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Specific Features of the Ecological Composition of Planktonic and Benthic Foraminifera in Surface Sediments of the Tatar Strait (Sea of Japan)

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Abstract—The fauna of planktonic and benthic foraminifera of the Tatar Strait was studied in the surface layer of sediments from bottom cores collected during cruise LV85 of the R/V *Akademik Lavrentyev* in May 2019. The communities of benthic foraminifera, consisting of living and dead shells, in their ecological appearance correspond to the modern cold-water oceanographic conditions of the sampling sites of the stations. Among the planktonic foraminifera, in addition to the dominant subarctic form *Neogloboquadrina pachyderma dex.*, there are single tropical and subtropical species (*Globorotalia inflata, Globigerinoides ruber*, and *Neogloboquadrina dutertrei*). The authors believe that the above-mentioned warm-water forms entered the Tatar Strait from the southwestern Sea of Japan with warm Tsushima Current waters. Fossil records of warm-water fauna in Pleistocene and Holocene sediments play an important role in interpreting the geological record in the northern Sea of Japan. Their presence in sedimentary sections makes it possible to trace the northward migration of warm currents and assess its influence on coastal ecosystems in the past.

Keywords: microfauna, Tsushima Current, Holocene, Pleistocene, Sea of Japan

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INTRODUCTION

In semienclosed marine waterbodies, special hydrological conditions often arise that affect not only the regional climate, but also the structure and functioning of planktonic and benthic communities. Such objects include the Sea of Japan, which is connected to the Pacific Ocean and its seas through narrow, shallow straits. An important element of the circulation of water masses in a particular basin is the distribution of warm and cold currents. The influx of warm and saline ocean waters from the East China Sea, transported by the Tsushima Current (northern branch of the Kuroshio Current) through the Korea Strait (130 m), plays an important role in the water–heat balance of the Sea of Japan. Along the coast of Primorye from the north is the less intensely cold Primorye Current (Fig. 1). The main outflow of water from the Sea of Japan is through the Tsugaru Strait (130–150 m) and La Perouse Strait (55 m). A more complex oceanographic environment in the Sea of Japan arose in the past during alternating glacial and interglacial periods. The glacioeustatic decrease in sea level to minus 120–130 m during the cold periods of the Pleistocene led to a reduction in the flow of Tsushima Current waters as a result of complete or partial isolation of the Sea of Japan from the south (Pletnev, 1985). Conversely, during warm periods, due to the rise in sea level, the "gates" of the Korea Strait opened completely and the role of the warm current increased. Thus, amplitude changes in sea level controlled the influx of warm Pacific waters from the south, enhancing the effect of global climate warming during interglacials era and causing additional cooling of the Japanese waters during cold periods (Pletnev and Grebennikova, 2007).

Currently, the influence of the Tsushima Paleocurrent on the natural environment of the southeastern and central Sea of Japan over the past 5 Ma has been established (Gallager et al., 2015). Actualistic criteria for identifying paleocurrents based on lithological and geochemical features and organic remains of flora and fauna have been developed (Fairbanks et al., 1982; Gallager et al., 2009, 2015; Oba et al., 1991). However, these tracers and paleogeographic constructions do not cover the northern Sea of Japan (Tatar Strait) due to its insufficient study. Meanwhile, the effect of the softening influence of the warm Tsushima Current is felt not only on the modern climate of the northern waters, but also on the adjacent coasts of Sakhalin Island and Primorye. For example, owing to this warm current, the southwestern slopes of Sakhalin Island are warmed; mixed broadleaf forests grow and predomi-

