# Onset of Connections between the Pacific and Arctic Oceans through the Bering Strait in the Neogene

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**Abstract**—New data on the Neogene diatoms, mollusks, and magnetostratigraphy in the North Pacific and surrounding structures suggest the Bering Strait incipient opening in the latest Miocene or probably in the earliest Pliocene. Stratigraphic positions of oldest Arctic migrants in the Pacific sequences and of Pacific migrants in the Arctic sections are defined. Tectonic processes and eustatic fluctuations as possible causes of the strait opening are analyzed. The consequent changes in biota migration directions, oceanic circulation, and bioproductivity of planktonic groups are discussed.

**Key words:** Neogene, Bering Strait, diatoms, mollusks, oceanic connections, biota migration.

## INTRODUCTION

The Neogene history of the Bering Strait has been considered in many publications. Pioneering works appeared in the 1960s–1970s, when new data on the Cenozoic of Iceland and the North Atlantic were obtained (Durham and MacNeil, 1967; Einarsson *et al.*, 1967; Strauch, 1970, 1972; Einarsson and Yu. Gladenkov, 1973; MacNeil, 1973; Yu. Gladenkov, 1974, 1976, 1978). In the next period of the late 1970s–1990s, the Neogene stratigraphy of Kamchatka, Japan, and Alaska was studied in detail (Allison, 1978; Yu. Gladenkov *et al.*, 1991a; *Detailed…*, 1992; Suzuki and Akamatsu, 1994; Ogasawara, 1998). The third information wave occurred at the turn of the century after Alaska sections had been restudied (Marincovich and A. Gladenkov, 1999, 2001; Marincovich, 2000; Marincovich *et al.*, 2002; A. Gladenkov *et al.*, 2002, A. Gladenkov, 2003). It is natural that views on the Neogene history of the strait and on its opening time changed during the last 35–40 years, but both problems remain challenging nowadays.

Yu. Gladenkov (1995) outlined seven solved and six unsolved problems of the paleo-Bering Strait history. Now, nearly ten years later, we can discuss them again and correct the strait development model. The latest data on Neogene diatoms (first of all), mollusks, and magnetostratigraphy of Kamchatka, Alaska, and Japan enable a more reliable dating and correlation of many formations of the North Pacific region. In turn, new stratigraphic interpretations elucidate the appearance time of the characteristic molluscan assemblage with *Astarte* in the Pacific sections. In opinion of many geologists, the assemblage penetrated into the North Pacific from the Arctic basin at the time of the Bering Strait

opening. The latter event has been also considered long as responsible for the appearance of Pacific molluscan assemblage with *Serripes groenlandicus* in Neogene deposits of the North Atlantic.

In addition to new regional materials, geochronology of general standard zonations has been more precisely correlated with the geomagnetic polarity time scale (Berggren *et al.*, 1995). The modern definition of the Neogene stage and zone boundaries eliminated previous uncertainties in stratigraphy of corresponding sedimentary sequences in the Pacific areas. The revised time spans of particular stratigraphic levels corrected essentially the previous correlation schemes (for instance, the age correction of some levels in the well-known Karaginskii section of northeastern Kamchatka is as great as 0.5 m.y.). As a result, the newly obtained geological data enable a more precise correlation of tectonic, climatic, and biotic Neogene events in the northwestern and northeastern Pacific.

