with a small-height run-up. In the sections of coastal peatlands of closed bays on Shikotan Island, up to 7–9 layers of mud and silty sands were found, these can easily be traced for more than 500 m inland. The grain-size composition of the mud is similar to the deposits of the 2011 Tohoku tsunami. The marine origin of these deposits is confirmed by the diatom analysis data.

Key words: 2011 Tohoku tsunami deposits, mud, grain size, diatoms, foraminifera, lesser Kuril Islands, Pacific Ocean.

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1. Introduction

The Tohoku tsunami of 11 March 2011 was one of the strongest events to have ever occurred in the Pacific Ocean; it was recorded along the entire Kuril Islands from the Lesser Kuril Islands in the south up to Paramushir Island in the north (KAISTRENKO et al. 2011, 2013; SHEVCHENKO et al. 2014). The Kuril Islands were in the periphery zone of the main tsunami propagation flux. The Tohoku tsunami run-up heights generally did not exceed 3 m on the coasts of the South Kuril Islands, located 750–800 km away from the source area. A particular feature of this event on the coasts of the Kuril Islands was heavy sea ice moving with the water (KAISTRENKO et al. 2013). The sedimentation during such an exclusive and intensive event requires special investigation. The water coming with the tsunami waves was filled with ice fragments, which increased the wave erosive capacity; this effect was especially strong in closed bays, where a mud cover was found to have formed (RAZJIGAEVA et al. 2013). In contrast, on the shores of open bays, the waves did not cause active erosion and left almost no deposits. The absence of deposits cannot be explained by the erosion during back flow, because it was not intensive. In all bays on the Pacific side of the island, the grass blades in the inundation zone were oriented landward, in accordance with the inflow. Locally, where the outflow was dominant, the grass blades were turned seaward and traces of soil erosion were found.

Some specific features of sedimentation during a tsunami with ice were reconstructed by MINOURA et al. (1996) for the 1923 Kamchatka event based on deposits collected 70 years after the tsunami. The study of the 2011 Tohoku tsunami deposits in the

region of the South Kuril Islands gives us a unique opportunity to examine the sedimentation of a tsunami with ice shortly after the event.

The study of the 2011 Tohoku tsunami in the South Kuril Islands also has another interesting aspect. In order to perform the reconstruction of transoceanic tsunamis of the past and to estimate their recurrence period, it is important to understand the difference between deposits formed in the periphery of the tsunami propagation and in the near-field zone of the highest run-up. The coastal area of eastern Japan was a region of very intensive research on the 2011 Tohoku tsunami deposits (ABE *et al*. 2012; GOTO *et al*. 2011, 2012; INUI *et al*. 2012; NAKAMURA *et al*. 2012; NARUSE *et al*. 2012; RICHMOND *et al*. 2012; SZCZUCIŃSKI *et al*. 2012; TAKASHIMIZU *et al*. 2012). The comparison of the characteristics of the 2011 tsunami deposits in the Lesser Kuril Islands with those collected on Honshu Island can explain the differences in the deposition mechanism in near-field and far-field areas.

The present paper is a continuation of our previous study, R2013, of the 2011 Tohoku tsunami deposits on the coasts of the Lesser Kuril Islands (RAZJIGAEVA *et al*. 2013). In R2013, we described the first deposit data collected from ice immediately after the event (i.e., in March 2011), and during the field survey in August–September 2011. The main purpose of R2013 was to examine the factors controlling tsunami sedimentation patterns in a variety of locations along the coast. We found that the characteristics of tsunami deposition varied significantly, essentially depending on local coastal topography; large differences were observed between the coasts of open and closed bays. Continuous mud deposits were found to have formed only on the coasts of closed bays. Our findings indicate that one of the crucial factors controlling the formation of the mud covers, even for coasts with insignificant run-up heights, was the presence of the ice. The main source of the tsunami mud deposits were the bottom inshore and offshore mud flows in closed bays with relatively low wave energy. However, we assume that if a tsunami of this scale occurred at an ice-free time of year, no mud covers could be formed.

One of the objectives of R2013 was to find differences of the 2011 Tohoku tsunami deposits from other coastal facies. The study of the composition of benthic foraminifera and diatoms indicated that the tsunami wave had entrained material from the upper shoreline. Considerable differences in the grain-size composition were found between the 2011 Tohoku tsunami deposits and the deposits associated with the 1994 Shikotan tsunami (IVANOV 1997; RAZZHIGAEVA *et al*. 2007). Additionally, it was discussed that tsunami sedimentation is significantly different from that of extreme storms, even with similar run-up values. The manifestation of the 2011 Tohoku tsunami in the Southern Kuril Islands was also examined by KAISTRENKO *et al*. (2013), who collected eyewitness reports and photos of tsunami effects on the coasts of these islands, in particular the results of interaction of tsunami waves with ice. They estimated maximum run-up heights and inshore inundation distances in various bays, however, they did not discuss tsunami sedimentation. SHEVCHENKO *et al*. (2014) examined coastal and offshore instrumental records of the 2011 tsunami. At Shikotan Island (Lesser Kuril Islands), the maximum recorded trough-to-crest wave height was almost 3 m, in close agreement with the field survey results (KAISTRENKO *et al*. 2013).

The purpose of the present paper is to analyze the specifics of the 2011 Tohoku tsunami sedimentation in the periphery zone, summarizing the 2011 observations and the new data obtained during the 2012 field survey. One of the objectives of this study was to compare results for the relatively remote Lesser Kuril Islands with those from the near-field zone on the northeastern coast of Honshu Island, Japan, where maximum run-ups of up to 40 m were observed (e.g., MORI *et al*. 2011). It is especially important to compare the composition of the muds formed under the tsunami with low and high run-ups, in diverse coastal environments and having different sources, and to show the unique properties of tsunami mud deposits within the closed bay coasts.

Another objective of the current paper was to thoroughly study the 2011 Tohoku tsunami deposits and to use the corresponding results to reveal and reconstruct historical tsunami and paleotsunami deposits. The 2011 Tohoku tsunami sediments that were recovered and examined from the coasts of closed bays of the Lesser Kuril Islands were critical

to understanding the sedimentological effects of tsunamis in general, and they stimulated further study of paleotsunami muds. While studying the coastal lowlands of closed bays, we have discovered that particular attention has to be paid to thin mud layers alternating with layers of peat. An interesting problem is to compare the Tohoku tsunami deposits in closed bays of the Lesser Kuril Islands with mud layers in the Holocene peat sections, attempting to understand whether they are traces of paleotsunamis and under what conditions they were formed.

2. Regional Setting

Lesser Kuril Ridge is a chain of islands stretching 100 km to the northeast from Hokkaido

Island; it runs parallel to Greater Kuril Ridge and is separated from Kunashir Island by South Kuril Strait, which is 48 km wide and up to 200 m deep (Fig. 1). The Lesser Kuril Islands include six medium-size islands, the largest being Shikotan and Zeleniy, and a number of smaller islands and rocks. Among those, only Shikotan Island has low-mountain topography, which prevented the deep penetration of the tsunami. An asymmetric relief with steeper slopes on the Pacific side of the island in many ways predetermined the configuration and development of the coastal zone. The other islands are flat and low (up to 40 m). The islands are separated by narrow (1.9–22.2-km-wide), shallow straits up to 54 m deep. The strait between Tanfiliev Island and Hokkaido Island is 7 km wide and 89 m deep (ATLAS OF THE KURIL ISLANDS 2009).
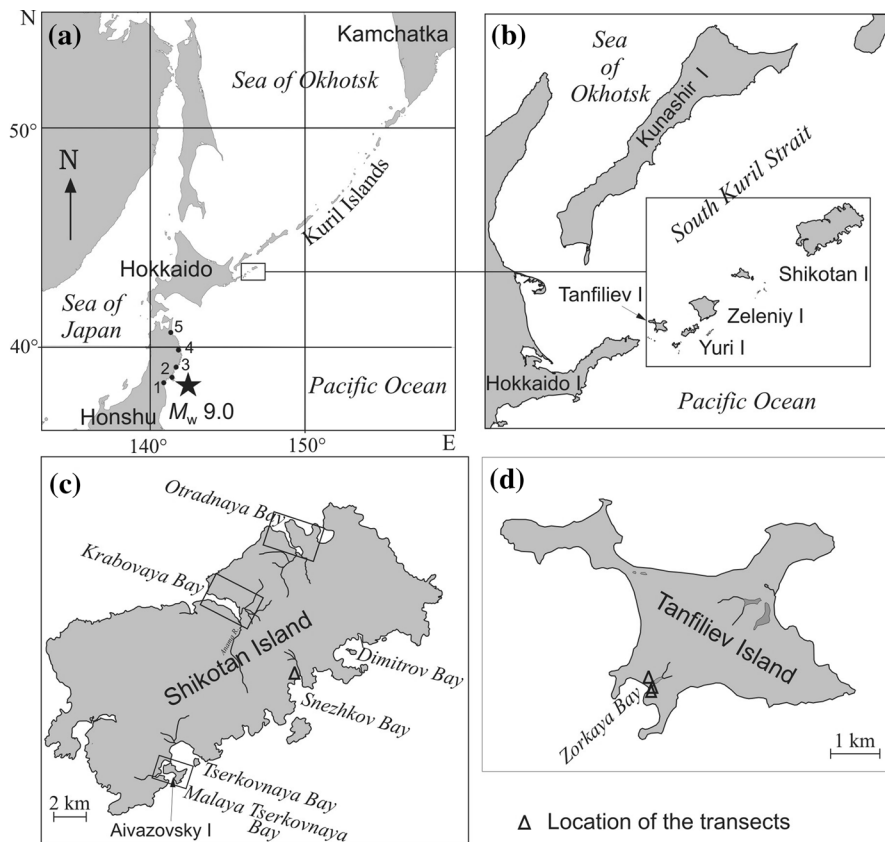

Figure 1
a Map of the study area with the epicenter of the Tohoku-oki earthquake (M_w 9.0) of 11 March 2011 indicated by a *star*. *Small circles* with numbers denote specific sites in Honshu Island (Japan) where tsunami deposits were examined by various authors: *1* Sendai Plain; *2* Matsushima Bay; *3* Hirota Bay; *4* Miyako City; and *5* Misawa coast. **b** The region of South Kuril and Lesser Kuril islands. **c, d** Maps of Shikotan and Tanfiliev islands, respectively, with the location of the transects denoted by *empty triangles*. *Boxes* are shown in Fig. 2

Typical shores of the islands are high, with abrasion and abrasion-denudation coasts with narrow beaches and open bays. In the heads of closed bays there are swampy coastal lowlands with ancient storm ridges directly behind the beaches. Low swampy isthmuses can be found only on Yuri Island. Closed bays can be divided into two types: those formed as a result of selective abrasion, separated from the ocean by protruding capes and small islands composed of more abrasion-resistant rocks. Others were formed due to the penetration of the sea into river valleys with small downstream slopes during the Holocene transgression. After a 0.7-m co-seismic subsidence of the island during the Shikotan Earthquake in 1994 (Yeh et al. 1995; Ivashchenko et al. 1996; Kaistrenko et al. 1997), the area around the small river mouth in the southern part of Malaya Tserkovnaya Bay was flooded, forming a narrow and shallow inlet. Its bottom, covered by mud and silted sands, is almost fully exposed during low tide.