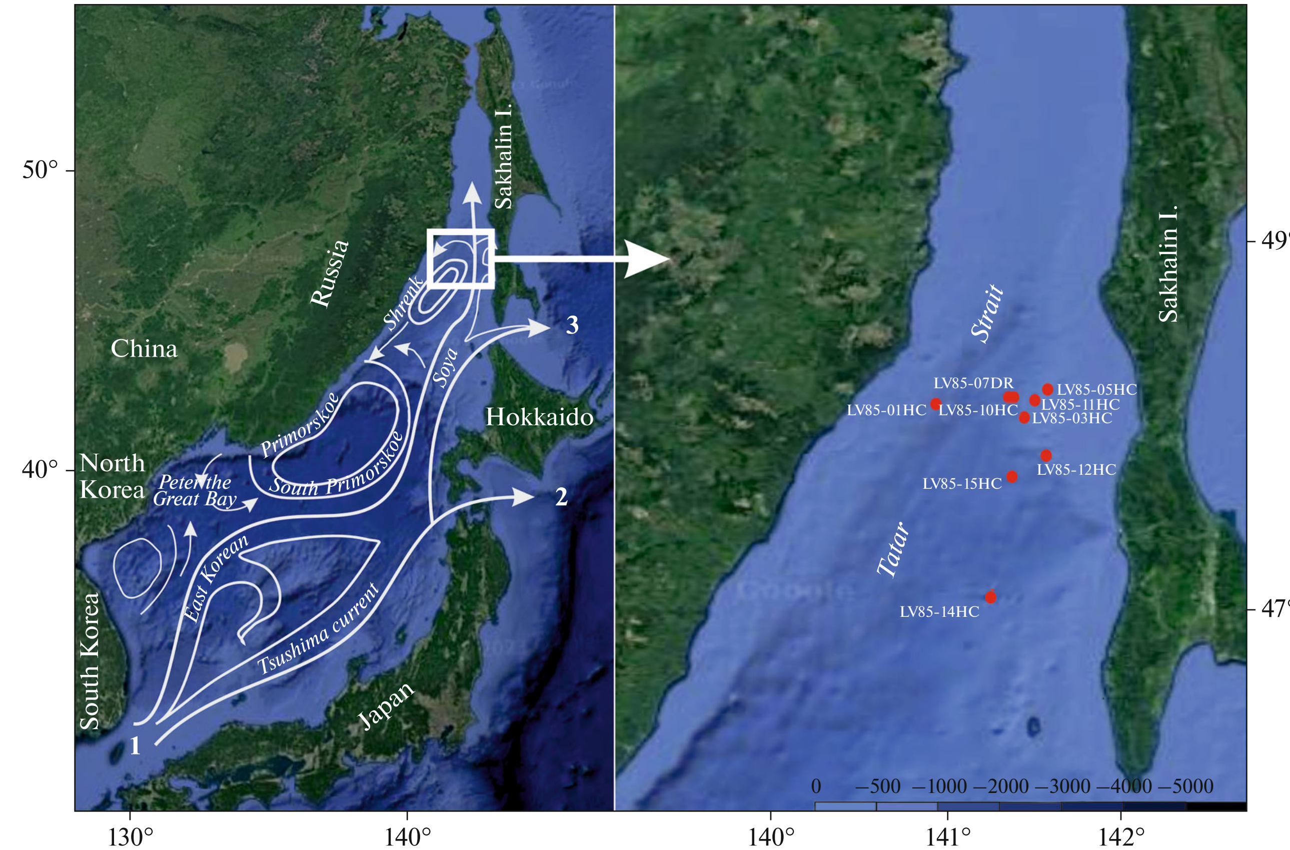

Fig. 1. Map of Sea of Japan region with locations of studied stations in Tatar Strait indicated in red and generalized diagram of water circulation after (Yurasov, 1991): (1) Korean Strait; (2) Tsugaru Strait; (3) La Perouse Strait.

nate there (Mikishin et al., 2022). At the same time, the other, unheated slopes are covered with taiga plant communities. One branch of the Tsushima Current, called the Sōya, goes around Hokkaido and significantly moderates the climate in the southern Sea of Okhotsk, including the Southern Kuril Islands (*Far Eastern*..., 2007). Another, branch, the western, in the warmest seasons penetrates Peter the Great Bay and warms the waters of Southern Primorye. In general, the Tsushima Current has and continues to play an important role in the formation and development of flora and fauna throughout the Sea of Japan. Therefore, in the authors' opinion, additional information is needed on its influence in the northern part of the sea, both at the present stage of the basin's development and in the past. The aim of this work is to study the ecological composition of planktonic and benthic foraminifera in surface sediments of the northern Sea of Japan, to identify the most indicative indicator species of the warm Tsushima Current, and, based on fossil finds thereof, to assess changes in the climate regime of this water area in the past.