### Present-Day Bering Strait as a Seaway

At present, the water exchange between the Pacific and Arctic oceans takes place through the Bering Strait (Fig. 1) owing to the main northward current and a minor countercurrent in its western part. The northward inflow of the North Pacific water into the Arctic basin is as great as $10^6$–$15^6$ m³/s (Shaffer and Bendtsen, 1994; Reason and Power, 1994). The Bering Strait is 96 km long, at least 86 km wide, and about 50 m deep. In spite of these comparatively small dimensions, the strait transports every year about 50 million tons of suspended terrigenous matter and 60 million tons of suspended biogenic matter from the Pacific basin into the Chukchi Sea (Pavlidis, 1982). The biogenic matter,
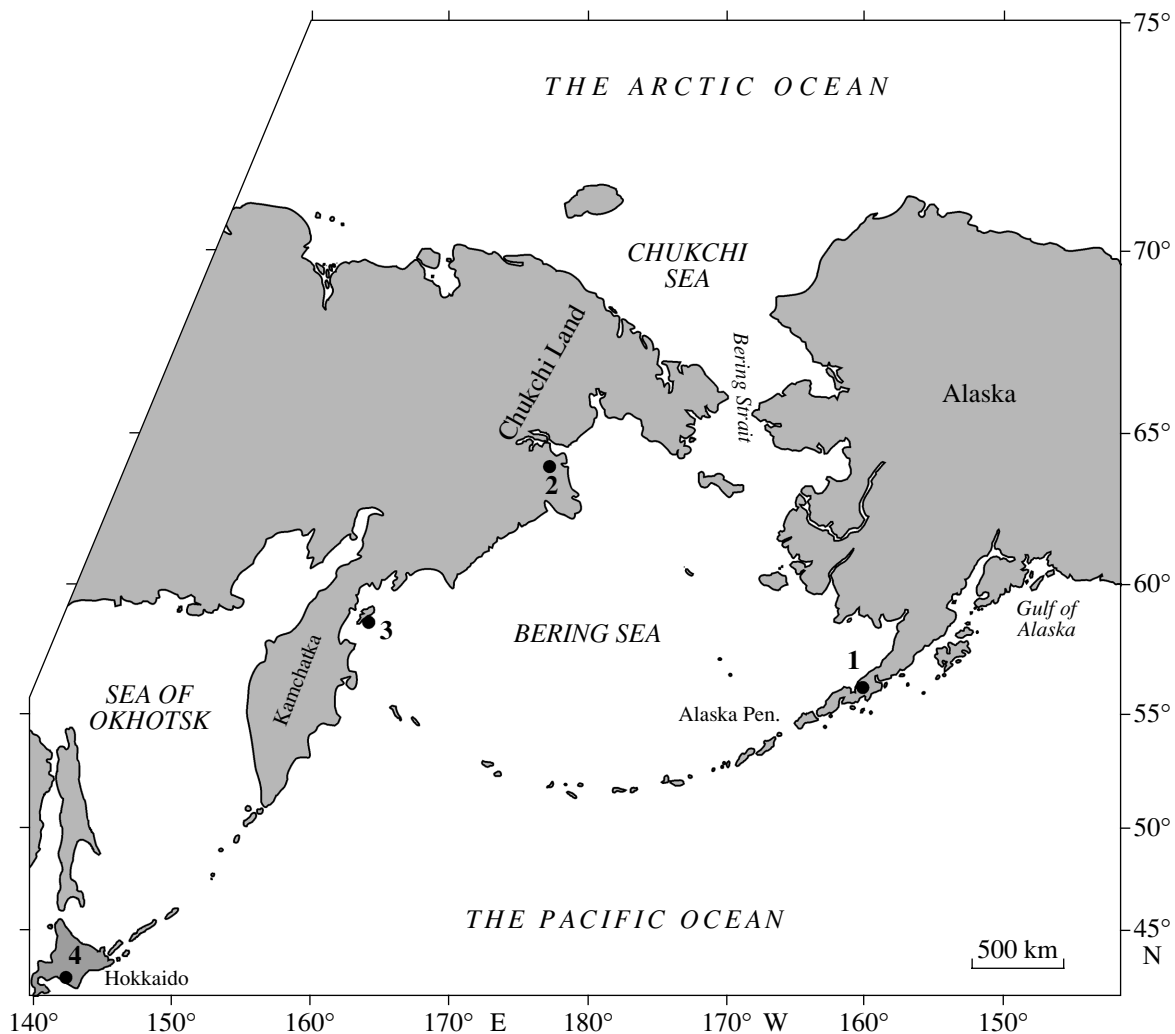
**Fig. 1.** The Neogene sections with the oldest *Astarte* (black circles) in the North Pacific region: (1) Alaska Peninsula; (2) Anadyr depression (Chukchi Land); (3) Karaginskii Island (northeastern Kamchatka); (4) Hokkaido (northern Japan).

mainly the diatom frustules, represents about 10% of components participating in sedimentation. Accordingly, a high content of biogenic silica is a distinctive feature of bottom sediments in the Chukchi Sea in contrast to those in the other Arctic seas (Pavlidis and Shcherbakov, 2000). In addition to oceanic circulation and sedimentation, the Bering Strait greatly affects the biota development in northern latitudes by promoting exchange of marine organisms between the Pacific and Arctic oceans. The asymmetrical, predominantly northward direction of the biota migrations is noteworthy therewith. Thus, the present-day Bering Strait can be reasonably considered as a typical seaway between two oceans, like other passages connecting the Pacific Ocean with different sea basins.