Deep closed bays are typical for Shikotan Island on the side facing the South Kuril Strait (Fig. 2). The bays are 2.9–3.5 km in length; their depths at the entrance are 10–16 m, gradually decreasing towards the head. There are narrow beaches along the sides of the bays, composed of coarse deposits. A lot of non-rounded debris falls down onto these beaches from cliffs and slopes. Large tidal flats, exposed during low tides, are typical for the bay heads. The amplitudes of the tides are about 1.1–1.9 m (Atlas of the Kuril Islands 2009). The extent of the tidal flats increased drastically after the co-seismic subsidence of the island during the 1994 Shikotan Earthquake. During high tides, large areas of peat-bogs lie below the sea level. Flooded peat in Otradnaya Bay stretches for 300 m. Underwater valleys with steep slopes, cut in loose deposits, are easily seen on tidal flats and in shallow zones near river mouths. The bottoms of the bays are covered by silty sand and mud.

One of the factors for the active development of swamps within the coastal lowlands and river valleys was the tectonic subsidence of the Lesser Kuril Islands in the Holocene, which continues to the present (Razzhigaeva et al. 2008b). The largest swamps are located on the coast of Krabovaya Bay. Thick Holocene marine and lagoon muds are buried beneath layers of peat.

Since the Tohoku tsunami took place in March 2011, it is important to provide data on the ice climatology of the South Kuril region (Atlas of the Kuril Islands 2009). Drifting ice in the straits appears in January, with ice cover reaching its peak in March, when there is heavy consolidated ice in the straits. Ice is also formed locally in shallow waters; open and semi-open bays do not freeze, but sometimes have drifting ice. Closed bays get frozen and the ice sheet breaks in late March–early April. Before the 2011 Tohoku tsunami, Krabovaya and Otradnaya bays were covered by thick ice. Zorkaya Bay on Tanfiliev Island and the strait between Lesser Kuril Ridge and Hokkaido Island were also covered by ice. According to witness reports, the tsunami broke the ice, carrying it out to the strait and back again, and finally depositing it on the shore. The ice blocks were up to 2 m thick.

The last large tsunami in the region of the South Kuril Islands occurred during the 1994 Shikotan Earthquake (Ivashchenko et al. 1996). High run-up heights (5–7 m) were measured on the Pacific side of Shikotan Island; maximum heights (up to 15 m) were in Tserkovnaya Bay. In the heads of closed bays of the South Kuril Strait, the maximum heights were 2.3–2.6 m (Kaistrenko et al. 1997). Deposits from this tsunami were found on top of the Holocene peats on the Pacific side of Shikotan Island (Razzhigaeva et al. 2007).

3. Materials and Methods

The research was based on the data of the 2011 Tohoku tsunami deposit, which was sampled from ice floes right after the tsunami and then half a year later—in August–September 2011, when the coasts were inspected to establish the tsunami run-up heights and inundation distances. Sampling was done along shore-perpendicular transects, using a description of tsunami traces, erosion zones, and identification of the inundation limit zone. Since in most cases the deposits were homogeneous (massive) and thin, one bulk sample was taken for each point. In stratified sections the samples were taken in each layer, depending on material size.

In August–September 2012, another inspection of the shore took place, aiming to find out how well the

deposits of the 2011 Tohoku tsunami were preserved 1.5 years after the event. The work was done on Shikotan Island on the shores of the closed bays of Krabovaya, Otradnaya and Malaya Tserkovnaya, and on Tanfiliev Island in Zorkaya Bay. At some locations, the Tohoku tsunami deposits were re-sampled and analyzed to determine whether their composition had changed. Peats were drilled along the profiles in Otradnaya and Krabovaya bays in order to study similar events of the past (Fig. 2). Inter-layers of mud, silty sands, and inclosed peat were also sampled.

Grain-size analysis of mud was made using an "Analysette 22" sedimentograph. Silty sand grain-size composition was studied using sieves with γ step. Large plant detritus was removed through a 1.6-mm sieve. Grain-size statistics were calculated using the logarithmic methods (phi) of moments of GRADISTAT v.4.0 software (BLOTT and PYE 2001). New data were obtained for Tohoku tsunami deposits at Malaya Tserkovnaya Bay and Zorkaya Bay, and for the paleotsunami muds of Krabovaya Bay and Otradnaya Bay.

Micropaleontological research included diatom and foraminifera analysis. Diatom analysis was made according to the standard techniques (THE DIATOMS OF THE USSR 1974) with a light microscope "Axioskop-Karl-Zeiss" at 1,200× magnification. The taxonomic composition of diatoms and their ecological characteristics were identified following KRAMER and LANGE-BERTALOT (1988) (THE DIATOMS OF THE USSR 1974, 1992). The percentage content was calculated from the total taxa.

Foraminifera that were studied after the deposits were washed through a 0.063-mm sieve under a binocular microscope. The following references were used to identify the ecology of the species (FORAMINIFERA OF FAR EASTERN SEAS OF THE USSR 1979; PREOBRAZHENSKAYA and TROITSKAYA 1996; SEN GUPTA 2002).

A full list of diatom species of the Tohoku tsunami sheets and benthic foraminifera from the tsunami deposits off the ice is given in (RAZJIGAEVA et al. 2013). New foraminifera data were obtained for the tsunami deposits of Shikotan Island and Tanfiliev Island. In an earlier article (RAZJIGAEVA et al. 2013) the data were given only for foraminifera from the Tohoku tsunami deposits sampled from the ice. New diatoms data were obtained for the Tohoku tsunami deposits of Zorkaya Bay and in the paleotsunami deposits of the Otradnaya Bay and Krabovaya Bay coasts.

Age assignments to the paleotsunami are based on radiocarbon dating and tephra stratigraphy. ^{14}C-dating of the samples was obtained on peat (5 cm thick), lying below tsunami deposits. The samples were treated with standard acid and alkali solutions. ^{14}C-dates were produced by liquid scintillation counting at St. Petersburg State University. The ^{14}C-dates were calibrated into calendar ages using CalPal software (www.calpal.de). Identification of the tephra was based on mineral components and glass composition. Volcanic glass was analyzed chemically using a CAMSCAN-4 electron microscope with an AN-10000 semiconductor spectrometer (from the Khlopin Radium Institute, St. Petersburg).

4. Specifics of Tsunami Sedimentation Within Closed Bays

The Tohoku tsunami on the Kuril Islands was seen as a fast sea-level uplift, and up to 3 waves were observed (KAISTRENKO et al. 2013). In spite of the small scale of the Tohoku tsunami in this region, the tsunami led to the accumulation of deposits of different compositions on the coasts of the Lesser Kuril Islands (RAZJIGAEVA et al. 2013). Only spots of sand and cobble were found on the shores of open bays; maximum tsunami run-up heights were marked by marine and anthropogenic waste, wood, grass, and algae heaps. Well-identifiable sediment sheets, presented as organogenic mud, were formed on the coasts of closed bays of Shikotan Island. Thick ice covered these bays before the tsunami. The presence of ice fragments in the water aggravated the eroding capacity of the waves. The material ripped off by the ice fragments was a source of mud deposits, accumulated in Krabovaya and Otradnaya bays (Fig. 3). The ice floes enhanced the bottom erosion on shoals and the destruction of peatland over low-lying coasts, even at modest ranges of run-up heights. Active erosion was found to occur on the peatlands, submerged below sea level or in the high tidal zone.
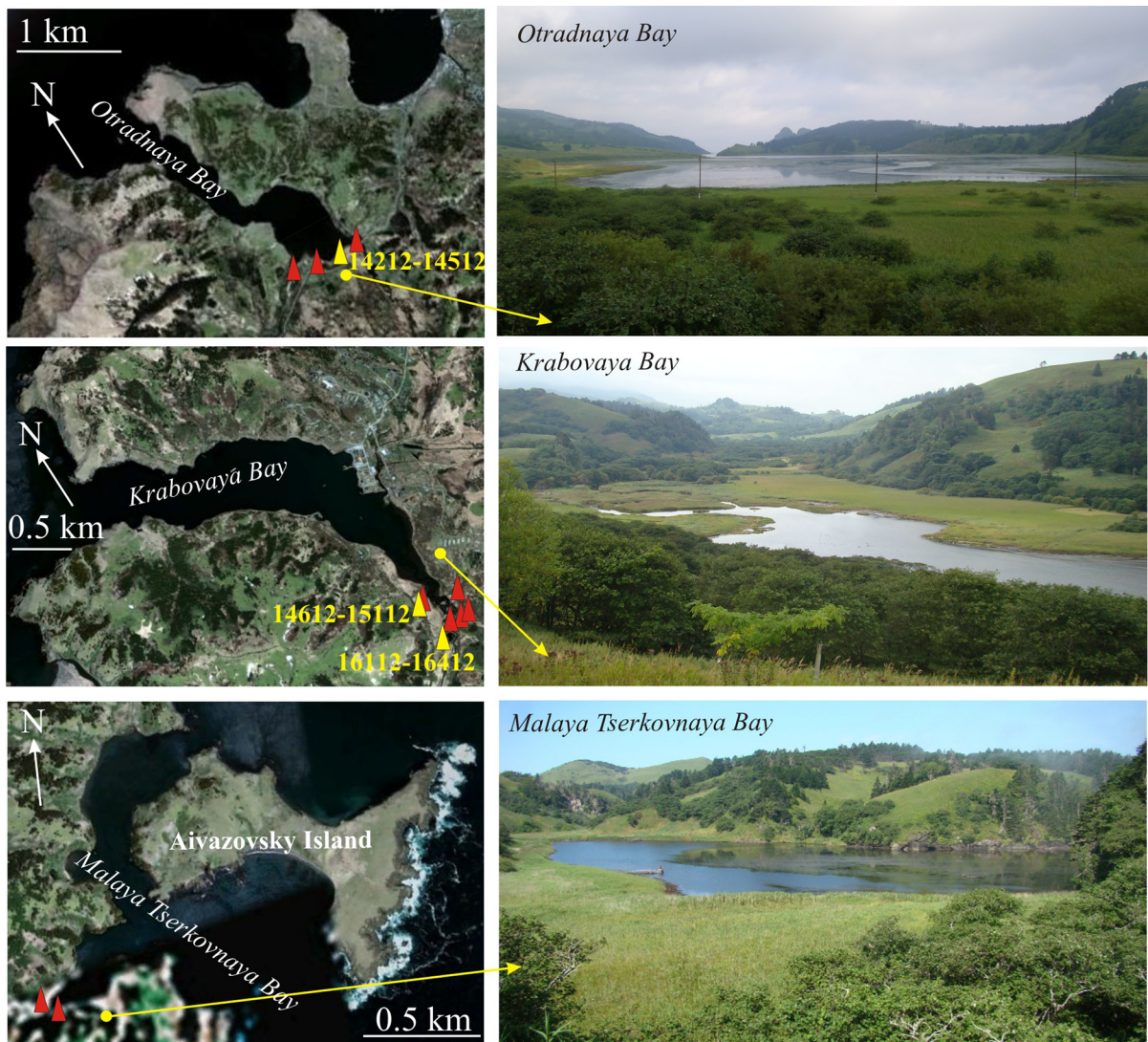
Figure 2
Location of transects on the coasts of three closed bays on Shikotan Island where the 2011 Tohoku tsunami traces and deposits were studied (*red triangles* the profiles and points) and where paleotsunami deposits were found (*yellow triangles* the profiles). Photo of Otradnaya Bay taken from the head of the bay, photo of Krabovaya Bay from the *right side*, and photo of Malaya Tserkovnaya Bay from the *right side*. *Yellow arrows* show the position of the photographer

