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Coastal Sedimentation Associated with the Tohoku Tsunami of 11 March 2011 in South Kuril Islands, NW Pacific Ocean

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Abstract—Sediment deposited by the Tohoku tsunami of March 11, 2011 in the Southern Kurils (Kunashir, Shikotan, Zeleniy, Yuri, Tanfiliev islands) was radically different from sedimentation during local strong storms and from tsunamis with larger runup at the same location. Sediments from the 2011 Tohoku tsunami were surveyed in the field, immediately and 6 months after the event, and analyzed in the laboratory for sediment granulometry, benthos Foraminifa assemblages, and diatom algae. Run-up elevation and inundation distance were calculated from the wrackline (accumulations of driftwood, woody debris, grass, and seaweed) marking the distal edge of tsunami inundation. Run-up of the tsunami was 5 m at maximum, and 3–4 m on average. Maximum distance of inundation was recorded in river mouths (up to 630 m), but was generally in the range of 50–80 m. Although similar to the local strong storms in runup height, the tsunami generally did not erode the coast, nor leave a deposit. However, deposits uncharacteristic of tsunami, described as brown aleuropelitic (silty and clayey) mud rich in organic matter, were found in closed bays facing the South Kuril Strait. These closed bays were covered with sea ice at the time of tsunami. As the tsunami waves broke the ice, the ice floes enhanced the bottom erosion on shoals and destruction of low-lying coastal peatland even at modest ranges of runup. In the muddy tsunami deposits, silt comprised up to 64 % and clay up to 41.5 %. The Foraminifera assemblages displayed features characteristic of benthic microfauna in the near-shore zone. Deep-sea diatoms recovered from tsunami deposits in two closely situated bays, namely Krabovaya and Otradnaya bays, had different requirements for environmental temperature, suggesting these different diatoms were brought to the bays by the tsunami wave entraining various water masses when skirting the island from the north and from the south.

Key words: Tsunami deposits, grain-size, Benthic Foraminifera, diatoms, South Kurils, Pacific Ocean.

1. *Introduction*

Studies of deposits related to modern tsunamis are important for understanding specific features of sediment transport and deposition on various types of coasts. They may also help to clarify factors that control the tsunami sediment composition and structure, which is of particular importance to paleotsunami reconstruction. Considerable attention has been given to the study of recent tsunami deposits, especially from large tsunamis, all over the world. Many recently published papers deal with sediment occurrence and composition, as well as with microfossil assemblages related to the largest tsunamis, such as the 1993 Hokkaido-Hansei-oki tsunami (Nishimura and Miyaji, 1995; Nanayama and Shigeno, 2006), the 1998 Papua New Guinea tsunami (Dawson, 2007), the 2004 tsunami in the Indian Ocean (Moore *et al.*, 2006; Horton *et al.*, 2011; Choowong *et al.*, 2008; Sawai *et al.* 2009; Chagué-Goff *et al.*, 2011; Paris *et al.*, 2007; Matsumoto *et al.*, 2010; Mamo *et al.*, 2009; Razzhigaeva *et al.*, 2006; etc.), the 2006 Kuril tsunami (MacInnes *et al.*, 2009a, b), the 2009 and 2010 South Pacific tsunamis (Fritz *et al.*, 2011; Chagué-Goff *et al.*, 2011; Clark *et al.*, 2011), the 2010 Chile tsunami (Fritz *et al.*, 2011; Horton *et al.*, 2011), and many others. Work initiated recently in Japan is aimed at studying sediments of the 2011 Tohoku tsunami triggered by a powerful earthquake on March 11, 2011, off the Honshu coast (Goto *et al.* 2011).

In the Southern Kuril Islands, the Tohoku tsunami arrived as a series of moderately high waves. The principal energy of the tsunami was directed toward northeastern Honshu and the Pacific Ocean (Simons *et al.*, 2011), while the Kuril Islands appeared to be at

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a periphery of the main direction of tsunami wave propagation. Run-up heights measured by eye-witnesses in the South Kurils were in the range of 0.5–3 m, with the maximum recorded in the Krabovaya Bay, Shikotan Is. (Kaistrenko *et al.*, 2011).

Although the tsunami in the South Kurils was of modest run-up and inundation, the sedimentological effect of the event is of considerable interest for paleo-reconstructions and inter-regional correlations of paleotsunamis. This study aims to analyze of factors that control tsunami sedimentation patterns in a variety of locations. Field sites selected to study the effect of the 2011 Tohoku tsunami encompass many differences in coastal structure, orientation in reference to the tsunami front, and tsunami run-up and inundation (Fig. 1). These field sites are the same locations as previous studies of the consequences and deposits of the extreme storms of 2006–2007 (Ganzey *et al.*, 2010), the 1994 Shikotan tsunami deposits, and paleotsunami deposits (Razzhigaeva *et al.*, 2008, 2011).

2. *Study Area and Methods*

In August–September of 2011 effects of the 2011 Tohoku tsunami were surveyed on the coasts of Kunashir, Shikotan, Zeleniy, Yuri, and Tanfiliev islands (Fig. 1). The studied bays vary noticeably in shoreline geometry, geomorphic setting, and are differently oriented to the tsunami front. These bays face either the Pacific Ocean or the South Kuril Strait.

The coasts of the islands are mostly dominated by marine erosion and denudation processes and are fringed with a narrow strip of beach. The Lesser Kuril Islands (Shikotan, Zeleniy, Yuri and Tanfiliev islands) have been subjected to tectonic subsidence through the Holocene; coseismic movement is typical, such as the 0.5–0.7 m subsidence on Shikotan Island from the 1994 earthquake (Levin *et al.*, 1997; Kaistrenko *et al.*, 1977). Coastal lowlands with a series of beach ridges are confined to bay heads and low-relief isthmuses. Most of the bays are open, although closed bays are typical on Shikotan Island. Closed bays are separated from the Pacific Ocean by small islands that have resulted from the active processes of coastal erosion. Bays that open towards the South Kuril Strait are mostly inundated mouths of small stream valleys. Coastal lowlands and the lowermost segments of river valleys are heavily waterlogged. Peatlands of a considerable area are often found in places of Mid-Holocene bays and completely overgrow coastal lakes (Razzhigaeva and Ganzei, 2006).

We described all traces of the 2011 Tohoku tsunami in these coastal settings, including measuring run-up height and inundation distance using the line marking the inundation limit (wrackline), recording evidence of erosion, and tracing the distribution of deposits. We also studied sediment collected from the ice surface immediately after the tsunami. Tsunami measurement and sampling were performed along shore-perpendicular transects, with run-up height and inundation distance calculated using field leveling. For each transect, we collected up to four samples, including vertical sections of tsunami deposits that contained coarse laminae.

Sand granulometry was studied using sieves with γ step and a high-precision Sartorius balance; in this way it was possible to obtain statistically valid data from small sample sizes. Mud sediments with particles of silt and clay were studied using «Analysette 22» sedimentograph.

Micropaleontological studies included analyses of Foraminifera and diatoms. Foraminifera were analyzed in samples taken immediately after the tsunami from the surface of ice floes broken and transported by the tsunami. Samples for diatom analysis were also taken from the ice right after the event and half a year later. Samples intended for benthos Foraminifera study were washed through a 0.063 mm sieve, dried and then studied under binocular microscope. Environmental characteristics of the species were determined using data from the literature (Saidova, 1975; Foraminifera of Far Eastern Seas of the USSR, 1979; Preobrazhenskaya and Troitskaya, 1996; Annin, 1999; Sen Gupta, 2002). Samples for diatom analysis were prepared following standard techniques (The Diatoms of the USSR, 1974) and were identified following Krammer and Lange-Bertalot (1988) and The Diatoms of the USSR (1988, 1992, 2002, 2008). Percentage content was calculated from total taxa.