### Geological History of the Strait

The investigation history of the Bering Strait is as long as several decades. The known results show that

Eurasia and North America were united by the Bering Land Bridge into a single supercontinent for about 100 m.y., beginning from the Albian Age of the Middle Cretaceous (Marincovich *et al.*, 1990). The Bering Land Bridge favored the exchange of terrestrial animals and plants between the Old and New World, as it is known from geological records. In addition, of the North Pacific, North Atlantic, and Arctic marine biotas are known to have developed separately during the Paleogene and a part of the Neogene. This suggests that the northernmost Pacific represented a giant sea gulf, and essential changes in communities of marine and terrestrial organisms took place in the northern high latitudes only after the Bering Strait opening, apparently in the Late Neogene. The strait opening favored the exchange between Pacific and Arctic marine faunas and floras for the first time but hampered migrations of Eurasian and North American terrestrial biota. However, the Bering Strait was open not permanently: paleontological data evidence for recurrent closures and open-

ings during the last 4.4 m.y. Data obtained by the mid-1990s suggest three periods of the strait opening within the interval of 4.4–2.0 Ma (early–late Pliocene), which stimulated migrations of mollusks between two oceans (Yu. Gladenkov, 1995; all the dates presented in this work are coordinated with the geochronological scale of Berggren *et al.* 1995). The strait opening and closure periods alternated, as it is evidenced by migrations of Asian and American terrestrial organisms. The strait repeatedly closed in the Quaternary time as well and acquired its present configuration at about 0.13 Ma. However, some problems of the Pacific–Arctic connections are still incompletely clear. Above all, we do not know the precise time and cause of the strait opening and the character and changes in direction of marine biota migrations with time. The results obtained recently can elucidate some of these problems.

## MATERIAL AND METHODS

### *New Data on the Bering Strait First Opening*

### Stratigraphic position of *Astarte* in Neogene sections of northeastern Asia

Despite all the data obtained in the last 35–40 years, the exact time of the first oceanic connection that greatly affected the development of the Arctic-Boreal biota had not been determined until recently. In the 1960s–1990s, some scientists, mostly Russian and American, tried to solve this problem. In general, the estimated age values ranged from 3.6 to 4.4 Ma though some older dates were also considered possible. As mentioned above, the assessments were based on the first occurrence of Neogene mollusks of Pacific origin in the North European sections (Yu. Gladenkov, 1974; Yu. Gladenkov *et al.*, 1980; and others) and on the stratigraphic position of the molluscan genus *Astarte* in the circum-Pacific areas of Kamchatka, Japan, and Alaska (Yu. Gladenkov, 1978). It was assumed that prior to the Bering Strait opening, Cenozoic *Astarte* was absent in the North Pacific but present in the North Atlantic and Arctic regions inhabited in general by biota of North Atlantic origin. *Astarte* penetrated into the Pacific Ocean only after the Bering Strait opening. So, the earliest occurrence level of *Astarte* in the North Pacific sections was expected to be indicative of the strait first opening in the Neogene (Durham and MacNeil, 1967; Yu. Gladenkov, 1976, 1978, 1995; Ogasawara, 1986; Vermeij, 1991). However, the appearance of the oldest *Astarte* in the North Pacific region failed to be precisely dated, because it was impossible to date the event based on the age-diagnostic planktonic microfossils. This issue is disputable even at present.