The peat bogs were eroded within local areas to a depth of 60 cm and their underlying silts became exposed. At the heads of the bays the tsunami also captured material from the steep sides of the flooded river valleys, cutting into the mud. In Krabovaya Bay, with narrow beaches composed of coarse-grained material, only spots of sands were found. In Otradnaya Bay, the tsunami manifestation was weaker, the ice was broken only at the head of the bay near the shore, and the tsunami flooded only local areas—far along the river valley and a "tongue" at the head of the bay (Fig. 3a).

Fine silt and clay material were deposited from suspension on the surfaces of ice, peat, and soil. Grain-size characteristics of the deposits were traced along the transects; the mode is uniform, and the proportion of other fractions is redistributed without a distinct pattern. A weakly expressed second mode appears on some curves, which may indicate a greater contribution from another source of material (Fig. 4).

Figure 3

Photos of the coasts **a**, **b** Otradnaya, and **c**, **d** Krabovaya bays on Shikotan Island after the 2011 Tohoku tsunami. The inundation limits are clearly visible. Heavy ice broken by tsunami waves and mud was deposted on the surface of the peatlands. The sea water deposited *dark grey* mud over the snow near the shoreline. In the area of Otradnaya Bay, tsunami run-up heights were insignificant; the tsunami broke thick ice only near the coast of the bay. The maximum inundated area occurred in the southwestern part of the bay. In the head of Krabovaya Bay, the tsunami brought heavy ice into the peatland and river mouth

Sometimes the share of coarser silt or fine sand grows and produces bimodal curves, and sometimes the amount of clay fractions grows in proximity to the water line. Most likely, it is associated with the matter transported by ice, which made the pattern of suspension settling more complex. A mode of 20–30 μm is well-defined in tsunami mud from various bays that suggests a consistency in the settling. Grain-size distributions are unimodal or bimodal, poorly and very poorly sorted (Fig. 5a). The distributions vary between finely skewed and symmetric (skewness from 0.05 to 0.58), to rare and very finely skewed (to 2.30). All distributions are mesokurtis (kurtosis from 2.54 to 3.02).

A pronounced cover of silty sands was formed in the southern part of the Pacific shore of Malaya Tserkovnaya Bay. The wave inundated up to 78 m inland and the sediment cover reached 65 m inland. The cover thickness grows 10–35 m inland, reaching a maximum depth (up to 14 cm) in small depressions. Farther inland, the thickness of the deposits drops sharply (0.5–1.0 cm). The deposition of silty sands was probably related to the lengthy water presence and sedimentation of material from both the bottom layer and suspension, when the wave had reached maximum inundation and lost its energy. The presence of stratified sections in tsunami deposits in Malaya Tserkovnaya Bay indicates that there were several waves. Grain-size characteristics of the deposits are consistent along transects: the share of silt grows moving inland along the transects, while the size of modal fractions changes very little; the average size of the grains barely changes (Fig. 6).

Shikotan tsunami (1994) deposits were found in this bay (RAZZHIGAEVA *et al.* 2012). These deposits have coarser fractions than the Tohoku tsunami deposits; they have polymodal grain-size curves, probably due to the fact that the tsunami in 1994 was
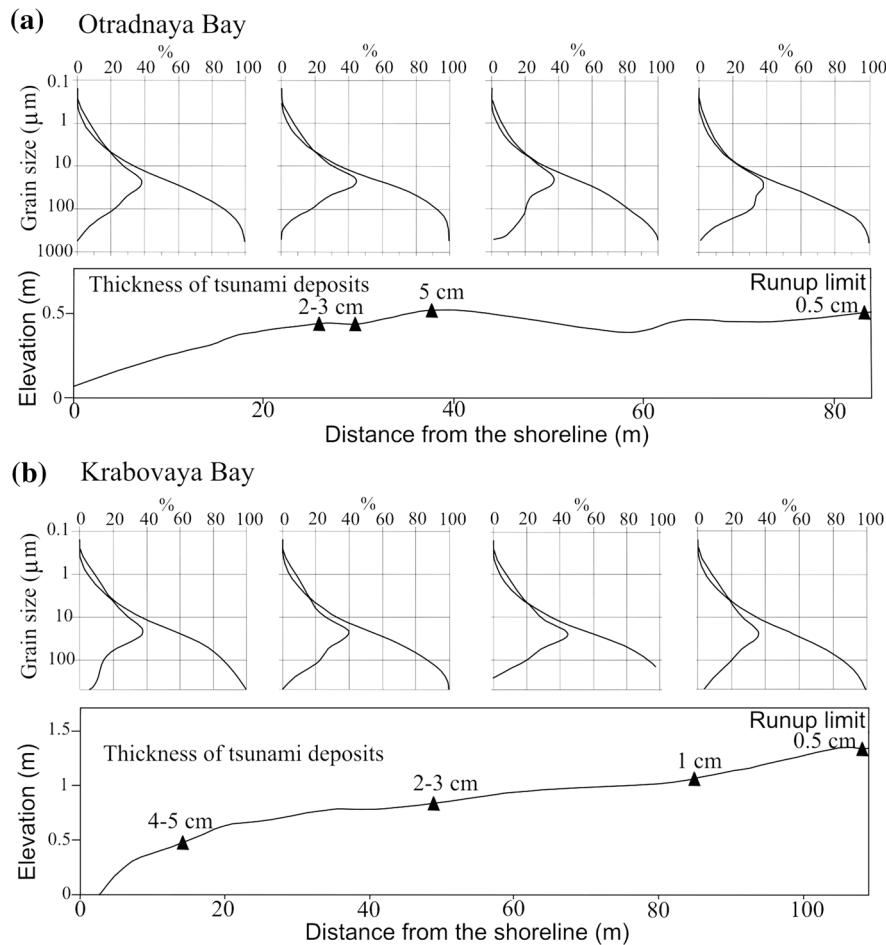
(a) Otradnaya Bay

(b) Krabovaya Bay

Figure 4

Landward changes in the grain-size distributions of the 2011 Tohoku tsunami deposits in **a** Otradnaya and **b** Krabovaya bays. The presented *curves* are composed from samples collected in the head of Otradnaya Bay (transect 21911) and on *left side* of Krabovaya Bay (transect 20111). *Black triangles* indicate sampling points

stronger, and therefore caused greater erosion with material supplied from a large area and different sources.

Diatom algae in the 2011 Tohoku tsunami deposits were presented by a mixture of marine and freshwater species with different ecologies. In total, 135 marine diatoms were found. Sub-littoral benthic forms prevail, which signals the inshore movement of the material from offshore. The presence of large frustules (up to 30 μm) of such species as *Cocconeis scutellum, Odontella aurita*, and the frequent occurrence of diatom colonies indicate the weak turbulence of the water flow. It is possible that the presence of diatoms in colonies provoked the mass deposition of frustules. Marine benthic species dominate in

stratified deposits of the coarser layers, while fine-grained layers contain increased amounts of plankton species. The composition of the freshwater diatoms depends on the type of terrestrial deposits engaged by the tsunami. As a rule, species from different environments are presented, reflecting the mixture of materials from different sources. The composition of the freshwater diatoms in tsunami deposits can be distinguished from freshwater diatoms of underlying peat, where dominating species are those typical of swamps; various representatives from *Eunotia* genera are noted.