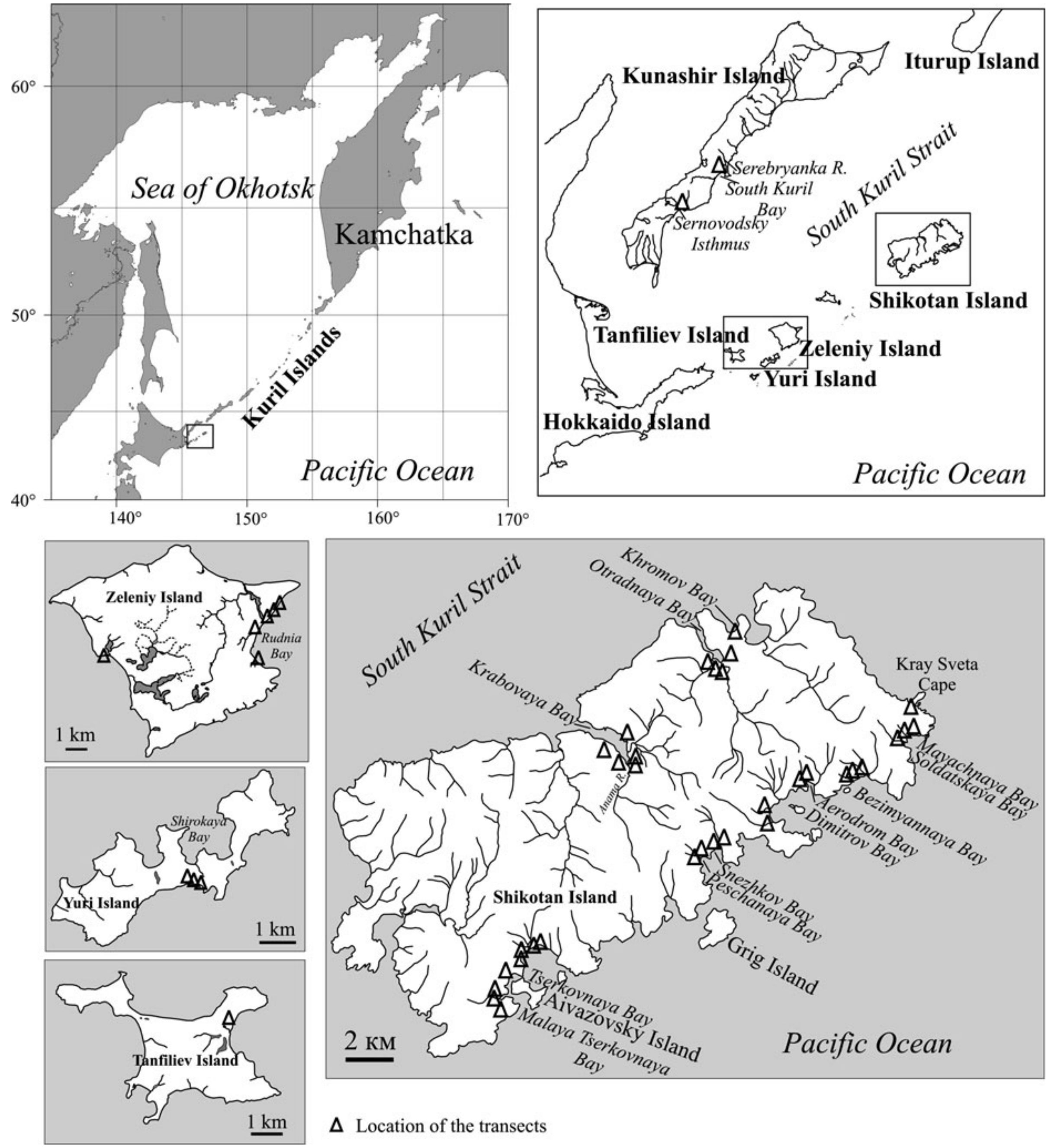

Figure 1
Study area

3. Wrackline and Distribution and Thickness of the Tsunami Deposits

When surveyed half a year after the earthquake, the traces of the 2011 Tohoku tsunami on the South Kurils, such as run-up and the maximum inundation limit was easily identifiable on most of the studied islands. Tsunami evidence was most distinct on Shikotan Island coasts. When measuring the inundation in some bays on Shikotan and Kunashir coasts, we used the photographs taken immediately after tsunami. The wrackline was most often marked with a ridge composed of debris, wood fragments, grass, eelgrass (*Zostera* sp.) and other seaweed, including the roots of *Laminaria* sp. (Fig. 2). Species typical of wetlands and beach ridges dominate the plant remains. Other debris of marine origin occurred occasionally, such as timber, barrels, mollusk shells,

Figure 2

Wrackline of the 2011 Tohoku tsunami on the Shikotan Island coast. **a** The limit of the wave runup is marked with wood fragments and grass—mage from the maximum inundation limit (Aerodrom Bay); **b**, **c** scattered pebbles and cobbles lying over last year's grass (Bezymyannaya and Aerodrom bays), **d**, **e** last year's leaves of *Leymus mollis* show inflow direction (Bezymyannaya and Dimitrov bays) remains of crab shells, and sponges. Flow directions were reconstructed from well-preserved blades of *Leymus mollis* (from the previous growing season) aligned with water flow. As a rule, the grass blades were oriented landward, in accordance with the inflow. Locally, where the outflow was dominant, grass blades were turned seaward (Fig. 2).

On most islands studied, run-up values did not exceed 3–4 m (Table 1). The highest run-up (up to 5 m) was measured at the southeast of Zeleniy Is. and on Shikotan Is., near Cape Kray Sveta ("Land End") (Fig. 1). The tsunami wave normally overflowed storm bars or ridges and penetrated onto the land for a short distance (Fig. 3). The maximum distance of wave penetration was recorded in stream mouths. On the Pacific side of Shikotan, tsunami waves inundated as far as 200 m (Peschanaya Bay), and more than 230 m on the South Kuril Strait side (Krabovaya and Otradnaya Bays). On Kunashir Island the tsunami waves went up the Serebryanka River valley over a distance of more than 630 m. On the small islands of the Lesser Kuril Arc, tsunami inundation did not exceed 100 m in stream mouths, or 70 m in general.

Table 1

The Tohoku tsunami run-up and inundation zone of South Kuril Islands

Island	Location	Run-up, *m*	Inundation zone, *m*
Kunashir	South Kuril Bay	0.77–2.64	45–630
Kunashir	Sernovodsky Isthmus	1.95	224
Shikotan	Kray Sveta Cape	3.34–4.71	20–70
Shikotan	Mayachnaya Bay	1.61–4.57	37–86
Shikotan	Soldatskaya Bay	2.08	53
Shikotan	Bezynyannaya Bay	2.14–3.57	27–71
Shikotan	Aerodrom Bay	1.18–2.99	40–192
Shikotan	Dimitrov Bay	1.91–2.95	24–80
Shikotan	Snezhkov Bay	2.21–2.75	42–78
Shikotan	Peschanaya Bay	2.60–3.76	58–205
Shikotan	Tserkovnaya Bay	2.19–3.51	65–100
Shikotan	Malaya Tserkovnaya Bay	0.92–2.17	15–78
Shikotan	Voloshin Bay	1.50	110
Shikotan	Khromov Bay	2.95	48
Shikotan	Otradnaya Bay	0.51–1.95	15–180
Shikotan	Krabovaya Bay	0.80–2.05	12–300
Zeleniy	Rudnya Bay	3.02–5.07	50–103
Yuri		2.25–2.75	40–72
Tanfiliev		2.20–2.54	27–49

On the open coast of Shikotan Is., the tsunami caused practically no erosion and left little sediment. Rare pebbles, cobbles or small spots of sand and gravel cover last-year's grass (Fig. 2). In Bezymyannaya Bay, pebble and gravel occur as small ridges aligned perpendicular to the shoreline.

The situation in closed bays of Shikotan was somewhat different. Tsunami deposits were found in southern Malaya Tserkovnaya Bay, which is separated from the ocean by Aivazovsky Island. The site in Malaya Tserkovnaya Bay is a small cove that was formed by coseismic subsidence in 1994. Within the cove's flooded river mouth a sandy silt and silty sand sheet, up to 78 m wide and 9 cm thick, was deposited by the tsunami. Its thickness decreases gradually landward to 1 cm and becomes discontinuous, with the sand occurring as separate patches.

Typically, the sands are massive. Locally, however, the sequence shows irregularities, with some coarse laminae less than 1 cm thick; the latter suggests two or three waves inundated the site (Fig. 5). During intervals of stagnant water first to settle out was the coarser material. Some patches of mud-capped sands are found on the coast of partially closed Snezhkov Bay. The presence of mud indicates a long period of standing of water when fine fractions could be deposited. Mud layers less than 5 mm thick and containing seaweed were found at the back of a storm bar near the river; they overlay coarse deposits from the 2006 to 2007 storms.

The closed bays on the South Kuril Strait side of Shikotan Island were ice-covered at the time of the tsunami, and the passage of the tsunami waves broke and transported the ice. The result was erosion of the seafloor and terrestrial erosion, including partial destruction of peatbogs even at relatively moderate run-up. A case of particularly active erosion was observed at the head of Krabovaya Bay; there the ice-loaded wave came onto an obstacle (a small escarpment, formed by a road) and completely destroyed the uppermost layer of peat and soil (about 0.6 m thick) and exposed the underlying marine mud. The width of the erosion zone in Krabovaya Bay exceeds 100 m (Fig. 4). Immediately beyond the erosional zone spotty deposits of silt (up to 5 cm thick) occur on lower tree branches and on the soil surface (Fig. 5). They are covered with *Zostera*—a seagrass