Table 1. Catalog of stations at LV-85 survey site

Station no.	Latitude, N	Length, W	Depth, m
LV85-01HC	48°12.024	140°35.491	390
LV85-03HC	48°10.176	141°07.21	767
LV85-05HC	48°13.863	141°23.011	332
LV85-07DR	48°07.251	141°09.90	625
LV85-10HC	48°07.744	141°10.431	617
LV85-11HC	48°07.999	141°18.902	323
LV85-12HC	47°42.700	141°22.138	303
LV85-14HC	47°03.934	141°02.795	1056
LV85-15HC	47°41.124	140°54.004	1051

MATERIAL AND METHODS

The materials for this study comprised surface samples of bottom sediments at nine stations in the Tatar Strait during cruise LV85 on the R/V *Akademik Lavrentyev* in May 2019 (Fig. 1; Table 1).

Sampling was done with a hydrostatic tube with a diameter of 12.5 cm and length of 550 cm. The sampling stations were in the depth range of 257–1056 m. To view the microfauna, wet sediment, the upper 2–3 cm, and a sample of 50–100 g were rinsed on a sieve of 0.05 mm in size and filled with a dye for 1–2 days—an

Table 2. Total planktonic foraminifera abundance in 50 g of sediment and relative abundance of species (%) in surface samples of Tatar Strait

Station numbers LV85	12	11	5	1	10	7	3	15	14
Species	Depth (m)								
	303	323	332	390	617	625	767	1051	1056
Neogloboquadrina pachyderma sin.(Ehrenberg), %	56	62	80	67	61	84	55	70	64
N. pachyderma dex.(Ehrenberg), %		2		<1					2
Globigerina bulloides sin., d'Orbigny, %	28	32	15	18	28	16	32	22	22
G.bulloides dex., d'Orbigny, %	10	4	5	12	11		12	8	12
Turborotalia quinqueloba (Natland), %	6			2			<1		
Globigerinita glutinata (Egger), %	<1			1					
Neogloboquadrina dutertrei (d'Orbigny), %		<1	<1						
Globorotalia inflated, d'Orbigny		<1	<1						
Globigerinoides ruber, (of Orbigny), %		<1	<1						
Number of shells per 50 g of sediment	22	18	14	50	750	20	1870	60	44

alcohol solution of rose bengal (70%), which stained the cytoplasm of foraminifera crimson. The staining technique makes it possible to separate "live" shells of benthic foraminifera from dead ones and to assess the autochthony of the burial of bottom fauna. In each sample, the number of shells and taxonomic species composition of foraminifera were determined to identify the specific features of the community structure at the studied stations. For a comparative description of the quantitative content of foraminifera shells, the number of ind. in each sample was recalculated per 50 g of dry sediment (Tables 2, 3). This is often done for sediments that have accumulated in areas with high terrigenous dilution and low foraminifera concentrations (Saidova, 2009). The study uses the foraminifera classification developed by A. Loeblich and G. Tappan (1987).

RESULTS AND DISCUSSION

In the studied microfaunistic communities, benthic (37 species) and planktonic (9 species) foraminifera were identified (Tables 2, 3). The abundance of planktonic foraminifera shells varies greatly from 10 to 1870 ind. in 50 g of dry sediment. The low abundance of planktonic foraminifera shells in sediment is associated with large supplies of terrigenous material, which greatly dilutes the biogenic component. The high shell count at station LV85-3 (1870 ind./50 g) and station LV85-10 (750 ind./50 g) is probably caused by local upwelling processes in the upper part of the island slope.