Ten different species of benthic foraminifera inhabiting the littoral and sub-littoral zone of Krabovaya and Otradnaya bays (PREOBRAZHENSKAYA and
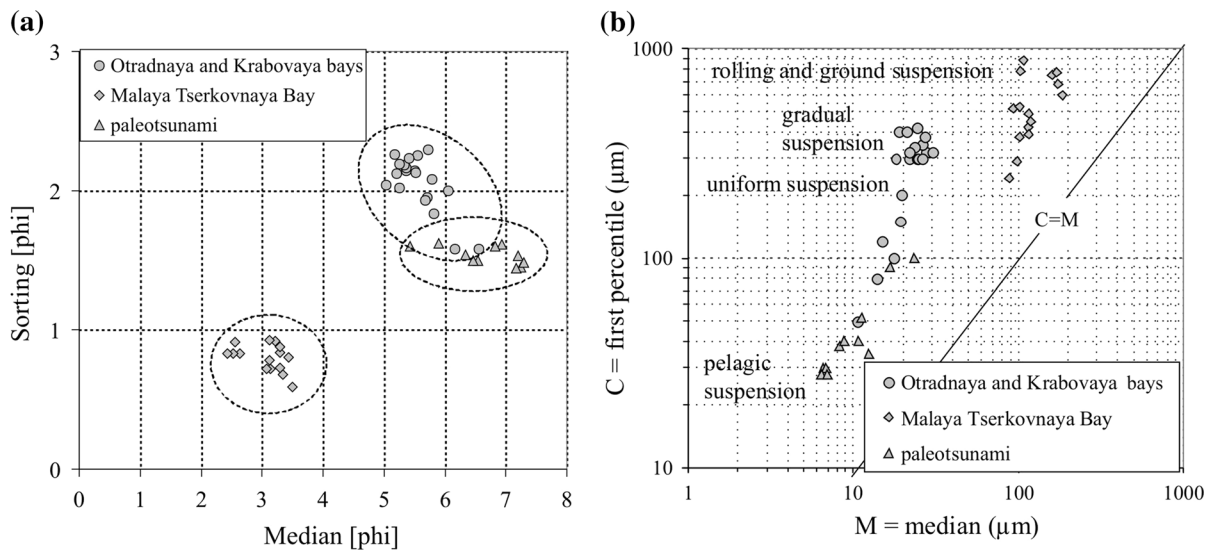
Figure 5
Position of the 2011 Tohoku tsunami deposits on the coasts of closed bays of Shikotan Island (Otradnaya, Krabovaya, Malaya Tserkovnaya bays) and paleotsunami mud in Krabovaya Bay (core 14912) and Otradnaya Bay (core 14512): **a** diagram of sorting and median; **b** Passega C-M diagram
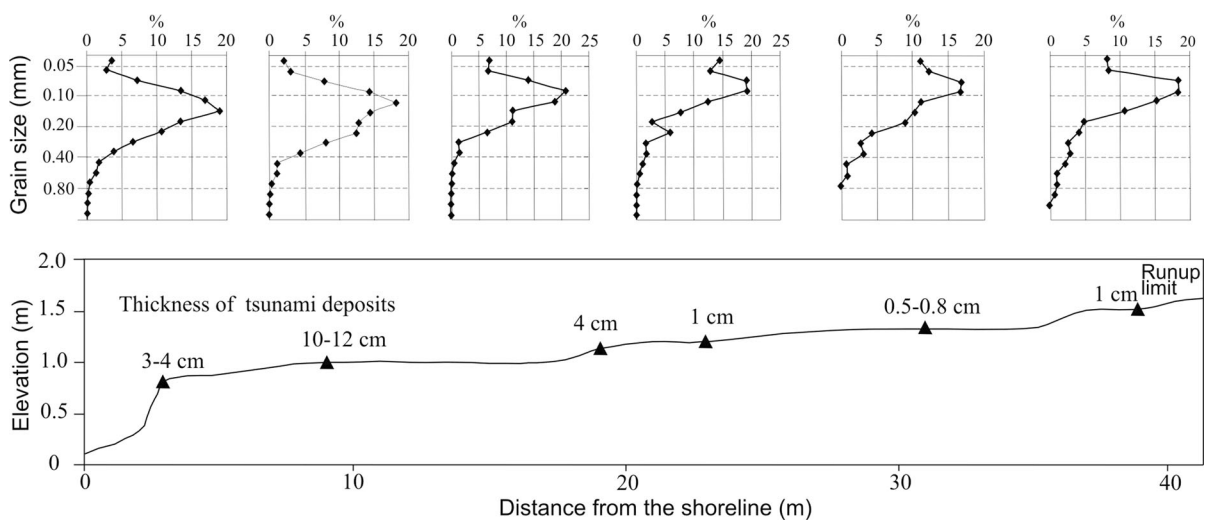

Figure 6
Landward changes in the grain-size distributions of the 2011 Tohoku tsunami deposits for the coast of Malaya Tserkovnaya Bay (the samples were taken in 2012). *Black triangles* indicate sampling points

Troitskaya 1996) were found in the tsunami deposits from the ice. *Jadammina macrescens* is dominant. Occasional agglutinating forms of *Trochammina* (*Trochammina japonica, Tr. inflate, Tr. pacifica, Tr. vinogradovi*) and *Miliammina fusca* were noted. Among the secretion species are *Cribroelphidium asterineum, Cr. etigoense*, and representatives of *Buccella* genus. All tests are well-preserved.

In the tsunami mud sheets, a high abundance (fossil concentration 12–27 individuals per 1 g of dry deposit) of benthic foraminifera was found within Krabovaya Bay in the tsunami deposits near the shoreline, where *Jadammina macrescens* prevails. This species is an inhabitant of the littoral zone of this bay (Preobrazhenskaya and Troitskaya 1996). Littoral *Miliammina fusca,* widespread in the intertidal

zone (0.5–5 m deep), *Labrospira jeffreysi*, and *Trochammina inflate,* usually living at depths of 5–10 m (FORAMINIFERA OF FAR EASTERN SEAS OF THE USSR 1979), were found in small numbers. The fossil concentration decreased inland (one individual per 1 g of dry deposit).

In Otradnaya Bay, where the tsunami was weak (KAISTRENKO *et al.* 2013), the tsunami mud included low concentrations of foraminifera (less than two individuals per 1 g of dry deposit) such as *Jadammina macrescens, Labrospira jeffreysi, Miliammina fusca,* and *Trochammina* sp., except for mud with abundant *Zostera,* located 26 m from the shoreline, where concentrations of foraminifera reached up to 64 individuals per 1 g of dry deposit. In one sample rare, *Proteonella* sp., and *Rhabdammina* sp. of poor preservation were found. Species of these genera have a wide habitat, from the subtidal zone to the deep sea, and the maximum number usually lives within depths of 70–120 m (FORAMINIFERA OF FAR EASTERN SEAS OF THE USSR 1979). Perhaps the tsunami waves brought these samples from the bottom of the bay.

On the Pacific side of the island (Malaya Tserkovnaya Bay) tsunami deposits had low concentrations of benthic foraminifera (1–3 individuals per 1 g of dry deposit). Rare tests of *Miliammina fusca* were found in the tsunami deposits. The presence of *Labrospira jeffreysi,* living at depths of 5–10 m, and *Eggerella scrippsi* of 15–50 m (FORAMINIFERA OF FAR EASTERN SEAS OF THE USSR 1979) demonstrates the input of material from deeper areas. There were also brown samples of *Trochammina inflate,* redeposited from Holocene marine sediments on the bottom of the bay.

A second study of the tsunami traces, undertaken in 2012, allowed us to evaluate the quality of the preservation of the material. Tsunami deposits on the top of the peat are moist, the redeposition of eolian transfer or washaway does not take place. The deposits are actively colonized by grasses. Technogenic (man-made) constructions, which are free of any tsunami deposits, are the exception. Grain-size analysis of tsunami deposits sampled in 2012 on the coasts of Otradnaya, Krabovaya, and Malaya Tserkovnaya bays shows the composition little changed and similar to the data of 2011. A re-examination of diatoms gave the same result.

In 2012, tsunami deposits were found on the coast of the semi-closed Zorkaya Bay (Tanfiliev Island), where the run-up heights reached 2 m. Before the tsunami, the bay and the strait between Tanfiliev and Hokkaido were covered with ice. The tsunami broke the ice, then the ice was drawn out of the bay into the strait, and finally it was brought back by the tsunami and deposited on the shore. The sedimentological situation was similar to that of open bays. Only small patches of well-sorted, fine sand (up to 4 cm thick) were found (Fig. 7a, b). Grain-size distribution curves are mainly unimodal (modes 0.125–0.16, or 0.2–0.25 mm), moderately well-sorted (σ 0.58–0.67), and symmetric (skewness 0.08–0.10). The main source of the deposits was the beach. Beach sand has almost the same distributions, but is better sorted (σ 0.44–0.49) than the tsunami deposits. In the center of bay behind the storm ridge, the tsunami deposit has a polymodal curve with peaks 0.2–0.25, 0.315–0.4, and 0.5–0.63 mm; the sand is moderately sorted (σ 0.76) and the distribution is symmetric and mesokurtic (Fig. 7c, d). At this place, fine sand from the beach, and medium sand with coarser fractions from the storm ridge were redeposited. The storm ridge sand is moderately sorted (σ 0.81), and has a coarsely skewed distribution.