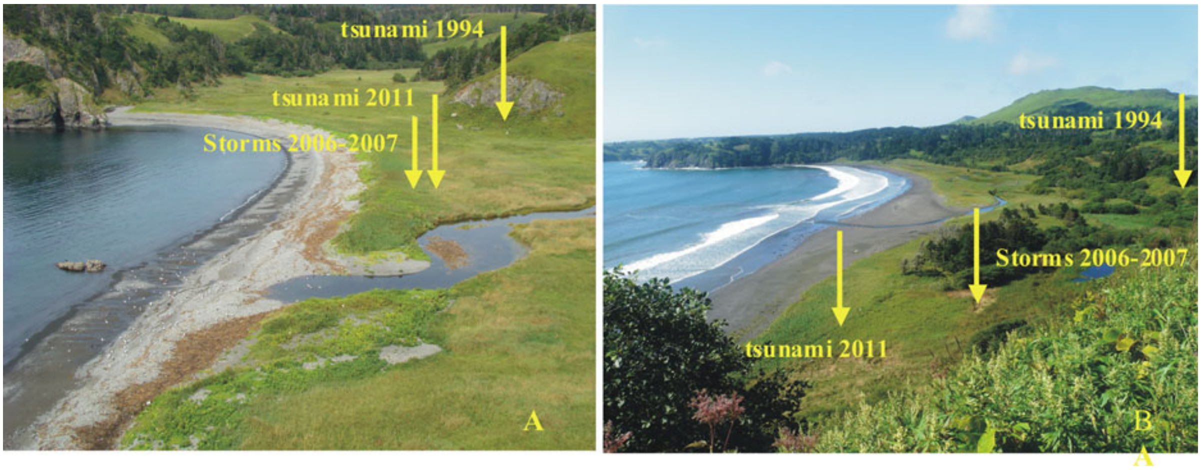

Figure 3
Run-up limit of the 2011 Tohoku tsunami, the 1994 Shikotan tsunami, and extreme (2006–2007) storm surge on Shikotan Island. **a** Bezymyannaya Bay, **b** Tserkovnaya Bay. Photos were taken September, 2011

Figure 4
Erosion zone (**a**, **b**) and peat rip-up clast (**c**) in Krabovaya Bay, Shikotan Island

(eelgrass) that usually grows at a depth of 1–4 m. The silt was also found on an iron barrel brought onshore by the tsunami. A thin silt layer (up to 2 cm) with tufts of grass (*Zostera* sp.) was also found on the bridge over the Anama R. where it had been brought by the tsunami with the ice floes (Fig. 5). There are rip-up clasts of peat up to 1.3 m in size lying on the bog surface over the previous year's grass. The peat is overlain with a 5-cm thick tsunami deposit traced at a distance of 60 km. The deposits are dominated by a brown silty-clayey mud with a sizeable proportion of organic matter. Similar mud rich in organic matter was found on the Otradnaya Bay coast, where the tsunami penetrated into the stream mouths and flooded the low coast at the bay head; the mud occurs as a sheet up to 5 cm thick or as isolated patches and occasionally includes tufts of *Zostera*; the tufts are also found hanging on trees and bush branches (Fig. 6).

In the Lesser Kuril islands, tsunami deposits (coarser sands with gravel) are found only on the Pacific coast of Zeleniy Island. They occur as small patches less than 0.5 m in size; their thickness does not exceed 1 cm. Only one case on Shikotan Island was recorded where the deposits were 10 cm thick.

The sediments sampled on ice floes on Kunashir island (near the Serebryanka River) immediately after the tsunami event are black and gray silty fine sand abounding with *Zostera* sp. and seaweed remains. On Shikotan (the Krabovaya Bay) the analogous sediments are silty-clayey mud with admixture of fine sand and seaweed.

4. *Grain Size Distribution of Tsunami Deposits*

The sediment left by the tsunami was highly varied in grain size. The sandy silt layers left by the tsunami on the Pacific side of Shikotan Island (Malaya Tserkovnaya Bay) evolved inland, with the content of silt increasing from 26.9–77.8 % and sorting improving landward. The distribution curves of deposits in Malaya Tserkovnaya Bay are bimodal or polymodal. The main mode is 0.08–0.1 mm, while the sand near the shoreline has modes of 0.1–0.125, 0.16–0.2 mm (Fig. 7). In sections with stratification, sand fractions dominate the coarser layers, with 54 % fine sand, 23.3 % medium sand, and 2.4 % coarse sand. The grain-size curves are bimodal, with modes of 0.1–0.125, 0.2–0.25 mm. Silt content from fine-grained deposits reached up to 47.9 %. Mode 0.08–0.1 mm is well pronounced. Mode 0.16–0.2 mm is typical for tidal flat deposits in Malaya Tserkovnaya Bay, which are characterized by single-modal curves, and a fine-sand fraction that reaches up to 74.3 %. The main source of the silt fraction in the tsunami deposits of Malaya Tserkovnaya Bay was the intertidal zone. Mud content of the tidal flat increased after the tsunami.

The Snezhkov Bay tsunami deposits mainly consist of fine sand (up to 57.8 %). The grain size curves are single-mode (0.2–0.25 mm). The same mode is typical for Snezhkov Bay's tidal flat sands, which are more sorted than tsunami deposits. At the location where the tsunami crossed a field of coarser-grained storm deposits from 2006 to 2007 (Ganzey *et al.*, 2010), the coarse sand and gravel content of the deposit increased up to 9.5 and 3 %, respectively. The grain-size curves became polymodal, with modes 0.315–0.4, and 0.5–0.63 mm appearing. In the muddy surficial layers left by the tsunami on the Snezhkov Bay coast, silt fraction was dominant (51.4–64.0 %) with a distinct mode at 20–30 µm (mean size is 15–16 µm), with a sizeable proportion of clay (up to 30.7 %). The distribution curve shows a single mode that is slightly asymmetrical due to admixture of coarse silt and fine sand (Fig. 7). The source of fine material was probably sediments of an oxbow lake eroded and redeposited by the tsunami.

On the coast of the South Kuril Strait, in Krabovaya Bay, tsunami deposits featured a high proportion of silt (50.1–59.1 %), as well as an abundance of clay (up to 41.5 %). The grain-size distribution curves are single- and bimodal, the 20–30 µm mode is well pronounced, and mean size is 10–21 µm. Bimodal curves are characteristic of the right side of the bay, where the coastal swamp is less extensive and sand fractions were supplied from the eroded coast in greater quantities. There are both symmetrical and asymmetrical (skewed) distribution curves of various types, showing the presence both fine clay and coarse silt grains, presumably supplied from different sources (Fig. 8). The material deposited on the bay sides, closer to the bay entrance, is

Figure 5
Tohoku tsunami deposits on Shikotan Is. **a** tsunami deposits with some coarse laminae, Malaya Tserkovnaya Bay, **b** silt with organic material found on an iron barrel brought by the tsunami, Krabovaya Bay, **c** silt deposits on tsunami-transported sea ice on the bridge over the Anama R., and **d** the same silt with *Zostera* sp. was sampled September, 2011, Krabovaya Bay, **e** silt mud cover and tsunami-transported sea ice on the coast of Otradnaya Bay, and **f** the same coast with mud cover at September, 2011. The photos **c** and **f** were taken by S.A. Karpenko, and I. Tomason

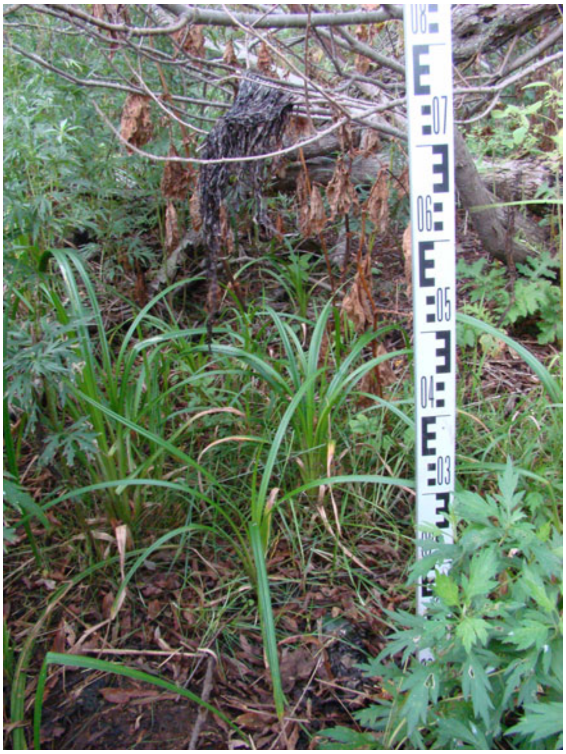

Figure 6
Zostera sp. on trees branches in Otradnaya Bay coast

well-sorted fine-grained sand (85.6 %) with an admixture of silt (9.1 %) and clay (5.3 %). In Otradnaya Bay, the tsunami mud is dominated by silt (51.8–61.6 %) with a high proportion of clay (up to 35.9 %) and mean size is 12–23 μm. The left side of the bay is noted for single-mode distribution curves (the mode being 20–30 μm), while at the head of the bay, the distribution is bimodal with additional mode at 80–100 μm suggestive of two sediment sources.

On Kunashir Island, tsunami deposits sampled from the ice mainly contain fine sand (fraction 0.1–0.25 mm–up to 81.7 %). The grain-size curves are single-mode (0.1–0.125, 0.125–0.16 mm) and the deposits are well sorted. The curves are similar to beach and tidal flat sands, which are the main source for the tsunami deposits.

5. *Benthic Foraminifera Assemblages of 2011 Tohoku Tsunami Deposits*

The Foraminifera assemblages in the tsunami deposits preserve specific benthic microfauna inhabiting littoral and sub-littoral zones. None of the studied samples contain deep-sea benthic Foraminifera.