Among the planktonic taxa, the following foraminifera significantly predominant: the subarctic variety *Neogloboquadrina pachyderma* sin. (55–84%), boreal species *Globigerina bulloides* (20–36%), and *Turborotalita quinqueloba* (0–6%). This faunal composition corresponds to the subarctic thanatocenosis found in the northern Sea of Japan with average annual water temperatures of 4–6°C (Pletnev, 1985). Completely unexpected among planktonic species were the discoveries of such warm-water forms as *Globigerinoides ruber, Globorotalia inflata, Neogloboquadrina durertrei,* and *N. pachyderma* dex. (Fig. 2), which now live only in the southern Sea of Japan with average annual water temperatures above 15°C (Domitsu and Oda, 2006). These species were found only at stations LV85-11 and -10, where the depths are 323 and 617 m, respectively. According to Japanese colleagues, the tropical species *G. ruber* migrates to the Sea of Japan with the Tsushima Current (Kitamura, 2001; Domitsu and Oda, 2006) and is its reliable indicator is *G. ruber*, a shallow-water species that inhabits surface waters during its life cycle (Fairbanks et al., 1982). The lower temperature limit of its habitat is limited by the 19°C isotherm (Hemleben et al., 1989).

The change in the content of sinistral (cold-water) and dextral (warmer-water form) *N. pachyderma* is also used as a Tsushima Current tracer (Oba et al., 1991). Although it is difficult to agree with this conclusion, since *N. pachyderma* dex., belongs to the southern boreal climate group. Its presence in the fauna of the southern Sea of Japan is most likely due to the geographical location of the waterbody and comfortable living conditions, not just the warm waters of the Tsushima Current (Pletnev, 1985). Even though in winter almost 50% of the area of the Tatar Strait is covered with ice, in summer, the water temperature rises to 18–20°C in the upper 10–15 m of the study area (*Far Eastern*..., 2007), creating favorable conditions for habitation and reproduction of *G. ruber* in the Tatar Strait. Below the 15 m isobath, the temperature decreases, and at a depth of 50 m, reaches 4°C (*Far Eastern*..., 2007). Since *G. inflata* and *N. dutertrei* live