One of the oldest dates for the Bering Strait opening (4.4 Ma) was established in the Neogene section of the Karaginskii Island, northeastern Kamchatka (Fig. 1), where the *Astarte* appearance level in the upper part of the Limimtevayam Formation (the base of Unit 12) was dated based on diatoms and magnetostratigraphic records (Yu. Gladenkov *et al.*, 1991a, 1991b; *Detailed...*, 1992). The specimens found were ascribed to a new species *A. limimtensis* (*Detailed...*, 1992). However, the date of 4.4 Ma is now doubted, and the corresponding level may be younger. The matter is that the level coincides with the boundary between the *Neodenticula kamtschatica* and *Neodenticula koizumii–Neodenticula kamtschatica* diatom zones (*Detailed...*, 1992), which is defined by the first occurrence of *Neodenticula koizumii* Akiba et Yanagisawa (Fig. 2). According to magnetostratigraphic records, that boundary is inside the interval of reversed magnetic polarity in the Limimtevayam Formation section. This part of the section is interpreted to correspond (*Detailed...*, 1992) to the C3n.1r paleomagnetic episode (the Gilbert Chron) at 4.48–4.29 Ma (Berggren *et al.*, 1995). However, the direct correlation with the paleomagnetic scale indicates that the first occurrence level of *Neodenticula koizumii* in the subarctic Pacific borehole sections is not older than 4.1–4.0 Ma (Barron and A. Gladenkov, 1995). Therefore it is possible that the *Astarte* appearance time in the Karaginskii section may postdate that previously suggested and can be correlative with the C2Ar episode of reversed polarity between 4.18 and 3.58 Ma.

In addition, no attention is paid to the fact that the stratigraphically lowest occurrence of *Astarte* (*Astarte*) sp. is near the base of Unit 10 in the basal part of the Limimtevayam Formation (Yu. Gladenkov, 1972), i.e., about 160 m below the level of first *Astarte limimtensis* (Fig. 3). It is difficult to precisely date the occurrence of *Astarte* sp. because of absence of microfossils at this level. A diatom assemblage found in the underlying Yununvayam Formation (about 140 m below the occurrence level of *Astarte* sp.) is correlative with diatoms of Subzone "a" in the North Pacific *Neodenticula kamtschatica* Zone of Barron and A. Gladenkov (1995) (Fig. 2), which ranges from 7.4 to 5.5 Ma. Stratigraphically higher beds of the Limimtevayam Formation, which are about 80 m above the *Astarte* sp. occurrence level, contain diatoms characteristic of the upper part of the *N. kamtschatica* Zone, most likely of Subzone "c" between 4.8 and 4.1 Ma. Thus, the oldest possible age of earliest *Astarte* may be approaching 7 Ma. However, in the Karaginskii Island section approximately 20 m below the beds with the oldest *Astarte*, there is a hiatus that separates the Limimtevayam and underlying Yununvayam formations. Diatoms have not been found in 120-m-thick deposits below the hiatus. This interval may correspond to a larger part of Subzone "a" of the *N. kamtschatica* Zone. Therefore, the first occurrence level of *Astarte* is most likely younger than 7 Ma. Moreover, the beds situated approximately 35 m higher than the occurrence level of *Astarte* sp. (Fig. 3) contain mollusks *Fortipecten kenyoshiensis* (*Detailed...*, 1992), which first appeared in the earliest Pliocene of the western Kamchatka, Sakhalin, and Japan (Yu. Gladenkov, 1988 and others). Thus, these facts suggest that
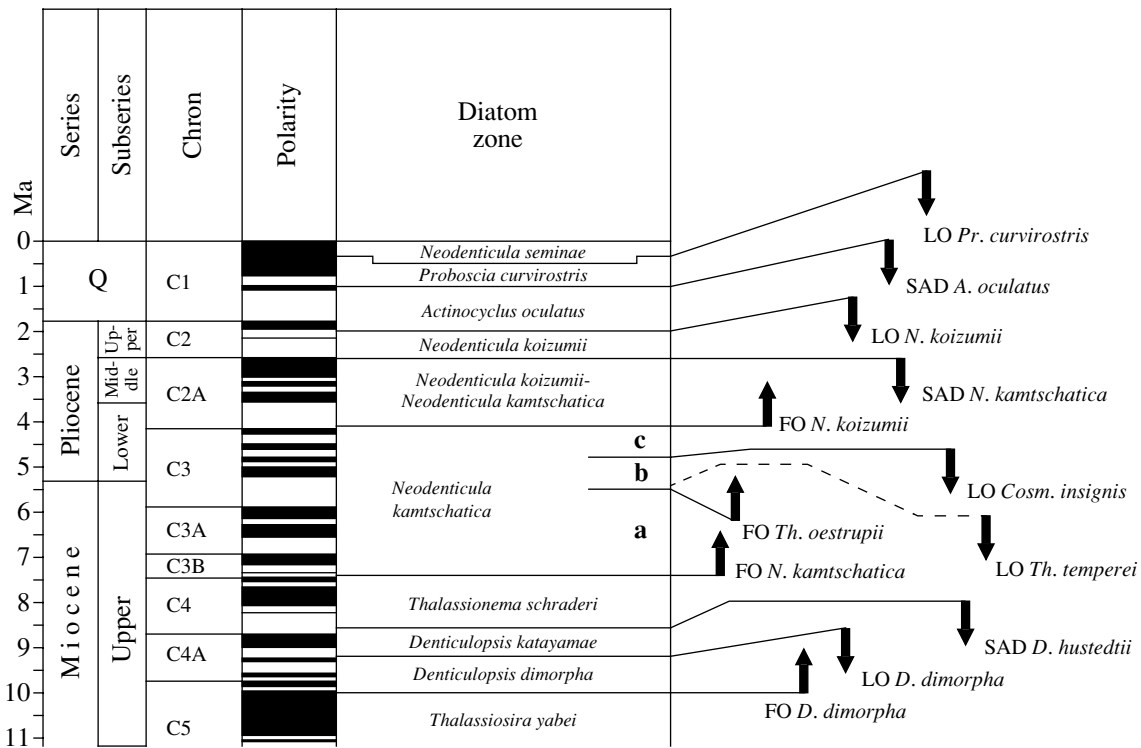
**Fig. 2.** The North Pacific diatom zonation for the last 11 m.y. (Barron and A. Gladenkov, 1995) correlated with the geochronological and paleomagnetic polarity scales (Berggren *et al.*, 1995); solid lines with arrows indicate datum planes between zones and dotted line denotes the last occurrence level of *Thalassiosira temperei*: (FO) first occurrence; (LO) last occurrence; (SAD) sharp abundance decrease; (a–c) subzones; (*D.*) *Denticulopsis*; (*N.*) *Neodenticula*; (*Th.*) *Thalassiosira*; (*Cosm.*) *Cosmiodiscus*; (*A.*) *Actinocyclus*; (*Pr.*) *Proboscia*.