The tsunami deposits on Kunashir Island are noted for the presence of numerous Foraminifera; 29 well-preserved species were identified there (Table 2). Benthic Foraminifera are mostly attributed to calcareous species, the most abundant from the Cribroelphidium and Buccella genera. Dominant species include *Cribroelphidium subarcticum*, *Cr. etigoense, Cr. asterenium, Elphidium exavatum, Buccella granulate, B. innusitata, B. hannai arctica*, and *B. hannai oris.* All of these species occur in the upper littoral zone of Kunashir Island (Annin, 1999), implying the material was transported from wide sand

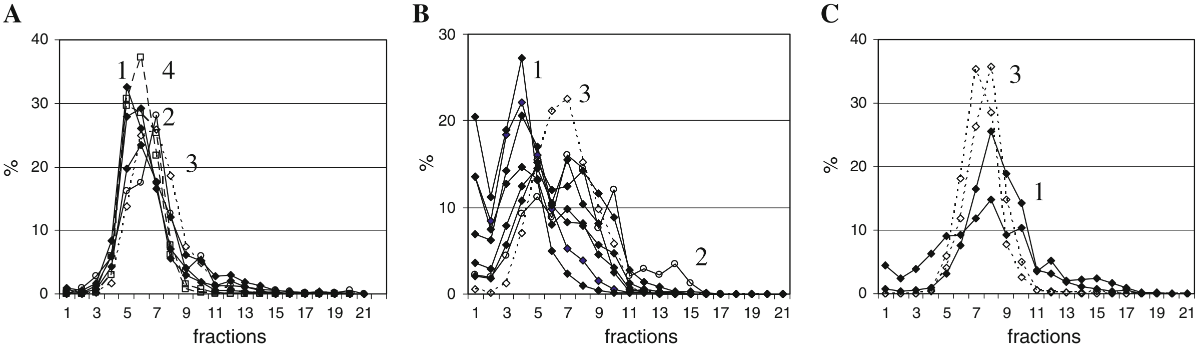

Figure 7
Grain size of 2011 Tohoku tsunami deposits on the Pacific coast of Shikotan Island. **a** South Kurile Bay, Kunashir Island; **b** Aerodrom Bay, Shikotan Island; **c** Snezhkov Bay, Shikotan Island. *1* Tohoku tsunami deposits, *2* 1994 Shikotan tsunami deposits, *3* tidal flat deposits, *4* beach deposits. Fractions: *1* <0.05; *2* 0.05–0.063; *3* 0.063–0.08; *4* 0.08–0.1; *5* 0.1–0.125; *6* 0.125–0.16; *7* 0.16–0.2; *8* 0.2–0.25; *9* 0.25–0.315; *10* 0.315–0.4; *11* 0.4–0.5; *12* 0.5–0.63; *13* 0.63–0.8; *14* 0.8–1; *15* 1–1.25; *16* 1.25–1.6; *17* 1.6–2; *18* 2–3; *19* 3–4; *20* 4–5; *21* >5 mm

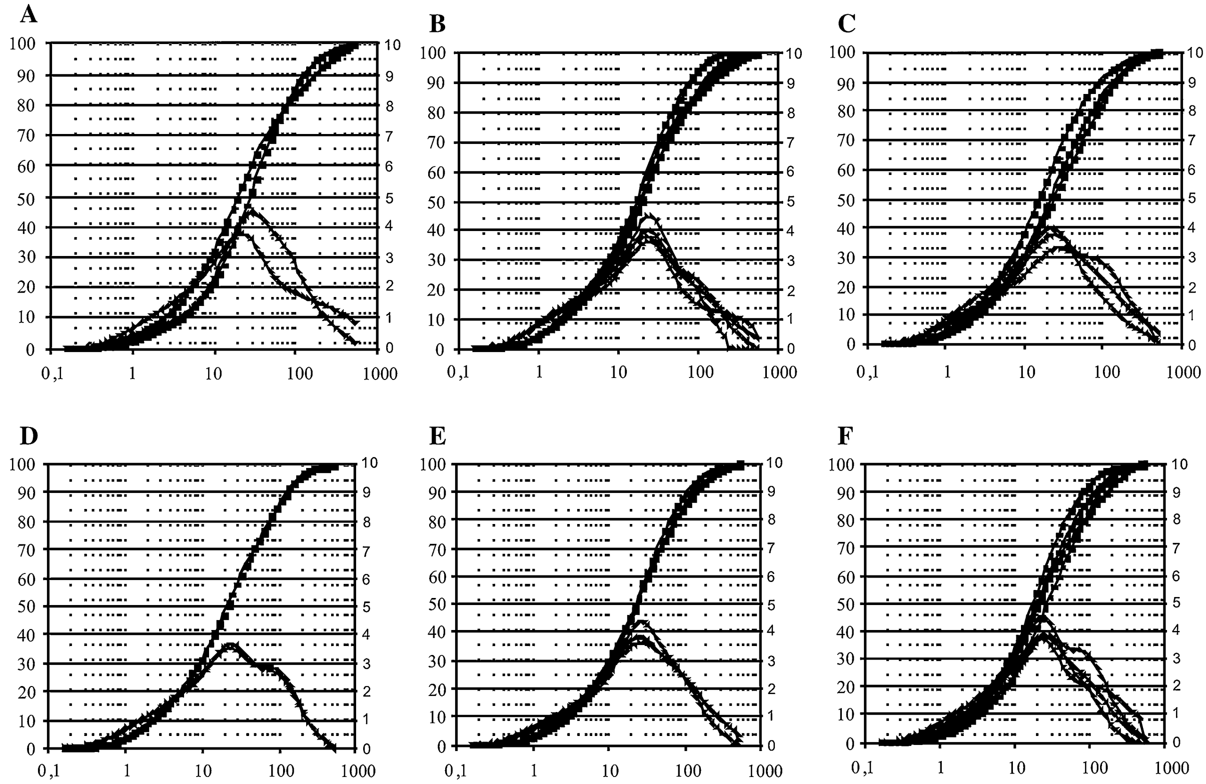

Figure 8
Grain size of 2011 Tohoku tsunami mud from the South Kurile Strait coast of Shikotan Island. **a** Snezhkov Bay, **b** Krabovaya Bay, south coast, **c** Krabovaya Bay, centre, tsunami deposits on tree, bridge and barrel, **d** Krabovaya Bay, north coast, **e** Otradnaya Bay, south coast, **f** Otradnaya Bay, centre

beaches, from the bench of the South Kuril Bay, or a combination of the two locations.

Benthic Foraminifera species recovered from tsunami deposits in Krabovaya and Otradnaya Bays on Shikotan are not nearly as numerous and diversified. Only 10 species have been found altogether and the species composition of the assemblage is different from that on Kunashir. *Jadammina macrescens*, an inhabitant of tidal flat marshes (Sen Gupta, 2002), is dominant. On Shikotan this species was found in the littoral region of closed bays; it is typical for depositional environments with moderate wave energy and the species is tolerant of water freshening (Preobrazhenskaya and Troitskaya, 1996). Some agglutinated forms of Trochammina genus (*Trochammina japonica, Tr. inflate, Tr. pacifica,* and *Tr. vinogradovi*) and *Miliammina fusca* were recorded. Of calcareous species, there were only *Cribroelphidium asterineum, Cr. etigoense*, as well as some representatives of Buccella genus. Some ostracoda species recovered from the deposits have not been studied.

6. *Diatoms Assemblages of 2011 Tohoku Tsunami Deposits*

The Tohoku tsunami deposits contain abundant marine diatoms, with 122 species identified altogether (Table 3).

The deposits sampled from ice floes on Shikotan contain a high proportion of sub-littoral *Cocconeis scutellum, Rhabdonema arcuatum, Arachnoidiscus ehrenbergii, Odontella aurita, Fragilaria fasciculata,* and *Triceratium arctica*. The presence of oceanic species, such as *Coscinodiscus oculus-iridis, Thalassiosira eccentrica,* and *Thalassiothrix longissima,* is noteworthy, as these species may have been brought from the open ocean by the tsunami wave.