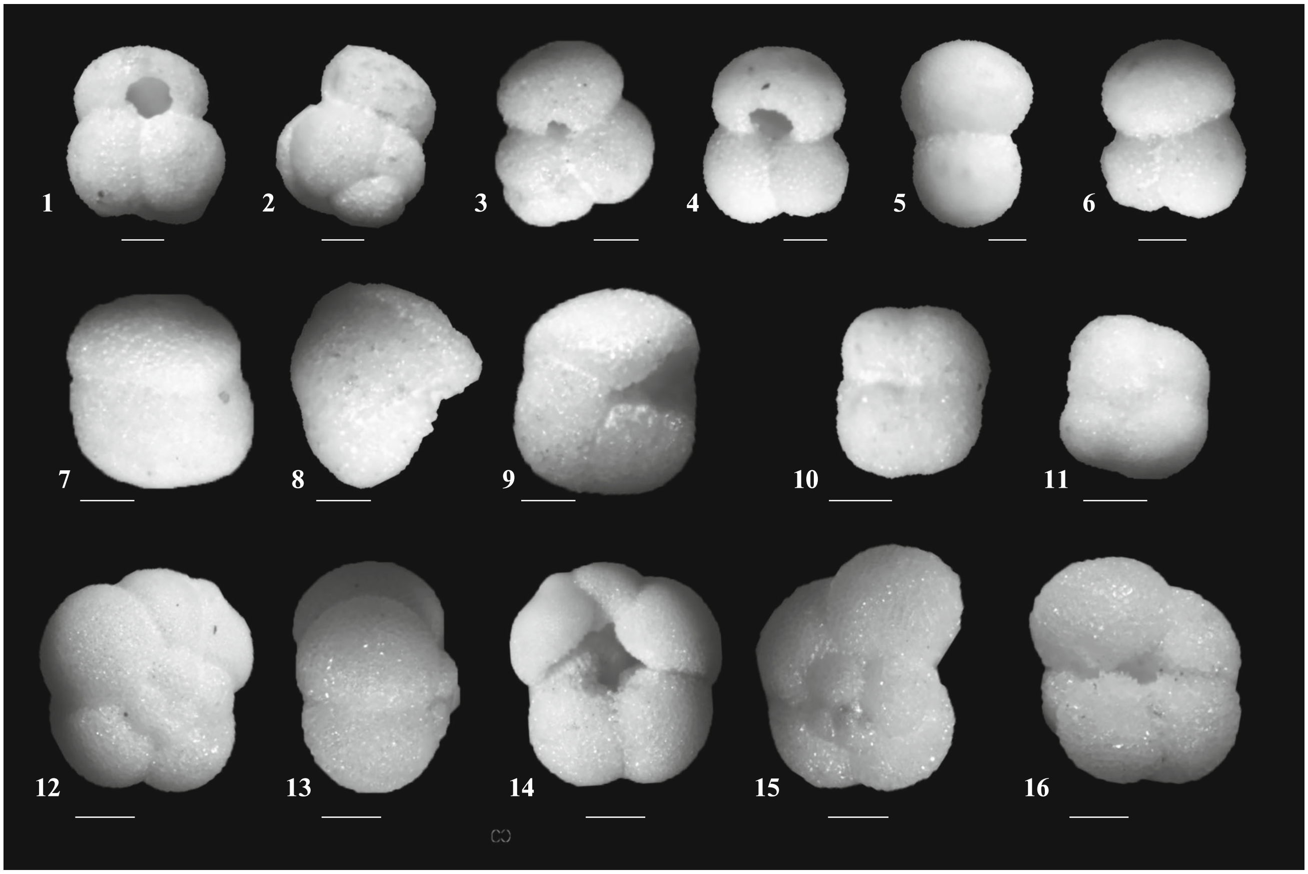

Fig. 2. Warm-water species of planktonic foraminifera found in surface samples of Tatar Strait: (1–6) *Globigerinoides ruber*; (7–9) *Globorotalia inflata*; (10–11) *Neogloboquadrina pachyderma* dex.; (12–16) *Neogloboquadrina dutertrei.*

at greater depths than *G. ruber*, such low temperature conditions are unsuitable for their reproduction. It is highly likely that *G. inflata* and *N. dutertrei* were transported to the survey site by a warm current as already dead shells. The average speed of the Tsushima Current in the northern Sea of Japan is about 0.2–0.4 m/s (Andreev, 2018), which allows empty shells of these species to be transported over long distances.

Finds of warm-water planktonic foraminifera shells have been noted in Quaternary sediments and more northern waters (Romanova, 2013). All of them are associated with the inflow of warm waters from more southern regions. Planktonic species *G. ruber* and *G. conglobatus* were encounted by Z.G. Shchedrina (1953) in bottom sediments of the Sea of Okhotsk near the northern coast of Hokkaido and the southern margin of Sakhalin. According to N.V. Belyaeva and I.I. Burmistrova (2003), these species could have penetrated from the West Pacific Ocean through the Tsushima Strait first into the Sea of Japan, and through the La Perouse Strait with the Sōya Current into the Sea of Okhotsk. Similar, but larger-scale, advection of warm Atlantic waters with tropical planktonic foraminifera fauna were noted in the Kara Sea (Oskina et al., 2019).