the first occurrence of *Astarte* in the Karaginskii Island section is restricted by the interval corresponding to Subzone "b" (5.5–4.8 Ma) and probably the upper part of Subzone "a" of the *Neodenticula kamtschatica* Zone, i.e., to the uppermost Miocene–lowermost Pliocene (Figs. 3, 4).

*Astarte* forms were also found in other regions of northeastern Asia, such as the Chukchi Peninsula (Anadyr depression), Sakhalin, and Japan. According to published data, the oldest *Astarte* occur in the Echinka Formation (270–530 m thick in total) that belongs to the upper part of the Telekai Horizon of the Anadyr depression (Agapitov *et al.*, 1976; Agapitov, 1991) (Figs. 1, 4). *Astarte* cf. (aff.) *montagui* is among the mollusks found in this formation. It is difficult to precisely date that formation lacking planktonic microfossils of biostratigraphic significance, although it may be the latest Miocene in age according to the described impoverished assemblage of benthic foraminifers (Agapitov, 1991).

In Japan, the oldest *Astarte* is known from the Atsuga Formation (about 2000 m thick) of central Hokkaido (Uozumi *et al.*, 1986; Suzuki and Akamatsu, 1994; Ogasawara, 1998; see Fig. 1). The Takikawa–Honbetsu molluscan fauna from the lower part of this formation includes *Astarte (Tridonta) alaskensis, A. borealis*, and *A.* sp. (Uozumi *et al.*, 1986; Suzuki and

Akamatsu, 1994). The beds with *Astarte* yielded no microfossils, but the fission-track age of tuff beds present 250 m higher in the section is 5.1 ± 0.2 Ma, and the lower age limit of the *Astarte* fauna was previously estimated to be 6.0 Ma. In the early 1990s, diatoms were found in four samples from separate levels of the Atsuga Formation (Sagayama *et al.*, 1992). Their assemblage correlative with that of Subzone "a" of the *Neodenticula kamtschatica* Zone suggests the latest Miocene age of the enclosing deposits. However, these diatoms do not associate with *Astarte* in the section.