Table 2

List of Foraminifera and their abundance from the Tohoku tsunami deposits on Kunashir and Shikotan Islands, South Kuril Islands

Species	Test wall composition	Kunashir Island, South Kuril Bay, near bridge	Kunashir Island, South Kuril Bay, near Serebryanka River	Kunashir Island, South Kuril Bay, near church	Shikotan Island, Krabovaya Bay, near Anama River	Shikotan Island, Otradnaya Bay	Shikotan Island, Krabovaya Bay
Buccella citronea Leonenko	c			1.7 (1)			
Buccella depressa Andersen	c	0.5 (1)					
Buccella frigida (Cushman)	c	0.9 (2)		1.7 (1)			
Buccella granulata (Lautenschleger)	c	11.8 (19)	17.9 (8)	11.7 (5)	3.4 (7)		3.7 (2)
Buccella hannai arctica Voloshinova	c	4.7 (8)	11.9 (5)	15.0 (7)			
Buccella hannai oris Levtchuk	c	5.7 (9)	3.0 (1)	8.3 (4)			
Buccella inusitata Andersen	c	10.8 (18)					
Buccella limpida Levtchuk	c			1.7 (1)			
Buliminella elegantissima (d'Orbigny)	c	0.9 (2)					
Canalifera fax (Nicol)	c	0.5 (1)					
Cassidulina teretis (Tappan)	c	0. (1)		1.7 (1)			
Cribroelphidium asterineus Troitskaja	c	7.1 (12)	1.5 (1)	6.7 (3)			
Cribroelphidium etigoense (Husezima et Maruhasi)	c	18.9 (31)	10.4 (5)	10.0 (4)	3.4 (7)		
Cribroelphidium goesi (Stschedrina)	c	0.5 (1)	16.4 (8)	3.3 (1)			
Cribroelphidium kusiroense (Asano)	c	3.3 (5)	3.0 (1)				
Cribroelphidium subarcticum (Cushman)	c	15.6 (25)	14.9 (7)	18.3 (8)			
Eggerella advena Cushman	a				3.4 (7)		
Elphidiella flos Troitskaja	c	4.2 (7)	1.5 (1)	1.7 (1)			
Elphidium advenum depressulum Cushman	c	0.9 (2)	1.5 (1)	3.3 (1)			
Elphidium excavatum (Terquem)	c	7.1 (12)	6.0 (3)	3.3 (1)			
Elphidium jenseni (Cushman)	c			1.7 (1)			
Florilus hadai Nesterova et K.Furssenko	c	0.5 (1)	3.0 (1)	1.7 (1)			

Table 2 *continued*

Species	Test wall composition	Kunashir Island, South Kuril Bay, near bridge	Kunashir Island, South Kuril Bay, near Serebryanka River	Kunashir Island, South Kuril Bay, near church	Shikotan Island, Krabovaya Bay, near Anama River	Shikotan Island, Otradnaya Bay	Shikotan Island, Krabovaya Bay
Jadammina macrescens (Brady)	a				62.1 (120)	78.9 (25)	74.1 (48)
Miliammina fusca (Brady)	a					5.3 (2)	
Pateoris hauerinoides (Rhumbler)	c	0.9 (2)		1.7 (1)			
Quinqueloculina arctica Cushman	c		1.5 (1)				
Quinqueloculina interposita Levtchuk	c	0.5 (1)	3.0 (1)	1.7 (1)			
Quinqueloculina sp.	c	0.5 (1)					
Retroelphidium subclavatum (Gudina)	c	0.9 (2)	1.5 (1)	3.3 (1)	3.4 (7)		
Retroelphidium subgranulosum (Asano)	c	1.4 (2)					
Rosalina vilardeboana d'Orbigny	c	1.4 (2)	1.5 (1)	1.7 (1)			
Rotalia sp.	c		1.5 (1)				
Trochammina inflate (Montagu)	a				6.9 (13)	10.5 (3)	
Trochammina japonica Ishiwada	a				6.9 (13)		
Trochammina pacifica Cushman	a				10.3 (20)		
Trochammina vinogradovi Didkovsky	a					5.3 (2)	22.2 (14)

Absolute abundance is shown in brackets (Ind./100 g)

c calcareous, *a* agglutinated

Diatom flora also were studied in the tsunami deposits sampled half a year after the event. As many as 60 marine diatom species (up to 56.3 %) were identified in tsunami sands samples from Malaya Tserkovnaya Bay on the Pacific side of Shikotan Island. Many species from the genera *Cocconeis* (10 forms), *Diploneis* (4), *Hyalodiscus* (4), and *Grammatophora* (3) were found. Sub-littoral benthic diatoms dominate, including *Cocconeis scutellum* (up to 10.6 %, mostly large frustules >30 μm), *C. pellucida* (up to 6 %), *Rhabdonema arcuatum* (up to 9 %), *Fragilaria fasciculata* (up to 8 %), *Synedra kamtschatica* (up to 5 %), *Melosira nummuloides* (up to 7.1 %), *Melosira moniliformis* (4.5 %), *Planothidium haukianum* (4.2 %). Plankton species reach 9.3 %, typically such sub-littoral cold-water species as *Odontella aurita* (2.1 %), *Hyalodiscus scoticus* (1.5 %), and *Actinoptychus senarius* (2.4 %). The species *Paralia sulcata, Navicula directa*, which are typical for bays, are also present. Various oceanic and neritic species were recorded, including northern boreal and arctoboreal *Thalassiosira eccentrica, T. gravida, T. pacifica, T. decipiens,* and southern boreal *Thalassionema nitzschioides, Coscinodiscus asteromphalus, C. radiatus, C. perforatus,* boreal *Coscinodiscus centralis* and boreal-tropical *C. concinnus*.

Forty-six species of marine and brackish-water diatoms (62 % of the total) were recovered from tsunami sediments on the right side of Malaya

Table 3

List of marine and brackish diatoms from the Tohoku tsunami deposits on Shikotan Island, South Kuril Islands

Species	Ecol.	Otradnaya Bay	Tsserkovnaya Bay	Malaya Tserkovnaya Bay	Snezhkov Bay	Krabovaya Bay
Achnanthes brevipes Ag.	pl	1				
Achnanthes brevipes var. *angustata* (Grev.) Cl.	pl	1–2		1		
Achnanthes brevipes var. *intermedia* (Kütz.) Cl.	pl	1	1	1–2	1	1
Achnanthes groenlandica (Cl.) Grun.	pl		1	1		1
Actinocyclus curvatulus Janisch	pn			1		1
Actinocyclus divisus (Grun.) Hust.	pn	1		1		1
Actinocyclus octonarius Ehr.	pb	1		1		
Actinoptychus senarius (Ehr.) Ehr.	pn			1–2		1
Amphora angusta (Greg.) Cl.	b	1		1		1
Amphora coffeaeformis Ag.	b	1–2		1		1–2
Amphora marina (W. Sm.) V.H.	b	1–2		1–2		1–2
Amphora proteus Greg.	b	1		1		1
Arachnoidiscus ehrenbergii Bail.	b	1–2	1	1	1	1
Bacterosira fragilis Gran.	pn	1		1		1
Caloneis amphisbaena f. *subsalina* (Donk.) Cl.	b	1				1
Caloneis brevis var. elliptica Grun.	b			1		1
Caloneis liber W. Sm.	b	1		1		1
Campylodiscus clypeus Ehr.	b			1		
Chaetoceros diadema (Ehr.) Gran	pn					1
Chaetoceros didymus Ehr.	pn	1				1
Chaetoceros furcellatus Bail.	pn			1		
Chaetoceros subsecundus Hust.	pn	1		1		1
Cocconeis californica Grun.	b	1		1–2		1
Cocconeis costata Greg.	b	1	1	1–2		1–2
Cocconeis decipiens Cl.	b			1		
Cocconeis dirupta Greg.	b			1		
Cocconeis interrupta Grun.	b	1		1		1
Cocconeis pellucida Grun.	b	1		1–2		1
Cocconeis scutellum Ehr.	b	3–5	5	2–4		2–4
Cocconeis scutellum var. *parva* Grun	b	1–2		2		1
Cocconeis stauroneiformis (Rabenh.) Okuno	b	1		2		1
Cocconeis verrucosa Brun.	b	1		1–2		1
Coscinodiscus asteromphalus Ehr.	po			1		
Coscinodiscus centralis Ehr.	po			1		
Coscinodiscus concinnus W. Sm.	pn			1		
Coscinodiscus marginatus Ehr.	po	1		1		1
Coscinodiscus marginatus var. *fossilis* Jouse	po			1		
Coscinodiscus oculus-iridis Ehr.	po	1		1	1	1
Coscinodiscus perforatus Ehr.	po			1		
Coscinodiscus radiatus Ehr.	po			1		
Delphineis surirella (Ehr.) Andrews	b			1		
Diploneis bombus Ehr.	b				1	1
Diploneis dydima (Ehr.) Cl.	b					1
Diploneis interrupta (Kütz.) Cl.	b	1		1		1
Diploneis pseudoovalis Hust.	b	1	1	1		1–2
Diploneis smithii (Breb.) Cl.	b	1		1		1
Diploneis smithii f. *rhombica* Mer.	b	1–2		1		1–2
Diploneis smithii var. *pumila* (Grun.) Hust.	b	1				
Diploneis subcincta (A. S.) Cl.	b	1				1
Fallacia pygmaea (Kütz.) Sticle et mann	b					1
Fragilaria fasciculata (Ag.) L.-B.	b	2–4	2	2–3		2–3
Fragilaria puchella (Ralfs) L.-B.	b	1–2		1		1–2
Gomphonema exiguum Kütz.	b	2–3		1		1–2
Gomphonema exiguum var. *minutissimum* Grun.	b	1–2		1		1