Among benthic foraminifera, 37 species with carbonate and agglutinated shells were found (Table 3). Shells with protoplasm make up a fifth and, in terms of species composition, are close to the entire community, including living and dead benthic foraminifera. The number of benthic foraminifera shells in sediment is low, varying from 18 to 129 ind./50 g of dry sediment. The greatest number of shells was recorded at stations with depths of 300–800 m. With increasing depth, the number of shells decreases to 18 ind./50 g sediment, but among them, the role of agglutinated forms increases to 30–45%. Carbonate shells at deep-sea stations are corroded and often show signs of dissolution. In our opinion, in the area of the survey site, bottom water is undersaturated in CO_2 during cold seasons, which leads to selective dissolution of calcareous shells as a result of an abnormally high carbonate compensation level. This issue requires further study.

Within the depth range of 303–390 m (stations LV85-12, -11, -5, and -1) in thanatocenoses of benthic foraminifers, carbonate shell species dominate: *Cribroelphidium batiale, Cassidulina subacuta, Globobulimina hanzawai,* and *Nonionellina labradorica*; to a lesser extent, species with an agglutinated shell have been noted: *Alveolophragmium orbiculatum, Cribrosto-*

Table 3. Abundance of live and dead benthic foraminifers, total abundance of shells per 50 g of sediment in studied samples

Station number	12		11		5		1		10		7		3		15		14	
Depth, m	324		323		332		390		617		625		767		1051		1056	
Genus, species alive/dead	l	m	l	m	l	m	l	m	l	m	l	m	l	m	l	m	l	m
Globobulimina hanzawai (Asano)	9	3							2	2		4	12	32				
Alveolophragmium orbiculatum Stschedrina	2	29				16	6	18		44				28				14
Nonionellina labradorica (Dawson)	2	29				4		18	4	18	2	44		16	2	22	2	14
Uvigerina akitoensis Asano	1	6		2				26		2								
Reophax dentaliniformis (Brady)	1	1												4				22
Cribroelphidium batiale (Saidova)		23	2	14	16	48	6	56		38	4	70		20	12	80		10
Trifarina kokozuroensis (Asano)		5						2				20		16				
Cibicides rotundatus Stschedrina		2						2						8				
Cribrostamoides scitulus (Brady)		4					2	4		14						16		
Haplophfragmoides rostriformis Troitskaja K.Furssenko		1			4	14				2		2						
Planocassidulina kasiwazakiensis Troitskaja		1						4						4				
Trochammina quadriloba Hoglung		7																
Reophax curtus (Cushman)			4	6			6	22		6				12	4	28		
Trochammina voluta Saidova			2	8		28		2	6	22				4		24		2
Cassidulina subacuta (Gudina)			2	14						2		4		4				
Discoislandiella umbonata (Voloshinova)			2	2					2	6		16						
Labrospira tunis (Cushman)				8														
Miliammina herzenstaini (Schluvberger)				2			6	26		28						8		4
Rhizammina surtida Saidova				2										12				
Lagena elongata(Ehrenberg)				1														

Table 3. (Contd.)

Station number	12		11		5		1		10		7		3		15		14	
Depth, m	324		323		332		390		617		625		767		1051		1056	
Genus, species alive/dead	l	m	l	m	l	m	l	m	l	m	l	m	l	m	l	m	l	m
Islandiella japonica (Asano et Nakamura)							2	52										
Nonionella japonica Asano								2		2								
Dentaliba sp.								2										
Dentaliba emaciata Reuss								2										
Tappanella niponica (Asano)								2		2								
Cibicidoides lobatulus (Walker et Jacob)									2	2								
Ammotium cassis (Parker)										8								
Cribrostamoides batialis Troitskaja K. Furssenko										20								
Nonionella digidata (Norvang)										4								
Alabamina multicamerata Nesterova												10		10				
Retroelphidium sp.												22						
Recurvoides contaryus sublitoralis Saidova												2						4
Pyrgo depressa (Orbigny)														2				
Uvigerina parvocostata Saidova														24				
Ammotium inflatum (Stschedrina)																16		
Recurvoides turbinatus (Brady)																12		
Brizalina sp.																2		
Number of live and dead shells	15	111	12	59	20	110	28	240	16	222	6	194	12	196	18	208	2	70
Sample weight in g	190		193		198		91.7		212.3		197		201.4		139		195.2	
Number of foraminifera in 50 g of sediment	33		18		32		129		56		51		51		81		18	

l—living; m—dead.