In Sakhalin, *Astarte* shells occur in Pliocene deposits (the Pomyr Formation) but their lowermost occurrences have not been precisely dated (Zhidkova *et al.*, 1974). Thus, the available data on the oldest known *Astarte* from Kamchatka, Chukchi Peninsula, and Japan characterize their age as ranging from the latest Miocene to earliest Pliocene (Fig. 4).

### Stratigraphic position of *Astarte* in the Pacific coast sections of North America

Until very recently, *Astarte* of late Miocene–early Pliocene age have not been known in North America, although some probably middle Pliocene *Astarte* were found in the Beringian Beds and elsewhere. Additional age information has been obtained recently for the old-
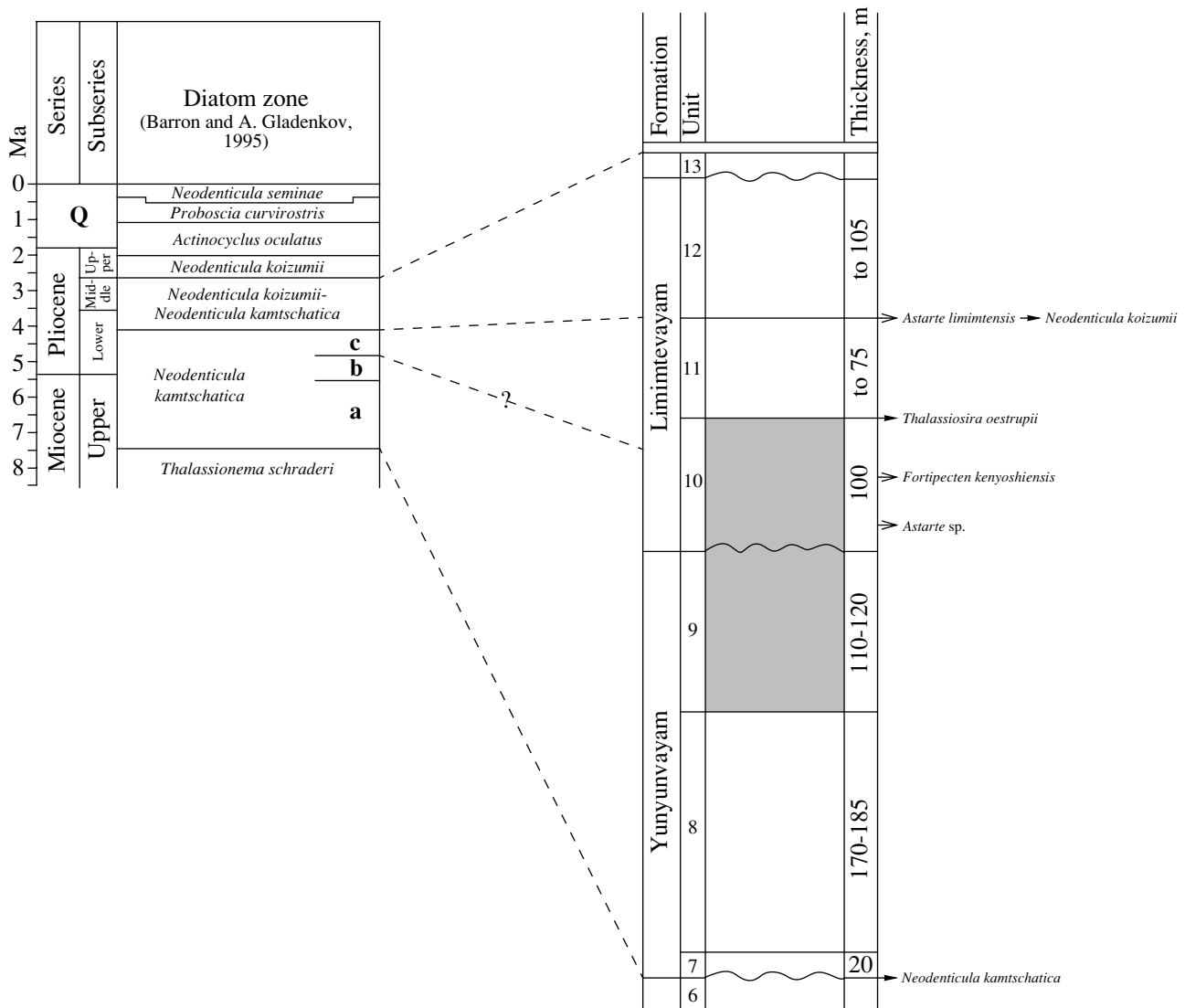
**Fig. 3.** The upper Miocene–Pliocene section of the Karaginskii Island with appearance levels of molluscan (white arrows) and diatom (black arrows) index species (*Detailed...*, 1992; Yu. Gladenkov, 1972); possible correlation between these levels and the North Pacific diatom zonation is shown (shaded intervals are lacking diatoms; other symbols as in Fig. 2).