Table 3 *continued*

Species	Ecol.	Otradnaya Bay	Tsserkovnaya Bay	Malaya Tserkovnaya Bay	Snezhkov Bay	Krabovaya Bay
Gomphonema kamtschatica Grun.	b	1–2		1–2		1
Grammatophora angulosa Ehr.	b			1–2		
Grammatophora hamulifera Kütz.	b	1		1	1	
Grammatophora oceanica (Ehr.) Grun.	b	1		1		1
Gyrosigma distortum (W. Sm.) Cl.	b	1		1		1
Gyrosigma spenceri (W. Sm.) Cl.	b			1		1
Gyrosigma strigele (W. Sm.) Cl.	b	1		1		
Hyalodiscus ambiquus Grun.	pl			1		1
Hyalodiscus obsoletus Sheshuk.	pl			1		1
Hyalodiscus radiatus (O Meara) Grun.	pl			1		1
Hyalodiscus scoticus (Kütz.) Grun.	pl			1–2		1
Istmia nervosa Kütz.	b			1		1
Lyrella forcipata (Grev.) Kar.	b	1		1		
Melosira lineata (Dillw.) Ag.	b	1–4		1		1
Melosira moniliformis (O.Müll.) Ag.	b	1		1–2	1	1–2
Melosira nummuloides Ag.	b	1		1–3		1–2
Navicula directa W. Sm.	pl	1–3	2	1–2		2–3
Navicula distans W. Sm.	pl	1				1
Navicula dithmarsica König.	b	1		1		1
Navicula granulata Bail.	b	1		1		1
Navicula grevillei Ag.	b			1		
Navicula marina Ralfs	b	1				1–2
Navicula spicula Hickie	b			1		
Navicula tenera Hust.	b			1		
Neodenticula seminae (Sim. et Kanaya) Akiba et Yanag.	po			1		1
Nitzschia acuminata (W.Sm.) Grun.	b	1		1		1
Nitzschia coarctata Grun.	b	1				1
Nitzschia constricta (Kütz.) Ralfs	b	1		1		1
Nitzschia hungarica Grun.	b					1
Nitzschia levidensis (W.Sm.) Grun.	b	1				1
Nitzschia levidensis var. *salinarum* Grun.	b	1–2				1
Nitzschia levidensis var. *victoria* (Grun.) Choln.	b	1				1
Nitzschia littoralis Grun.	b	1				1
Nitzschia marginulata Grun.	b	1				1
Nitzschia plana W. Sm.	b	1				1
Nitzschia sigma (Kütz.) W. Sm.	b	1		1		1–2
Nitzschia tryblionella Hantzsch	b	1				1
Odontella aurita (Lyngb.) Ag.	pl	2–3		1–2	1	2–5
Opephora marina (Greg.) Petit	b	1–3		1–3		2–3
Opephora marina var. *nana* Loss.	b	2		2		
Paralia sulcata (Ehr.) Kütz.	pl	1–3		1–2		1–2
Plagiogramma staurophorum (Greg.) Heib.	b	1		1		1
Planothidium hauckianum (Grun.) Round et Bukht.	b	1–3	1	1–3		3–4
Pleurosigma af. *elongatum* W. Sm.	b			1		
Pleurosigma af. *formosum* W. Sm.	b			1		1
Porosira glacialis (Grun.) Jorg.	pn			1		1
Pyxidicula zabelinae (Jouse) Makar. et Moiss.	pn	1				
Rhabdonema arcuatum Kütz.	b	1–3		1–2		1–3
Rhizosolenia hebetata (Bail.) Gran.	po			1		1
Rhopalodia musculus (Kütz.) O.Mull	b	1				
Stephanopyxis nipponica Gran. et Jendo	pn					1
Surirella fastuosa (Ehr.) Kütz.	b	1				
Surirella gemma Ehr.	b	1–2				
Synedra kamtzschatica Grun.	b	1		1–2		1
Thalassionema nitzschioides Grun.	pn	1		1		1

Table 3 *continued*

Species	Ecol.	Otradnaya Bay	Tsserkovnaya Bay	Malaya Tserkovnaya Bay	Snezhkov Bay	Krabovaya Bay
Thalassiosira anguste-lineata (A.S.) Fryxel et Hasle	pn	1		1		1
Thalassiosira bramaputrae var. *septentrionalis* (Grun.) Makar.	pl					1
Thalassiosira decipiens (Grun.) Jorg.	pn	1		1		1
Thalassiosira eccentrica (Ehr.) Cl.	po	1		1		1
Thalassiosira gravida Cl.	pn	1		1		1
Thalassiosira kryophila (Grun.) Jorg.	pn	1		1		1
Thalassiosira leptopus (Grun.) Hasle et G.Fryx.	pn			1		
Thalassiosira nordenskioldii Cl.	pn	1				1
Thalassiosira pacifica Gran et Angst	pn			1		
Thalassiosira punctigera (Castr.) Hasle	pn					1
Thalassiothrix longissima Cl. et Grun.	po	1		1		1
Trachineis aspera Cl.	pl	1		1		1–2
Triceratium arcticum Bright.	b	1		1–2		1

o oceanic, *n* neritic, *l* littoral, *b* benthic; *p* planktonic; abundance: *1* <1 %, *2* 1–5 %, *3* 5–10 %, *4* 10–20 %, *5* >20 %

Tserkovnaya Bay, near the stream mouth. Most of species are typical for partly freshened nearshore water, including benthic brackish-water and marine *Opephora marina* (5.4 %), *Planothidium haukianum* (4.7 %), *Cocconeis pellucida* (3 %), *Planothidium delicatulum* (2.1 %), *Fragilaria fasciculata* (3 %), *Melosira nummuloides* (3 %), *M. lineate*, and marine *Grammatophora hamulifera*. Planktonic diatoms included sub-littoral *Achnanthes brevipes* var. *intermedia, Odontella aurita, Hyalodiscus scoticus*, *Navicula directa,* fragments of *Triceratium arctica*, as well as neritic and oceanic *Coscinodiscus oculus-iridis, Thalassiosira eccentrica, T. kryophila, T. gravida, Thalassiothrix longissima, T. gravida, Thalassionema nitzschioides,* and *Actinocyclus curvatulus.*

Stratified tsunami deposits sampled at the same site, especially those deposits with coarser laminae, show a noticeably lower proportion of marine species but with a prevalence of benthic forms. Small-frustule species are dominant, such as *Planothidium haukianum* (19.4 %), *Planothidium delicatulum* (3.6 %), *Opephora marina* (5.6 %), and *Amphora marina* (3.2 %). The proportion of planktonic diatoms is low, with only the sub-littoral *Navicula directa* and fragments of pelagic *Coscinodiscus oculus-iridis,* and *Thalassiosira decipiens* found.

The overlying fine sands yielded 36 species (up to 62 % altogether), dominated by sub-littoral benthic *Cocconeis scutellum* (27.3 %), *Planothidium haukianum* (4.7 %), *Melosira nummuloides* (3.7 %), and *Opephora marina* (3 %). Planktonic forms included the sub-littoral *Hyalodiscus obsoletus, H. scoticus, Lyrella forcipata, Odontella aurita, and Actinocyclus octonarius,* as well as oceanic and neritic *Rhizosolenia hebetata, Thalassiothrix longissima, Thalassionema nitzschioides.*

The freshwater assemblage is dominated by species characteristic of shallow water bodies with different in salinity, including mesohalob *Navicula halophila* (up to 20 %), *Navicula tenneloides* (49.4 %), *Hippodonta hungarica, Fragilaria construens* f. *venter, and F. brevistriata.* Individual layers in the tsunami deposit were dominated by species more characteristic of running water—*Diatoma mesodon* (31.3 %), *Planothidium lanceolatum* (14.4 %), *Rhoicosphenia abbreviata* (12.8 %), and *Fragilaria arcus* var. *recta* (4.5 %). The freshwater species composition suggests erosion of fluvial deposits both in the stream valley and on the bottom of the bay; the latter was originally a former river mouth inundated as a result of coseismic subsidence in 1994.

Nine marine species were found in marine garbage in Tserkovnaya Bay (66.9 %). *Cocconeis scutellum* (55.7 %) is dominant. Plankton species are represented by sub-littoral *Achnanthes brevipes* var. *intermedia, A. groenlandica, and Navicula directa.* Among freshwater species, the abundant *Navicula* *tenelloides* is typically found in shallow pools or wetlands with moss substrate.

Sands sampled in the Snezhkov Bay yielded 5 marine species, including sub-littoral benthic *Melosira moniliformis, Grammatophora hamulifera, Arachnoidiscus ehrenbergii, Achnanthes brevipes* var. *intermedia*, and fragments of oceanic *Coscinodiscus oculus-iridis*. No marine diatoms were recovered from the mud cap; dominant freshwater species, *Diatoma mesodon* (24.4 %), *Fragilaria arcus* var. *recta* (12 %), *Rhoicosphenia abbreviata* (9.1 %), *Planothidium lanceolatum* (6.2 %), and *Encyonema silesiacum* (6.2 %), are typical for running water.