In the sands of the tsunami in the eastern part of the bay, 36 species of marine and brackish diatoms (up to 58.7 %) were found. The largest content of diatoms was found under a large car tire, which protected the deposits from the rains. Diatoms in the sediment at the top of the bay were rare. In all samples, the majority of the diatom frustules were broken, especially with the larger frustules, which may be due to breakup by ice. Sublittoral benthic species prevail: *Cocconeis scutellum* (14.5 %), *C. costata* (9.6 %), *C. stauroneiformis* (2.6 %), and *Grammatophora hamulifera* (2.6 %); *Navicula directa, Amphora marina, Anaulus maritimus, Arachnoidiscus ehrenbergii, Cocconeis californica, C. decipiens, C. verrucosa, C. scutellum* var. *parva, Cyclotella striata, Grammatophora angulosa, Lyrella pigmaea, L. forcipata, Istmia nervosa, Tabularia tabulate,* and *Achnanthes brevipes* var. *intermedia* were present too. Among plankton species, *Paralia sulcata* (6.1 %) is dominant, and *Hyalodiscus scoticus, H. obsoletus, Trachyneis aspera, Odontella*
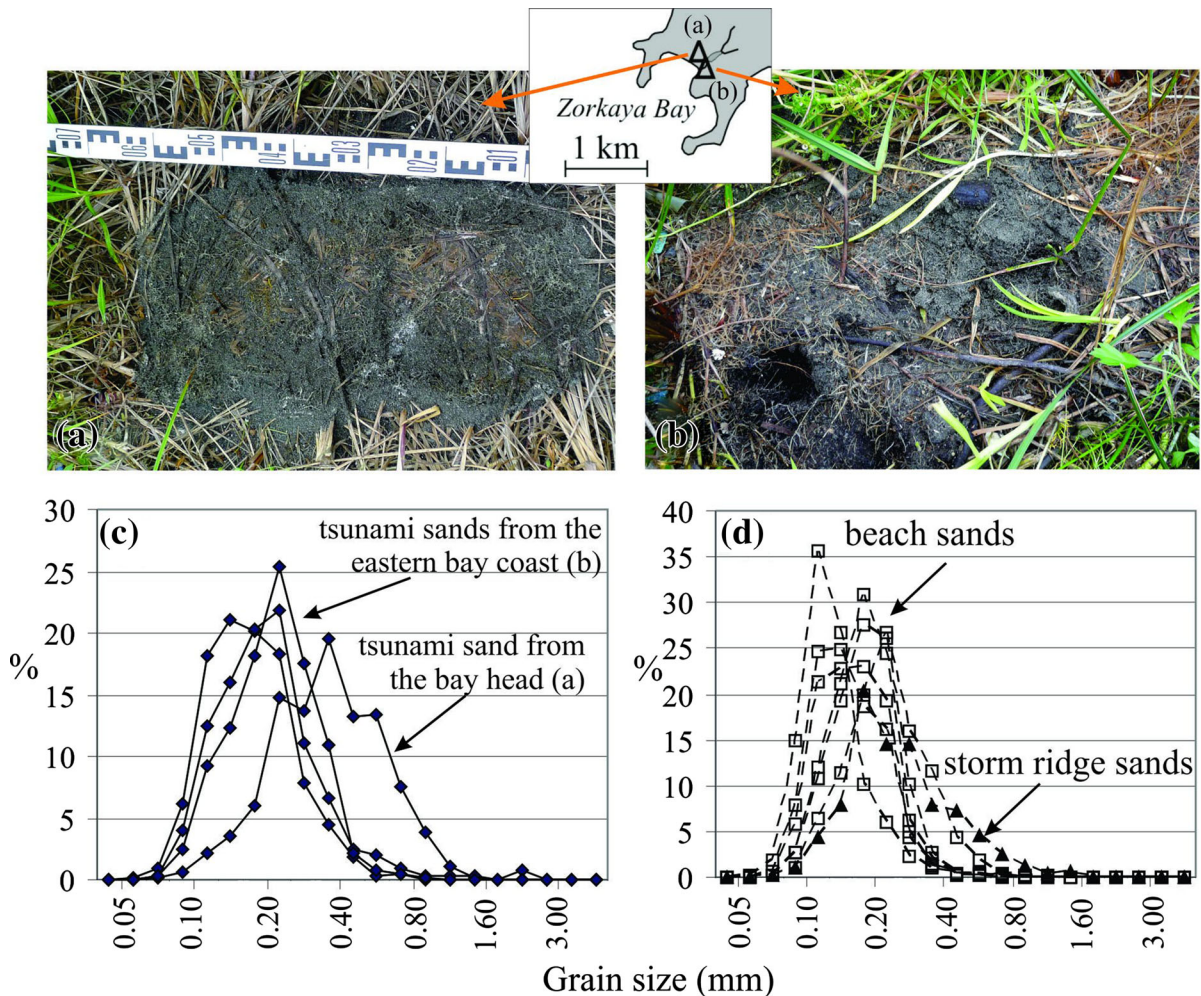
Figure 7

2011 Tohoku tsunami deposits on the coast of Zorkaya Bay, Tanfiliev Island. Patches of well-sorted, fine sand: **a** under a buoy at the head of the bay, distance from shoreline 21 m, height 2.2 m, thickness of deposits 2–2.5 cm; **b** under a big car tire, eastern coast, distance from shoreline 25 m, height 1.4 m, thickness of deposits 4 cm. The grain size of the deposits: **c** Tohoku tsunami sands from the eastern part of the bay and the head of the bay; **d** beach sands (*squares*), and storm ridge sand (*triangles*)

aurita, Actinoptychus senarius, and *Navicula dithmarsica* were found. Neritic and oceanic species are represented by northboreal and arctoboreal *Thalassiosira eccentrica, T. gravida, T. kryophila, T. hyalina, T. decipiens, Thalassiothrix longissima, Coscinodiscus oculus-iridis, Bacterosira fragilis,* and southboreal *Thalassionema nitzschioides, Coscinodiscus asteromphalus,* and *Thalassiosira leptopus.*

Freshwater diatoms include species living in different terrestrial environments. Species typical for weak moisture and weak swamping surfaces dominate: *Pinnularia lagerstedtii* (17.9 %), *P. intermedia* (1.8 %), *Luticola mutica* (up to 8.8 %), *L. ventricosa* (2.1 %), *Diadesmis contenta* (7.5 %), and *Hantzschia amphioxys* (up to 7.7 %). Species typical for shallow lakes, polls, and little streams were also met: *Achnanthidium minutissimum* (5.1 %), *Navicula perminuta* (8.1 %), *Encyonema silesiacum* (1.3 %), *Nitzschia paleaceae* (2.6 %), *Staurosira venter, Pseudostaurosira brevistriata, Rhoicosphenia abbreviata, Cocconeis placentula,* and plankton *Aulacoseira italica, A. alpigena.* Wetland species *Eunotia bilunaris, E. crista-galli,* and *E. praerupta* are present too.

Only one sample of benthic foraminifera—*Globobulimina* sp. was found in the tsunami sand. A

small (1.5 mm), well-preserved shell from the Gastropoda class was also found in one sample.

5. Tsunami Sedimentation of the Periphery Zone in Comparison to the Near-Field Area

For a better understanding of the peculiarities of sedimentation on the 2011 Tohoku tsunami periphery, we tried to compare the data acquired from the Lesser Kuril Islands with those in the near-field zone of maximum run-up heights on the Sendai Plain (northeastern coast of Honshu Island), located in close proximity to the source of the 11 March 2011 earthquake (ABE *et al.* 2012; JAGODZIŃSKI *et al.* 2012; PILARCZYK *et al.* 2012; RICHMOND *et al.* 2012; SZCZUCINSKI *et al.* 2012; TAK-ASHIMIZU *et al.* 2012) on Sabusawa Island at Matsushima Bay—20 km to the northeast from Sendai (GOTO *et al.* 2012), and on the shore of closed Hirota Bay—130 km from the epicenter (NARUSE *et al.* 2012). The maximum run-up height reached 39.7 m in the area of Miyako City, and the inundation distance was up to 5 km (MORI *et al.* 2011).

5.1. Deposit Distribution and Geometry

Usually, when the run-up height is <5 m and erosion is weak, the tsunami does not leave easily identifiable deposits (DAWSON and SHI 2000). On the periphery of the Tohoku tsunami, on the coast of the South Kuril Islands, the deposit cover had been formed only in the heads of closed bays and the narrow-entrance inlets of Shikotan Island, where the tsunami run-up heights were less than 3 m. In the area adjacent to the epicenter of the tsunami on the coast of Honshu Island, the wave inundated several kilometers inland, while on the Lesser Kuril Islands, the inundation distance was usually only a few tens of meters, whereas along the river valleys it was up to 300 m (KAISTRENKO *et al.* 2013). Continuous deposit sheets have been formed only on the shores of closed bays of Shikotan Island, and they are not extended (maximum is 106 m long); in the heads of the bays, the deposits cover the inundation areas completely. One of the factors that controlled erosion and sedimentation in these bays was the presence of ice in the tsunami waves. In Malaya Tserkovnaya Bay,

the sediment sheet was found up to 65 m inland, which corresponds to 83 % of the inundation distance. Small spots of sand and cobble were found on the edge of closed bays and some open bays, where erosion was weak. Such traces of tsunamis in geological sections are difficult to find.

On the coast of Honshu Island, deposits cover almost the entire inundation area of the Sendai Plain, where the tsunami traveled up to 5.5 km inland (ABE *et al.* 2012; JAGODZIŃSKI *et al.* 2012; PILARCZYK *et al.* 2012; RICHMOND *et al.* 2012; SZCZUCINSKI *et al.* 2012; TAKASHIMIZU *et al.* 2012). If the inundation distance on the Sendai Plain had been shorter than 2.5 km, the maximum limit of the tsunami deposit layer (≥ 0.5 cm thick) extended to over 90 % of the inundation distance, and the sand layer reached 57–76 % of the inundation distance where the tsunami inundated more than 2.5 km inland (ABE *et al.* 2012). Salt contamination down to 15 cm and the formation of salt crusts on the soil after the tsunami were observed up to 4 km inland (CHAGUÉ-GOFF *et al.* 2012). After the water receded, the tsunami sands were actively transported by wind, and 2 months later, the tsunami deposits were covered by eolian sands up to 15–20 cm thick (RICHMOND *et al.* 2012). On the swampy coasts of the Lesser Kuril's closed bays, the Tohoku tsunami deposits are wet, and as a rule, dense sheets were not redeposited.

5.2. Erosion, Basal Contact, and Deposit Thickness

The erosion in the periphery zone of the 2011 Tohoku tsunami was, in general, weak, and its intensity cannot be even remotely compared with the erosion caused by the tsunami on the coasts of Honshu Island. In the closed bays of Shikotan Island, where the tsunami broke the ice, the presence of ice in the water increased the eroding capacity of the waves. The bottoms of shallow bays and coastal peatlands were eroded and large pieces of peat were found in the inundation zones. The most active erosion was observed at the head of Krabovaya Bay where two eroded zones were found (up to 100 m wide) and the soil cover and peat were destroyed (0.6 m thick). The basal contact of the tsunami deposits was sharp; there was no erosion and the deposits lay on the previous year's grass (Fig. 8). The basal contact is clearly visible 1.5 years after the

tsunami. The grass and algae are preserved. In the authors' opinion, this is different from deposits in the near-field area close to the tsunami source, i.e., the zones of maximum run-up. On Honshu Island, where the tsunami caused strong erosion, the basal contact of the tsunami deposits on different underlying deposits is sharp (ABE *et al*. 2012; GOTO *et al*. 2012; SZCZUCINSKI *et al*. 2012; TAKASHIMIZU *et al*. 2012).