est *Astarte* discovered in the upper part of the Bear Lake Formation of the Sandy Ridge section, southwestern Alaska (Marincovich and A. Gladenkov, 1999, 2001; Marincovich, 2000; and others, see Fig. 1). In the 1970s, geologists of the Mobil Oil Company collected there molluscan specimens, which are now stored at the California Academy of Sciences, San Francisco, USA. Reexamination of the collection revealed presence of *Astarte* forms, the oldest of which, e.g., *A. borealis*, are established in two neighboring stratigraphic levels of the section. Shells and casts of fossil mollusks were specially treated to extract the diatom remains. Frequently it is difficult to detect diatoms in the rock matrix because of their frustules disintegration under influence of mechanical and chemical factors during sedimentation, fossilization, and catagenesis. On the other hand, diatom valves can be preserved in shells

and concretions buried in fine sediment, being protected from influence of above factors (Barron and Mahood, 1993; and others). This approach was used to discover the Neogene marine diatoms. More than 100 good and satisfactory preserved diatom taxa were found in five molluscan shells from two oldest *Astarte*-bearing levels (A. Gladenkov, 1999, 2001a; and others). In taxonomic composition, the established diatom assemblage appears to be characteristic of Subzone "b" in the North Pacific *Neodenticula kamtschatica* Zone of Barron and A. Gladenkov (1995). The lower boundary of the zone is defined by the appearance of *Thalassiosira oestrupii* (5.5 Ma) and the upper one by the last occurrence of *Cosmiodiscus insignis* (4.8 Ma) (Fig. 2). Both species and zonal index species are components of the Alaskan diatom assemblages. Accordingly, the *Astarte* levels mentioned above are concluded to be the
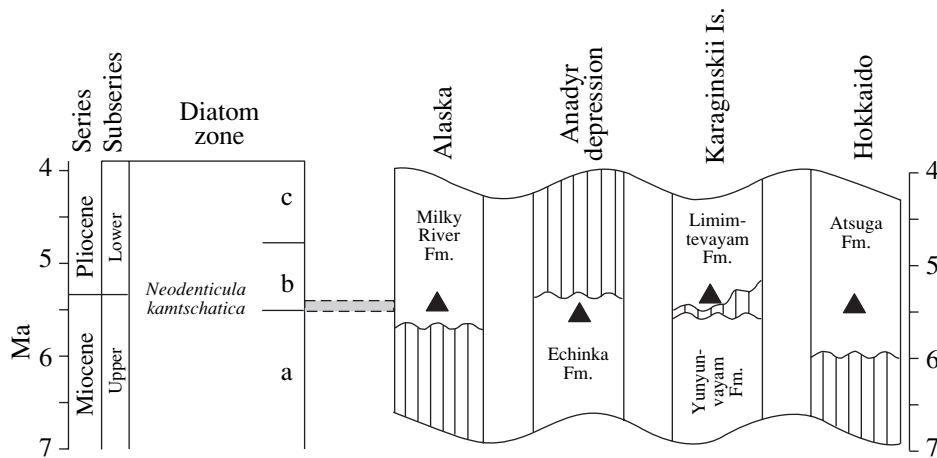
**Fig. 4.** Stratigraphic position of the oldest Neogene *Astarte* (triangles) in structures surrounding the North Pacific (letter symbols a–c denote subzones)