As many as 56 marine species (51.5–73.8 %) were identified in tsunami deposited muds in Krabovaya Bay (open towards the South Kuril Strait). The species in this bay are highly diverse, including species from genus *Nitzschia* (11 forms), *Cocconeis* (8), *Diploneis* (8), and *Hyalodiscus* (4). A high content of sub-littoral planktonic species (up to 32.4 %) is observed in tsunami deposits in Krabovaya Bay, although not in other studied locations. The assemblage is dominated by sub-littoral benthic species *Cocconeis scutellum* (11.4 %), *Planothidium haukianum* (18.0 %), *Opephora marina* (5.6 %), *Rhabdonema arcuatum* (5.0 %), *Gomphonema exiguum* (2.3 %), and *Amphora marina* (1.6 %), and by planktonic speices *Odontella aurita* (26.0 %), and *Navicula directa* (3.6 %). Some tests of *Nitzschia littoralis, N. levidensis,* and *N. levidensis* var. *salinarum* and others typical of semi-closed bays were also found. The oceanic and neritic assemblage includes northern borean and arctoboreal species *Thlassiothrix longissima, Thalassiosira eccentrica, T. gravida, T. nordenskioldii, T. kryophila, T. punctigera, T. anguste-lineata, Rhizosolenia hebetata, Coscinodiscus marginatus, Coscinodiscus oculus-iridis*, and *Bacterosira fragilis,* along with *warm* water inhabitants—*Thalassionema nitzschioides, Coscinodiscus asteromphalus,* and *C. perforatus*. Species belonging to the freshwater diatom assemblage—*Planothidium lanceolatum, Fragilaria subsalina, F. construens f. venter, Amphora lybica,* and *Cocconeis placentula*—are characteristic of many different types of water bodies. One sample appears to be dominated by species typical for shallow lakes with highly mineralized water, such as *Frustulia creusburgiensis, Navicula libonensis, N. radiosa,* and *Nitzschia liebetruthii*.

Mud deposited by the tsunami on the left side of Otradnaya Bay yielded as many as 41 species of marine diatoms (31.2–88.3 %). High diversity of species from genus of *Nitzschia* (11 forms), *Cocconeis* (8 forms), and *Diploneis* (6 forms) is typical for the bay. Dominant species include sub-littoral benthic *Cocconeis scutellum* (up to 45.6 %, of which 32.5 % have valves >30μm), *C. costata* (3.9 %), *C. californica, C. pellucida, Fragilaria fasciculata* (up to 12.3 %), *F. pulchella* (3.4 %), *Gomphonema exiguum* (up to 8.1 %), *Melosira lineata* (10.4 %), *Planothidium haukianum* (4.1 %), planktonic *Odontella aurita* (up to 4.4 %), *Navicula directa* (up to 3.6 %), and *Surirella gemma* (1.5 %); some *Achnanthes brevipes* var. *intermedia, Paralia sulcata, Trachyneis aspera,* and *Triceratium arctica* are also found. Considerable species diversity is recorded in genus *Nitzschia* (*N. littoralis, N. levidensis, N. levidensis* var. *salinarum, Nitzschia plana, N. marginulata ets.*). A wide variety of species was observed in the oceanic and neritic diatom assemblage, including arctic *Thalassiosira kryophila*, arctic boreal and northern boreal *Thalassiosira gravida, T. eccentrica, T. decipiens, Thalassiothrix longissima, Bacterosira fragilis*, *Coscinodiscus oculus-iridis* (in fragments), and southern boreal *Thalassionema nitzschioides*. The tsunami deposits (mud) sampled at the head of the Otradnaya Bay, 84 m from the water edge, contain 27 marine diatom species (77.1 %). The assemblage is dominated by sub-littoral benthic species, mostly cold-water *Cocconeis scutellum* (28 %), *Fragilaria fasciculata* (7.5 %), *Rhabdonema arcuatum* (6.6 %), *Planothidium haukianum* (5.0 %), and *Opephora marina* (3.8 %), with planktonic *Navicula directa* (6.1 %), *Paralia sulcata* (5.7 %) and south boreal *Actinocyclus octonarius*. The neritic diatoms include south-boreal *Thalassionema nitzschioides* and arctic-boreal *Thalassiosira gravida*.

Marine species number of diatoms is 50 (53.2–82.1 %) in a sample taken at distance of 30 m from the shoreline. The dominant species are *Cocconeis scutellum* (up to 34.4 %, mostly with large size valves), *Odontella aurita* (up to 6.5 %, often with large size valves), *Opephora marina* (up to 6.3 %), *Gomphonema exiguum* (up to 6.2 %), *Planothidium haukianum* (up to 5.4 %), and *Arachnoidiscus ehrenbergii* (up to 2 %). *Nitzschia levidensis, N. levidensis var. salinarum, N. levidensis var. victoriae, N. littoralis, Cocconeis pellucida, C. californica* also appear, but proportion of *Paralia sulcata* is only 2 %.

Samples in Otradnaya Bay contain a wider assortment of neritic and oceanic diatoms, in particular cold-water *Coscinodiscus marginatus, C. oculus-iridis, Thalassiothrix longissima, Thalassiosira eccentrica, T. gravida, T. decipiens, T. angustelineata,* and *T. eccentrica, Thalassionema nitzschioides.* The freshwater assemblage includes species of many different environmental preferences, such as *Fragilaria construens* f. *venter, F. subsalina, F. pinnata, Hippodonta hungarica, Nitzschia frustulum, N. dubia, Rhoicosphenia abbreviata, Navicula cari, N. perminuta,* and *N. rhynchocephala,* which are typically found in different kinds of water bodies. An increase in the number of species characteristic of flowing water—*Rhoicosphenia abbreviata, Meridion circulare, Fragilaria capucina* var. *vaucheriae,* and *Diatoma hyemalis* a.o.—indicates potential erosion and redeposition of fluvial sediments. In the mud collected from the marsh surface, dominant species are *Pinnularia lagerstedtii, P. ignobilis, Navicula cincta, Luticola mutica*—inhabitants of wetlands.

7. Discussion: Sediment Transport and Deposition in a Tsunami

The run-up of the 2011 Tohoku tsunami on the South Kuril Islands was not very high. According to V. Korcuntsev (oral communication), the head of the seismic station in Yuzhno-Kurilsk, the tsunami wave moved like a swift tide. However, in spite of the modest run-up values, specific sedimentologic characteristics of the event can be identified. One of the primary factors controlling sedimentation appears to have been ice cover in closed bays and fast ice on the shore. The icebreaking by the tsunami waves induced bottom erosion on the shoals and destruction of peatlands even at small height of the waves. Studies of the tsunami deposits show that the deposition processes varied considerably on different segments of the coast, likely the result of the interaction of the tsunami wave with local topographic and bathymetric features and the shape of the coastline. Similar to other tsunami (Chagué-Goff *et al.*, 2011), the depositional pattern of the Tohoku tsunami in the South Kurils was controlled by the geomorphic setting of the inundated zone and the offshore bathymetry.

The sediments of the Tohoku tsunami, both in the South Kurils and in Japan (Goto *et al.*, 2011), are diversified in composition. As a generalization, a tsunami with run-up less than 5 m is unlikely to leave a deposit (Dawson and Shi, 2000). This was true of most bays in the South Kuril Islands, where the only traces left by the tsunami were debris, wood fragments, dead grass, etc. Such traces generally cannot be identified in geological sequences.

However, continuous sediment covers were deposited in the closed bays of Shikotan Island, even though tsunami run-up was less than 3 m. Those particular bays had been covered with a thick layer of sea ice before the tsunami; the entrainment of ice floes into the tsunami increased wave erosion, more so in places where the wave encountered an obstacle, no matter how small it was. The material stripped by ice floes served as a source of mud for the fine-grained deposits in Krabovaya and Otradnaya bays. The silt and clay particles settled from suspension on the surface of the ice, peat, or soil; after the tsunami had retreated and the ice had melted, the fine material formed a sheet of mud. There was no ice on the Pacific coast at the time of the tsunami, thus fine-grained deposits are not found on the Pacific coasts.

Stratigraphy of sediments in Malaya Tserkovnaya Bay provides evidence of the passage of several waves during the tsunami event. Silty sands most probably formed during a prolonged stand of water when both bedload and suspended fine material were deposited, after the wave had reached its maximum and completely spent its energy. The sediments lie over the previous year's grass without visible traces of washout.

On Kunashir, the tsunami traces are negligible; a thin sand layer reported to occur on ice floes immediately after the event could not be found half a year later. Similarly, tsunami sediments in the southern Lesser Kuril Islands were rare; only isolated patches were found on Zeleniy Island.

The grain size distribution of tsunami deposits does not show noticeable changes either vertically or horizontally. Although an admixture of silt increases slightly landwards, the modal fraction dimensions do not change and the mean grain size varies only slightly. In the silt sheets, much like the sands, the mode is constant along shore-perpendicular profiles, while the distribution of other size fractions varies slightly and irregularly. Admixtures of coarse silt particles or fine sand occasionally increase in proportion with distance from the coast, so that the grain distribution curves become bimodal. In some locations, the proportion of clay increases near the water edge. In all probability, the process of fine particle deposition from suspension was complicated due to the material transport by ice floes. It is worth noting that the mode 20–30 μm persists in fine-grained tsunami deposits sampled in different bays and may be considered indicative of common pattern in the material settling from suspension or of a commonality in the original mode of the source material.

Comparison of the grain size composition of the 2011 Tohoku tsunami and the 1994 Shikotan tsunami deposits shows that the 1994 deposits generally have more coarse fractions (Fig. 7). The 1994 deposts are polymodal curves, probably due to the fact that the tsunami in 1994 was larger and caused greater erosion, resulting in a larger and potentially more diverse source area for deposit material.