The thickness of the tsunami deposits strongly depends on the intensity of the erosion processes and the presence of sources of friable material in the coastal zone, and on the relief of the underlying surface. The thickness of the tsunami sheets on Shikotan Island was no more than 5 cm due to the absence of wide, sandy beaches and the deficit of material in the coastal area.

The thickest sheet (up to 14 cm) was found in Malaya Tserkovnaya Bay with a wide tidal flat. This thickness decreases in the inland direction and depends on local topography. In general, the thickness of the tsunami sediment sheets on the periphery is much smaller than in the near-field zone close to the tsunami source area. The thickness of deposits of the 2011 Tohoku tsunami on Sendai Plain on the northeastern coast of Honshu Island is approximately 25–35 cm and, in some places, as much as 50 cm, depending on the proximity of the material source and the relief of the underlying surface (ABE *et al*. 2012; JAGODZIŃSKI *et al*. 2012; SZCZUCINSKI *et al*. 2012; TAKASHIMIZU *et al*. 2012). On Sabusawa Island, the deposit sheet is up to 80 cm thick (GOTO *et al*. 2012).

Figure 8
Tohoku tsunami deposits on Shikotan Island. **a**, **b** The tsunami deposits, Malaya Tserkovnaya Bay (photo 2011), **c**, **d** the tsunami deposits, Malaya Tserkovnaya Bay (photo 2012), **e** the tsunami deposits, Krabovaya Bay (photo 2011)

5.3. Sedimentary Structures and Vertical Variation

As a rule, tsunami deposits on Shikotan Island have a substantial thickness. Sand with mud cups was found on the shore of semi-closed Snezhkov Bay. Stratified deposits were found at only one point on the coast of Malaya Tserkovnaya Bay, where the section had 2–3 distinguishable layers, at the base of which more coarse layers were discovered (up to 1 cm thick) (Fig. 8b). Such deposits indicate that there were 2–3 significant tsunami waves, and that the coarsely-graded material was the first to settle. Eyewitnesses of the event on Shikotan Island observed three tsunami waves, the second and third waves being significantly higher (KAISTRENKO et al. 2013). The coarse layers have fewer marine diatom species, and sub-littoral benthic diatoms prevail. The fine deposits have a greater concentration (up to 62 %) and diversity (up to 36 species) of marine species; the number of plankton forms also increases and oceanic diatoms appear. The same pattern was observed in the deposits of the 2004 Indian Ocean tsunami in Thailand (SAWAI et al. 2009).

Unlike in the periphery regions, the deposits of the Tohoku tsunami on Sendai Plain in Honshu Island are often well-stratified horizontally, though massive sands can also be found. Deposits on most of this territory were probably brought in by the first major wave; the incoming flow deposits prevail, while deposits of the return flow were found only locally (ABE et al. 2012; TAKASHIMIZU et al. 2012). In the upper portion of the tsunami deposits, a higher concentration of diatoms was recorded (SZCZUCINSKI et al. 2012). There were four units of normal and reversed grading found on the coast of Hirota Bay; this finding is an indicator of several tsunami waves affecting this area and settling the material from incoming and return flows (NARUSE et al. 2012).

5.4. Grain-Size Distribution Transportation and Deposition of the Material

The grain-size composition of the Tohoku deposits on the Lesser Kuril Ridge is considerably diverse—from boulders and pebbles on the open bay coasts to mud in the heads of the closed bays. The extended sheets are composed of mud with a prevalence of silt (up to 61.6 %) and contain high concentrations of grains smaller than 10 μm (up to 41.5 %). The deposits are poorly sorted; the grain-size distribution curves are unimodal (mode is 20–30 μm) with a weakly expressed second mode in some cases. The deposits with bimodal curves were found on the coasts where more sandy fractions were brought in during the coast wash-out. The grain-size distribution curves are symmetric and asymmetric—finely skewed due to different proportions of clay fractions. There are no considerable changes in the grain-size composition of mud deposits along the transects. In the area of Malaya Tserkovnaya Bay, where the 2011 tsunami deposited silty sand, inland fining was observed. On the Passega C-M diagram (Fig. 5b), the samples of tsunami mud taken from this closed bay on Shikotan Island form a field of finer material than the Tohoku mud on Sendai Plain (SZCZUCINSKI et al. 2012).

Unlike the situation on the periphery, the tsunami deposits of Sendai Plain get finer and their differentiation becomes clearer inland (CHAGUÈ-GOFF et al. 2012; JAGODZIŃSKI et al. 2012; SZCZUCINSKI et al. 2012; TAKASHIMIZU et al. 2012). The coarse material, as well as poorly and moderately sorted sands, turn into medium-grained sands, and then into sand with a mud cap; then 2-2.3 km from the shore, mud begins to prevail and the deposits become poorly sorted (SZCZUCINSKI et al. 2012). In the Arahama area, located to the north of the Natori River, a layer of mud (up to 4 cm) covering the sand appears in depressions between beach ridges, the mud having settled from stagnant water (TAKASHIMIZU et al. 2012). On Sabusawa Island, among the sand left by the tsunami, cobbles and pebbles have been found, together with numerous mollusk shells and their fragments; the mud caps were found only on the eroded areas of rice fields (GOTO et al. 2012). On the northeast coast of Honshu Island where the tsunami eroded the landward surface of sand dunes, the composition of deposits is close to that of dune sands and the grain size of the deposits decreases inland (NAKAMURA et al. 2012).

5.5. Insights from Diatom Analysis

Rich diatom complexes, represented by the mixture of marine and freshwater species of different

ecologies, were found in deposits of the 2011 Tohoku tsunami in closed bays of Shikotan Island and Zorkaya Bay, Tanfiliev Island. Unlike tsunami deposits on Honshu Island (Sendai Plain), where diatom frustules were broken (SZCZUCINSKI *et al.* 2012), the diatom frustules in tsunami deposits on Shikotan Island are well-preserved. Large frustules of sub-littoral benthic species are common; some of the diatom colonies that were found indicate a weak turbulence of the flow and a small transfer distance. Diatoms with small frustules also settled in colonies. On Tanfiliev Island, most of the frustules of marine and brackish diatoms in the tsunami deposits were broken, possibly by ice with sand. The high content (up to 88.3 %) and the diversity of marine diatoms is typical for the deposits. Sub-littoral benthic. as well as sub-littoral plankton species are dominant, and different oceanic and neritic diatoms, typical for different marine water types (from subtropical to Arctic) have also been identified. Freshwater species typical for different environments, such as lakes, rivers, flood-plain lakes, wetlands, swamps, and soils, are present in various proportions.

On Honshu Island, there are no typical marine diatoms in the transect along the Sendai airport (SZCZUCINSKI *et al.* 2012). The content of marine and brackish species in the deposits is <20 %; in general they can be found in the sand cover closer to the sea. Generally, the number of diatoms increases inland. In the mud zone, only freshwater and brackish-water species were found, and their composition was similar to the diatom composition of soils. No more than 2 % of marine diatoms were found in the Arahama area, and their number drops noticeably inland (TAKASHIMIZU *et al.* 2012). The composition of freshwater diatoms is similar to the composition of rice field soils. A lot of plankton species were carried out by the tsunami from the Teizan-bori Canal and Minami Naga-numa Pond located between the beach ridges; the transfer of plankton diatoms occurred over small distances.

5.6. Insights from Foraminifera Analysis

The 2011 Tohoku tsunami deposits of closed bays on Shikotan Island have a small number of benthic foraminifera tests. Only sub-littoral species were found

in the Shikotan Island samples collected immediately after the tsunami from the ice surface; these species are extant and widespread in both tidal and littoral zones of the Lesser Kuril Islands (PREOBRAZHENSKAYA and TROITSKAYA 1996). Good shell preservation indicates a short transfer distance and weak turbulence. Sub-littoral benthic foraminifera also prevail in the tsunami mud sheets. The presence of these species, which inhabit both the littoral and sub-littoral zones (5–10 and 15–50 m deep), is evidence that the material seems to have been transported from the seafloor of the bay. Small amounts of re-deposited species were found in deposits on Shikotan Island. This is also related to the poor preservation of foraminifera in the Holocene marine deposits in the South Kuril Islands, where the carbon material dissolves. In contrast to the Tohoku deposits on the Sendai Plain, fossil species were abundant and were eroded from the marine Miocene and Pliocene deposits, and their amount increased inland (PILARCZYK *et al.* 2012). The species composition of the foraminifera is more diverse in the tsunami deposits on the Sendai Plain. Foraminifera tests in locations with high run-up heights have traces of disintegration, destruction, and balling (PILARCZYK *et al.* 2012).

5.7. Sediment Sources

The 2011 Tohoku deposits on the coasts of the Lesser Kuril Islands are a mixture of materials from different sources in different proportions. The results of grain-size analysis and studies of biofossil composition allow us to provide the qualitative analysis of the material, though it is difficult to identify the input of individual sources to this material. A simpler picture can be observed in the open bays, where the sources of well-sorted sands were the beaches, tidal flats, and nearshore regions. Pebbles and boulders were transferred from beaches and storm ridges. The patterns of deposit formation were more complex in closed bays. Here, the material came from offshore, where both marine and terrestrial deposits were washed out. The erosion took place in the inundation zone, where various types of terrestrial deposits were eroded.

The unimodal grain-size distribution curves show a re-deposition of the material from one source, while

the bimodal curves are typical for those tsunami deposits that have several sources of material. The main source of the mud fractions is the re-deposited marine mud, which is not common for large-scale tsunami deposits, in which the fine fraction usually has a terrestrial origin (RAZZHIGAEVA *et al.* 2006; SAWAI *et al.* 2009; GOTO *et al.* 2011; SZCZUCINSKI *et al.* 2012). The mineral part of the tsunami mud in Otradnaya and Krabovaya bays was brought from the bottom of the bays; the abundant organic deposits indicate that peats were washed from both coastal and submarine areas of the bays.