moides scitulus, Reophax curtus, and *Trochammina voluta*. Station LV85-1, sampled from a depth of 390 m, showed the maximum abundance of benthic foraminifera (129 ind./50 g). Here, in addition to the above-mentioned species, a high participation of the carbonate species *Uvigerina akitaensis* and *Islandiella japonica* was noted.

At stations LV85-10,-7, and -3, in the depth range of 617–767 m, the abundance of shells and species composition of benthic foraminifera do not differ significantly from the above-described fauna, which inhabits the depth range of 303–390 m. The most representative in the communities are carbonate species *C. batiale* and *N. labradorica* at depths greater than 1000 m, while the role of agglutinated species *R. curtus* and *T. voluta* increases.

In general, the fauna of benthic foraminifera is characteristic of the continental slope of the northern Sea of Japan, where terrigenous–clayey silts predominantly accumulate under conditions of high oxidation potential (Annin, 2002). The benthic foraminifera do not contain such warm-water species as *Asterorotalia gaimardii* and *Heterolepa margaritiferus*, which penetrate from the East China Sea and live in the southwestern Sea of Japan in the Tsushima Current zone (Gallagher et al., 2009; Hoiles et al., 2012). All this indicates that warm Tsushima Current jets do not have a particular effect on the temperature regime of bottom waters and the composition of benthic communities in the study area at depths greater than 300 m.

Thus, our micropaleontological analysis in the Tatar Strait confirmed the possibility of using modern and fossil finds of tropical and subtropical species of planktonic foraminifera as reliable indicators of the influence of the Tsushima Current on the study area. Their shells are small in size and have rather thin walls, which indicates the oppressed conditions of their habitat. The absence of thermophilic species at stations with depths greater than 400 m is due to their selective dissolution or limitation of the width of the flow of warm currents along Sakhalin. More accurate data could be obtained from regular observations of plankton catches, since warm-water species probably penetrate only in abnormally warm years.

CONCLUSIONS

(1) The study of planktonic and benthic foraminifera in surface sediments at the LV85 site complements and expands general information on the distribution patterns of this group of organisms in a little-studied region of the Tatar Strait. In the studied foraminifera complexes, 46 species and their varieties were identified: 37 of them are benthic, and 9 are planktonic. The greatest number of their shells is noted in the depth range of 300–800 m, apparently due to local upwelling in the upper part of the island slope of Western Sakhalin. Living individuals of benthic foraminifera make up 10–18% of the total number of shells, and they are identical in their species composition to the entire foraminifera community, including dead shells. Increased agglutinated foraminifera and corroded calcareous shells indicate increased selective dissolution carbonate species within the isobaths of 800–1000 m. Among the benthic foraminifera, no penetration of thermophilic species from the south was noted.

(2) The subarctic *N. pachyderma* sin. dominates the studied planktonic foraminifera fauna at all stations (55–84%). The appearance of such warm-water planktonic foraminifera *G. ruber* and *G. inflata* in surface sediments of the Tatar Strait with its cold oceanographic conditions is explained by their transport by the surface flow of the warm Tsushima Current in autumn–summer from the Korea Strait. From the standpoint of actualism, findings of shells of the warm-water species *G. ruber* and *G. inflata* in Holocene and Pleistocene sediments may be good indicators of the penetration of warm waters of the Tsushima Paleocurrent into the northern Sea of Japan. The presence of shells of the equatorial–tropical species *G. ruber* in the fossil community indicates an increase in surface water temperatures in the northern Sea of Japan in past eras to 19°C or higher.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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