The grain size of the tsunami deposits depends not only on the characteristics of the tsunami wave itself, but also largely inherits characteristics of the source material. In open bays, the tsunami deposits were well-sorted sands similar to sediments of the beach, foreshore and the upper part of the shoreface, implying this was from where the bulk of the material was supplied. Silty clays were deposited by the tsunami wave in closed bays, the source of the material being seafloor mud and other products of seafloor sediment erosion within the bays. Single-mode curves of grain-size distribution suggest the material was supplied from a single source, while bimodal and polymodal curves are typical for sediments supplied from two or more sources. It should be mentioned that the source of silt material in the Tohoku tsunami deposits was mostly redeposited marine sediments; usually that is not characteristic of tsunami deposits. However, tsunami deposit studies are generally located along coasts of different geomorphic setting than the southern Kuril Islands, and thin fractions are mostly derived from sources on land (Sawai *et al.* 2009; Goto *et al.*, 2011).

The species composition of benthic Foraminifera in the deposits suggests that the tsunami wave entrained material from the upper shoreface. Only sub-littoral species occur, many of which inhabit the surf zone or tidal marsh. Their well-preserved shells imply that they have been transported for a short distance under condition of weak turbulence; such conditions are expected during modest tsunami run-up. When the run-up exceeds 10 m (a case not observed in the southern Kurils for the 2011 Tohoku event), Foraminifera shells found in tsunami deposits are mostly poorly preserved and well rounded. As an example, the 2006 tsunami deposits on Simushir contained benthic Foraminifera with thick porcelaneous walls; such Foraminifera are characteristic inhabitants of open shelf or continental slope at a depth of 50–1,000 m (Razzhigaeva *et al.*, 2009). Benthic Foraminifera assemblages described in deposits of the 2004 tsunami on the island of Simeulue (150 km off the west coast of Sumatra) were dominated by species typical of coral reefs, lagoons and inner shelf. The presence of benthic Foraminifera typically inhabiting the outer shelf and continental slope suggests a limited quantity of material was brought from greater depths by the tsunami. Such species are found in the tsunami deposits formed under many values of run-up, although they are particularly abundant where the tsunami wave height exceeded 8 m. Dominant among coral fragments were species typical of the shallow-water part of the reef with corals from a depth of 5–12 m only occasionally found. Large blocks of reef limestone were also brought by the tsunami from moderate depths as judged from coral species composition (Razzhigaeva *et al.*, 2006).

Rich assemblages of diatoms have been identified in the 2011 Tohoku tsunami deposits in the South Kuril Islands. As typical of tsunami deposits, they appear to contain a mixture of marine and freshwater diatoms with many different ecological requirements (Hemphill-Halley, 1996; Grebennikova *et al.*, 2002; Dawson, 2007; Sawai *et al.* 2009; Horton *et al.*, 2011). Sub-littoral benthic species prevail in the group of marine diatoms, suggesting that the material came mostly from offshore. Noteworthy in the 2011 Tohoku deposits was the presence of large (up to 30 μm) frustules attributed to *Cocconeis scutellum,* and *Odontella aurita*. Unlike deposits of a tsunami with high run-up, where diatom frustules would be heavily broken (Grebennikova *et al.*, 2002; Dawson, 2007; Sawai *et al.* 2009), diatoms recovered from the Tohoku tsunami deposits in the South Kuril Islands are reasonably well preserved. Quite often the diatoms occurred in communities (colonies), implying weak turbulence and currents, such as conditions existing during small tsunami run-up, in order to be deposits. However, the occurrence of diatom in colonies could promote faster settling of the diatoms, including those with small valves, allowing for better preservation. In case of stratified tsunami sediments, coarse sand laminae are dominated by marine benthic species, while fine-grained sands layers have a higher proportion of planktonic ones. The same regularity was noted in deposits of the 2004 tsunami in Indian Ocean on Thailand coasts (Sawai *et al.* 2009).

An interesting result of the diatom analysis in the tsunami deposits on Shikotan was the difference in environmental temperature regime of species from the deep-sea assemblages. In the tsunami deposits sampled on the Pacific side of the island (Malaya Tserkovnaya Bay), though cold-water species are dominant, south-boreal species frequently occurred. On the other side of the island, facing the South Kuril Strait (Krabovaya and Otradnaya bays), the warm-water south-boreal species are almost completely absent from the deposits, with only two fragments found in two samples. Presumably, the diatoms with different environmental requirements were brought by the tsunami wave that entrained different water masses when skirting the island.

The freshwater diatom assemblages provide information on continental sediments redeposited by the tsunami. More often than not, the assemblages include freshwater diatom species characteristic of many different environments; the mixing of environments may be result of integration of the material coming from multiple sources. If a single sediment type was eroded, the assemblage would consist of diatoms with similar environmental preferences. For example, if the tsunami passed through an oxbow lake or eroded actively fluvial sediments, the assemblage would be dominated by the species typical of flowing streams. If lacustrine sediments were subjected to erosion, the dominant species would be those typically inhabiting lakes.

No obvious post-depositional processes acted to modify the tsunami deposits in the half year after the tsunami, unlike the many processes affecting the deposits in Japan (Goto *et al.*, 2011). Wind erosion likely did not occur because the tsunami deposits overlie a wet swamp surface and were therefore moist enough to have eolian transport inhibited. The deposits were overgrown with grass all over the field area in the half year since deposition and no erosional traces were observed.

The run-up values of the Tohoku tsunami in the South Kurils were similar to the extreme storm surge recorded in 2006–2007 (Ganzey *et al.*, 2010). Some bays experienced less inundation during the tsunami than during the 2006–2007 storms (Fig. 3). The tsunami sedimentation was essentially different from that of the extreme storms, even with the similar run-up values. The storm surge produced a thick (up to 0.7 m) sheet of coarse deposits forming a narrow strip near the first storm bar (Ganzey *et al.*, 2010). The tsunami of comparable height generated little, if any, surface erosion and in most bays rarely left a deposit except for occasional cobbles and pebbles. In Tserkovnaya Bay on Shikotan, for example, a storm left a sheet of sand up to 0.5 m thick, the 1994 Shikotan tsunami [5–8 m run-up and 180 m inundation (Yeh *et al.*, 1995; Kaistrenko *et al.*, 1997; Levin *et al.*, 1997)] left a sand layer less than 1 cm thick (Razzhigaeva *et al.*, 2007), while the 2011 Tohoku tsunami (3 m run-up) left no deposits.

In the closed bays of Shikotan Island, storm deposits from 2006 to 2007 formed a narrow strip of sediments along the shoreline, while the tsunami left extensive sheets of fine material. At the time of strong storms, slope deposits on the bay sides were subject to intense erosion and as a result, a sizeable volume of angular coarse debris was brought towards beach. This coarse material was repeatedly redeposited in the surf zone and incorporated into the storm deposit near the shoreline. Compared to the storm deposits, the tsunami deposits were more fine-grained, with a noticeable admixture of silt and clay particles. At the time of tsunami, the material was partly supplied from the bay bottom, while another part was produced by erosion and redeposition of terrestrial sediments of different facies.

The data obtained by the studies of the 2011 Tohoku tsunami are of considerable importance in interpreting materials on paleotsunami deposits on the Kuril Islands. In the case of the 2011 Tohoku tsunami, we know the characteristics and specific features of its passage through the South Kurils, as well as the sources of clastic material forming the deposits. In addition, the Tohoku tsunami deposits were undisturbed and had not be subjected to significant post-depositional processes at the time of study. As a result, this investigation and others similar are important for developing methodical approaches to reconstructing catastrophic events of the past and understanding characteristics of tsunami deposits in regions peripheral to the main direction of wave propagation. The observations in this study also help to understand the mechanism of the better preservation of detailed geological records in the deposits of closed bays (Razzhigaeva *et al.*, 2011) in comparison with open coasts. In particular, when studying sedimentary sequences on coasts of closed bay, one should pay attention to thin laminae of silty and clayey mud, rich in organic matter, as they may be originally related to tsunami. The significance of such organic-rich sediments for paleo-tsunami identification has been noted by Chagué-Goff *et al.* (2011).

8. Conclusions

The 11 March 2011 Tohoku tsunami came to the South Kurils as waves of moderate height. The characteristics of tsunami deposition varied, essentially depending on local coastal topography. Half a year after the event, traces of the tsunami could be only seen in most of bays as a wrackline (a strip of marine pebbles, wood fragments, dry weeds, *Zostera* sp., etc.). In open bays, deposition was limited to widely scattered cobbles, pebbles and spots of sand. However, in closed bays, extensive sheets of sediments were deposited. One of the factors that produced a considerable effect on tsunami deposition was the presence of sea ice cover, which was broken and transported even at moderate tsunami wave heights. The ice floes were instrumental in bottom erosion of bay bottom and the destruction of peatlands on the low coasts. On such coasts, tsunami deposits were mostly organic muds, with a large proportion of silt and clay. The silty sand deposition was likely related to prolonged periods of stagnant water, when fine-grained material could settle from suspension. The Tohoku tsunami deposits are different from other coastal facies, as well as from sediments left in the southern Kuril Islands by other recent tsunami. As determined by analysis of benthic Foraminifera and diatom assemblages, the material for the deposit was mostly supplied from the upper portion of shoreface and from continental formations belonging to various facies. Good preservation of microfossils and the presence of colonies of benthic marine diatoms suggest low turbulence during tsunami flow and a short distance of transportation.

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