The fact that the material came from the offshore area is proved by the presence of marine diatoms, among which sub-littoral benthic and plankton species prevail. Neritic and oceanic diatoms, and possibly some of the sub-littoral plankton species, appear to have come in with the marine water, and not because of bottom erosion. Marine diatoms found in debris marking the inundation zone also came with the marine water. The tsunami carried live colonies of diatoms that settled out in the tsunami deposits. The composition of the benthic foraminifera also indicates the contribution of material from the bottom of the bays.

The freshwater diatom complex reflects the supply of material from different terrestrial sources. If diatoms with a similar ecology dominated in the tsunami deposits, then we could assume that a single type of terrestrial deposits had been washed out. If there was a mixture of freshwater diatoms of different ecologies in the deposits, it would mean the active erosion and re-deposition of material from different terrestrial sources. Tsunamis can wash out terrestrial deposits located below the sea level. This is particularly true of the Lesser Kuril Islands, where tectonic subsidence is the main tendency of the Holocene. For example, the composition of freshwater diatoms in the tsunami deposits from Malaya Tserkovnaya Bay indicated the active erosion of river deposits, mainly in the areas near the river mouth flooded by the sea. The composition of freshwater diatoms in Otradnaya and Krabovaya bays proves the re-deposition of the material from various terrestrial sources: peats, soils, alluvial deposits, paleolakes, and ponds of different types. In one instance where freshwater diatoms were the only diatoms in the tsunami deposits—in mud caps on the shore of the semi-closed Snezhkov Bay—their composition proved the re-deposition of the material from the flood-plain lake deposits.

The sources of the material in the closed bays of Shikotan Island on the periphery of the Tohoku tsunami, and in the near-field area on Honshu Island, adjacent to the epicenter, differ considerably. Severe erosion took place in the flooded area of Sendai Plain (ABE *et al.* 2012; CHAGUÈ-GOFF *et al.* 2012; PILARCZYK *et al.* 2012; SZCZUCINSKI *et al.* 2012). Little material came directly from the sea; the main sources of sandy fractions were the beach and dunes. Because of the beach and dune wash off, the tsunami had formed a cover of sand deposits, stretching up to 1 km inland. Starting from 1 to 2 km inland, the input of these sources dropped and the erosion of the local soil and material coming from the Teizan-bori Canal became the main source of the tsunami deposits. Further inland, the main source of mud is soil erosion, especially the erosion of rice paddy fields (SZCZUCINSKI *et al.* 2012; TAKASHIMIZU *et al.* 2012).

6. Application to Paleotsunami Research

Usually for paleotsunami reconstruction, the layers of marine sands are used; they form sheets, stretching inland beyond the storm surf zone (ATWATER 1987; MINOURA and NAKATA 1994; DAWSON and SHI 2000; PINEGINA and BOURGEOIS 2001; MACINNES *et al.* 2009; etc.). Numerous paleotsunami sands were found on the Pacific side of Shikotan Island that allow reconstruction of large events for the last 6,000 years (RAZZHIGAEVA *et al.* 2008a; NISHIMURA *et al.* 2009). During studies of the last large-scale tsunami deposits, mud caps were often found (ABE *et al.* 2012; CHAGUÉ-GOFF *et al.* 2011; GOTO *et al.* 2011; RAZZHIGAEVA *et al.* 2006; RAZJIGAEVA *et al.* 2013; SAWAI *et al.* 2009), but layers of mud in the sections of coastal lowlands are not commonly used as indicators of paleotsunamis. This relates to the difficulty of their identification. It is hard to prove their marine origin; the research on the Sendai Plain showed that the terrestrial facies are often the sources of mud (SZCZUCINSKI *et al.* 2012; TAKASHIMIZU *et al.* 2012).

The studies of the 2011 Tohoku tsunami deposit distribution on the coasts of the Lesser Kuril Islands showed that even during a weak tsunami, considerably large mud sheets are formed on the coasts of closed bays; this mud is not easily destroyed, and gets actively colonized by grass. Consequently, it can be well-preserved in sections. Peat on the coasts of closed bays may contain traces of a moderate tsunami that occurred in historic times and during the Holocene. Studying paleotsunamis on Shikotan Island, we devoted less time to the closed bays located on the coast of South Kuril Strait than to the open bays of the Pacific side (RAZZHIGAEVA et al. 2012).

Within the Tohoku tsunami inundation zone in Krabovaya and Otradnaya Bays, the peatlands were drilled along the profiles from the shoreline inland. Also, peatland located at the head of Krabovaya Bay beyond the zone of maximum Tohoku tsunami inundation was drilled. Up to 7–9 layers of greenish-gray mud (up to 8 cm thick) and muddy sands (up to 20 cm thick) were found (Fig. 9). The thickness of some layers, which we could correlate, decreases inland. Some thick layers of deposits have vertical stratification and include layers rich with sand and mud. All layers have clear basal contacts, which could be traced from the coastline into the land. We believed that these deposits were of paleotsunami origin, and that was confirmed by the diatom data.

Only tsunamis can deposit mud on the peat surface at such a great distance from the shoreline. Strong storms throw only a lot of algae and Zostera, which lie on the surface of the peat a few meters from the shoreline. There are no deposits within the strong-storm surf zone.

The number of mud layers varies among the cores due to the different preservation of layers in the sections. In some cases, paleotsunami deposits can occur in the form of small lenses, and drilling does not always find these lens. As a result, a layer may be found in one core, but in other cores the deposits of this age are absent. Radiocarbon dating of the underlying peat determined the age of some paleotsunamis (350 ± 110 BP, 390 ± 110 cal. yBP, LU-7058; 390 ± 40 BP, 430 ± 70 cal. yBP, LU-7088; 620 ± 100 BP, 620 ± 60 cal. yBP, LU-7059; $1,010 \pm 100$ BP, 940 ± 110 cal. yBP, LU-7089) (Fig. 9).

The peat sections on the coasts of Otradnaya Bay and Krabovaya Bay recorded that strong tsunamis occurred in this region. Deposits of paleotsunamis of similar age were found and were widespread on the coasts of the Lesser Kurils and Eastern Hokkaido (NANAYAMA et al. 2003, 2007; RAZZHIGAEVA et al. 2012).

More detailed paleotsunami records were found in the coastal lowland sections of Krabovaya Bay. The top of the peatbogs do not have deposits of another historical tsunami that occurred in the early 17th century. So, the uniqueness of the Tohoku tsunami situation was caused by the presence of fragments of ice in the water that increased the erosion effect. Small lenses of mud in the top of the peat bog on the left side of Krabovaya Bay (looking from the head of the bay) can possibly be traced to a tsunami in 1994. The 1994 tsunami strongly manifested on the Pacific side of the island, where its deposits were found on the coasts of several bays (RAZZHIGAEVA et al. 2007, 2012).

At the head of Krabovaya Bay, such layers of mud could be traced more than 500 m inland. The base of the cores exposed the lagoon mud formed during the Late Holocene transgression; the top of this unit is approximately one meter higher than the tidal zone. The volcanic ash Ta-c of the Tarumai Volcano (2.4–2.5 ka) from southwestern Hokkaido Island was found in the upper part of the marine unit. The ash was formed by yellow silt (2–4 cm in thickness), and glass chemistry analysis suggests that this ash is derived from Ta-c eruption of volcano. The glass compositions of the ash are medium-K, similar to the Tarumai Volcano tephra (FURUKAWA and NAKAGAWA 2010). The peat, above Ta-c ash, includes eight layers of mud that could be traces of tsunamis that have happened in the last 2,400 years. Paleotsunami inundation distances have been calculated for the Late Holocene transgression, when the sea level was higher than the present, taking into account the position of the ancient coastline deposits.

Usually, volcanic ashes in the Holocene peat bog sections of Shikotan occur as lenses and have small thicknesses; and it is difficult to find them in the drilling cores. We could not find tephra layers in the section of peatland located in more dynamic environments on the eastern and western sides of Krabovaya Bay and at the head of Otradnaya Bay.
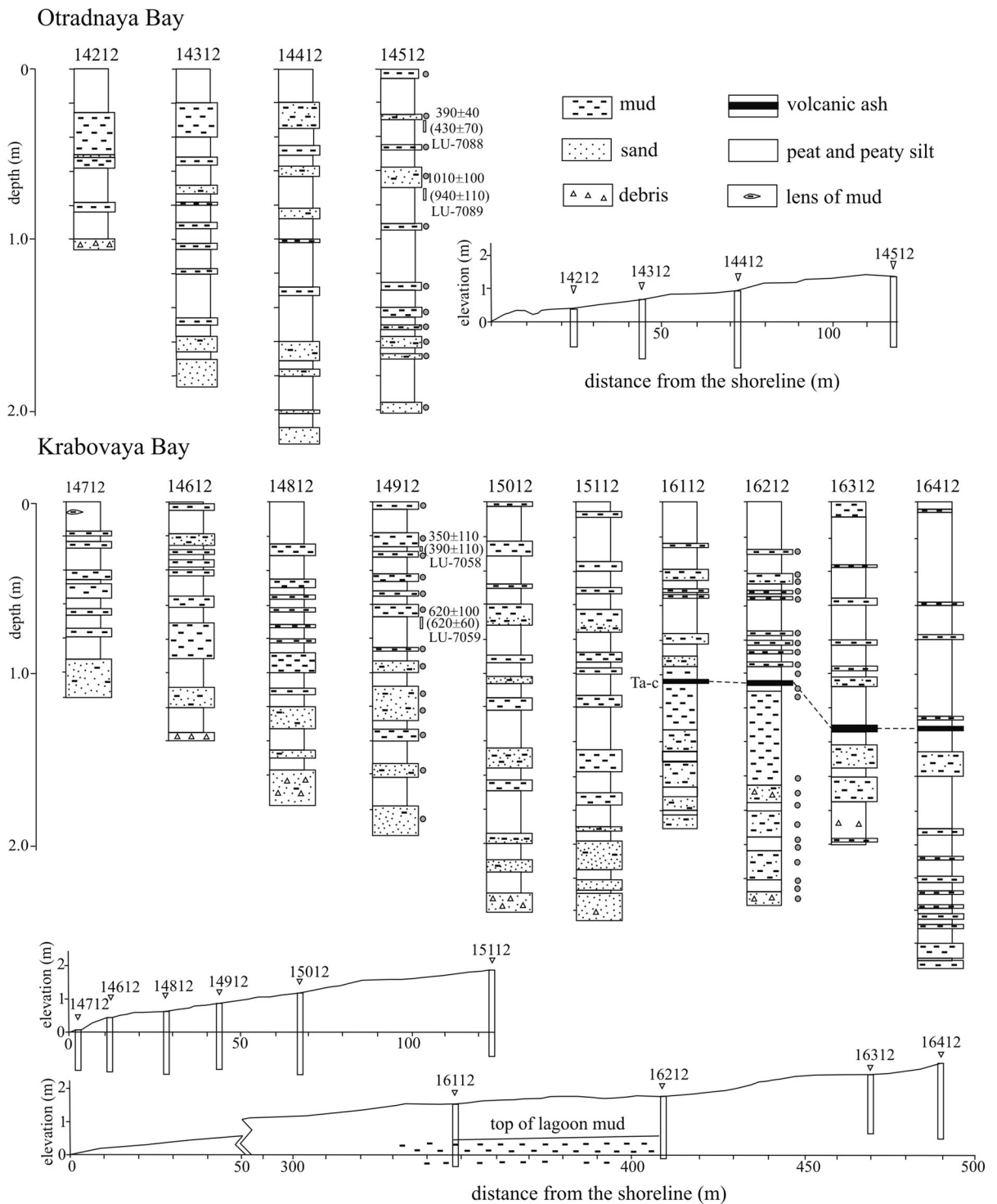
Figure 9
Paleotsunami deposits in peat sections on topographic profiles from **a** Oradnaya and **b** Krabovaya bays, Shikotan Island. *Boxes* indicate the position of the samples for radiocarbon dating, the age is in *brackets*: cal. yBP. *Circles* show the location of samples for the diatom analysis

The grain-size composition of the ancient tsunami mud is similar to the deposits of the 2011 Tohoku tsunami, which proves a likeness of sources and a similarity between their erosion-accumulation processes. If a tsunami occurred at a time of the year when the closed bays were covered by ice, the deposit sheets could have been formed, even with a small run-up, due to increased erosion by water with ice. But, we think that usually, only major tsunamis could lead to the accumulation of long deposit sheets.

Figure 10 shows grain-size curves of the Tohoku tsunami deposits and Late Holocene deposits of different ages, found at the same sites. Grain-size distribution curves in Otradnaya Bay paleotsunami mud is unimodal (mode 20–30 μm, sometimes 10–20 μm), almost symmetrical, with a tail of fine fractions (skewness from 0.65 to 0.84), and mesokurtic. The sand fraction is insignificant (<2.2 %). Grains <10 μm prevail in deposits of Krabovaya Bay (up to 69 %) without sand. The mode is pronounced: 10–20 μm. The distribution curves in more ancient layers are finely skewed (skewness from 0.46 to 0.76), from mesokurtic to platykurtic (kurtosis 2.44–3.03); in the fine pelitic (1–2 μm) area, bimodal properties have been observed. There is a tendency for clay fractions to decrease and the silt amount to increase from ancient to recent deposits. The similarity of grain-size distribution of paleotsunami mud and Tohoku tsunami deposits shows that the sources of the material and the conditions of deposition were very similar.

The marine origin of deposits is confirmed by the diatom data. Marine diatoms are found in all layers. From 14 to 31 marine species are found in deposits of Otradnaya Bay and their content percentage varies from 9 to 39 %. The preservation of frustules differs. As a rule, diatoms are well-preserved only in two layers, probably associated with major tsunamis, and the frustules are broken. Sub-littoral benthic and plankton species prevail in all layers. Plankton species dominate among sub-littoral diatoms in the deposits formed by a stronger tsunami (*Paralia sulcata* up to 13.7 %, *Odontella aurita*, *Actinocyclus octonarius*, *Hyalodiscus scoticus*, *Trachyneis aspera*, *Thalassiosira bramaputrae*), along with different neritic and oceanic species: northboreal and arctoboreal (*Thalassiosira gravida*, *T. eccentrica*, *Chaetoceros dyadema*, *Coscinodiscus granulosus*, *Actinocyclus curvatulus*), and southboreal (*Thalassionema nitzschioides*, *Actinocyclus divisus*, *Coscinodiscus*). Freshwater diatoms reflect the re-deposition of the material from swamps and shallow ponds with neutral or weakly alkaline pH.

From 15 to 38 marine diatoms are found in the paleotsunami deposits in Krabovaya Bay, which comprise 12.4–66.7 % in section 14912, located on the left side of the bay. The content of marine diatoms decreased (2.4–39.1 %) in the paleotsunami mud in peat section 16212, situated inland. Thicker mud layers include more marine diatoms. The frustules in all layers are well-preserved. Sub-littoral benthic and plankton species are dominant. The deposits with diatoms, typical of shallow semiclosed bays, were most probably formed by the tsunami that provoked the erosion within the shallow water zone and tidal flats. Layers of deposits with marine diatoms, probably indicating deeper bays, were formed during major tsunamis resulting in bottom erosion at greater depths. In most of the layers, neritic and oceanic diatoms are present (*Thalassiosira gravida*, *T. eccentrica*, *Porosora glacialis*, *Coscinodiscus marginatus*, *Actinocyclus divisus*, *A. curvatulus*, *Thalassionema nitzschioides*, *Coscinodiscus asteromphalus*, *Thalassiothrix* sp.). Freshwater diatoms indicate that there was material re-deposition from various sources: peats, peaty soils, and deposits of shallow ponds of different types with neutral or weakly alkaline pH. The proportion of material from various terrestrial sources varies in the tsunami deposits of different ages. Among freshwater diatoms in the deposits of ancient tsunamis, we can find different species of *Eunotia* and *Pinnularia* genera, typical of swamps. These species are almost absent in the 2011 Tohoku tsunami deposits.

7. *Conclusions*

The comparison of tsunami deposits from the periphery and from the near-field area close to the tsunami showed a considerable dissimilarity in their distribution, grain-size composition, biofossils, and sedimentation. These differences are predetermined by diverse erosion and sedimentological processes,
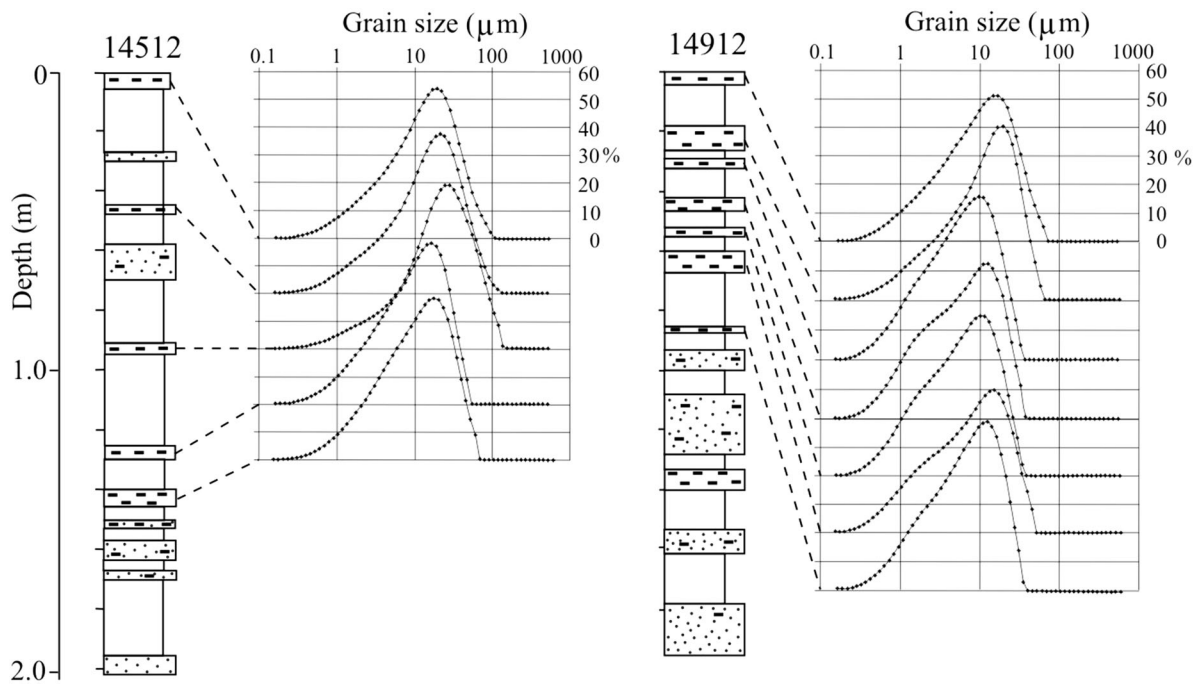
Figure 10
Grain-size distribution curves of the 2011 Tohoku tsunami, and paleotsunami mud samples of different ages from the peatbog of Otradnaya Bay (Core 14512) and the *left side* of Krabovaya Bay (Core 14912). The 2011 Tohoku tsunami and paleotsunami deposits were sampled at the same site

which in turn, indicate the strength of the respective tsunami. Depending on the run-up heights, configuration of the shoreline, and the local topography, the erosion character was different, which reflects the variety of sources of the incoming material. Diverse deposition conditions due to different turbulence of the flow also influenced the deposit composition. In the zones that were remote from the tsunami source, the deposit sheets were formed only on the coasts of closed bays, where the erosion was aggravated by ice fragments in water. The material was mainly transported from the marine source. A lot of fine fractions, good preservation of biofossils, and the presence of diatom colonies indicate the weak turbulence of the flow and short-distance transport. In the near-field zone located in the vicinity of the tsunami source, the most active erosion occurred in flooded areas, which led to the formation of thick deposit sheets. Beaches and dunes were the main sources of sand, while the eroded soil provided mud. In general, terrestrial sources played an important role in the tsunami deposit formation.

The studies of the 2011 Tohoku tsunami on the coasts of the Lesser Kuril Islands showed that muddy layers in the section of coastal lowlands in closed bays could be indicators of paleotsunamis. More detailed records of paleotsunamis could be preserved on the coasts of such bays, in contrast to the coasts of open bays.

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