oldest in Alaska, ranging in age from 5.5 to 4.8 Ma, and the first opening of the Bering Strait was supposed to be within this time interval (Marincovich and A. Gladenkov, 1999, 2001; and others). However, the precise positions of earliest *Astarte* and diatoms in the Sandy Ridge section was established in 1998–1999, when a group of geologists headed by L. Marincovich Jr. restudied the section and sampled the bed-by-bed collection of mollusks and rocks for diatom analysis (A. Gladenkov, 2001b, 2003; Marincovich *et al.*, 2002; A. Gladenkov *et al.*, 2002). The field work showed that the lowermost *Astarte*-bearing interval is in the lower part of the Milky River Formation (Fig. 3) discriminated by Galloway (1974) but not to the upper part of the Bear Lake Formation as supposed previously (Detterman *et al.*, 1996). The angular unconformity that separates these formations in the Sandy Ridge section is 28 m below the lowermost occurrence of *Astarte* (*A. borealis*). An assemblage of well-preserved and diverse diatoms was discovered in samples from the level with *Astarte*. The assemblage contains all the forms found there earlier (Marincovich and A. Gladenkov, 1999, 2001) and confirms the previous age interpretation. In addition, the assemblage includes some other age-diagnostic species, the most important of which is *Thalassiosira temperei* (Brun) Akiba et Yanagisawa. Its last occurrence level is a useful Neogene biostratigraphic marker in the North Pacific (Barron, 1980, 1992; Akiba, 1986; Akiba and Yanagisawa, 1986; Yanagisawa, 1990; and others). According to the latest data, this level is dated at 5.4 Ma (Yanagisawa and Akiba, 1998) (Fig. 2). Respectively, the joint occurrence of *T. temperei, T. oestrupii, Neodenticula kamtschatica*, and *Cosmiodiscus insignis* at the same stratigraphic level suggests that the age of the oldest *Astarte* in the Milky River Formation is between 5.5 and 5.4 Ma (Fig. 4). Accordingly, the Bering Strait opened for the first time most likely in the latest Miocene 5.5–5.4 m.y. ago. This conclusion is consistent in general with paleontological data from

Kamchatka, Chukchi Peninsula, and Japan, where the oldest known *Astarte* are of a similar age and can be attributed to the latest Miocene. However, possible errors in dating may extend the *Astarte* age range up to the earliest Pliocene inclusive (Fig. 4).

## RESULTS AND DISCUSSION

### *Marine Biota Migrations between Oceans*

Impossibility of marine biota migrations through the Bering Strait before the latest Miocene is suggested by data on distribution of Pacific mollusks in the North Atlantic sections. Occurrence of these mollusks is recorded beginning from the Pliocene *Serripes groenlandicus* Zone (with *Clinocardium ciliatum, Macoma calcarea, Modiolus modiolus, Musculus niger, Mya pseudoarenaria, Neptunea decemcostata,* and other forms) in England, the Netherlands, and Iceland, where the zone was established (Yu. Gladenkov, 1976, 1978, 1988; Yu. Gladenkov *et al.*, 1980; and others). In particular, the Sr isotopic age of 4.8–4.7 Ma is determined for the first appearance level of Pacific molluscan species *Mytilus edulus, Modiolus modiolus, Mya truncata, Buccinum undatum*, and *Neptunea angulata*, in the Netherlands (Meijer, 1993), although *Mya* and *Buccinum* forms were previously considered as the late Miocene migrants to the North Atlantic (Strauch, 1970).

On the other hand, there is a serious evidence for invasion of the diatom taxa, which are not older than in the latest Miocene–earliest Pliocene, from the North Pacific into the North Atlantic and Arctic (or vice versa). An example is *Neodenticula kamtschatica*, a typical Neogene species of the North Pacific. It appeared at about 7 Ma and became widespread in the Late Miocene and Pliocene. Being of the Pacific origin, the species is an endemic of the high and middle northern latitudes. Outside the North Pacific, it is known

only from Pliocene deposits of the Norwegian Sea (Dzinoridze *et al.*, 1978; *The History...*, 1979). The invasion of Pacific floral elements through the Bering Strait into the Arctic basin during the time span of 5.5–4.8 Ma is also inferable from the diatom distribution in a section that was sampled by vibradrilling in the Chukchi Sea, the site coordinates 70°55′8″N and 165°57′6″W, water depth 44 m (Barron, private communication of 2001). The assemblage from this site is correlative with Subzone "b" of the *Neodenticula kamtschatica* Zone and includes *Pyxidicula zabelinae, Cosmiodiscus insignis, Thalassiosira gravida, T. oestrupii, Th. jouseae, Porosira* aff. *punctata*, and others (Barron, unpublished data).

It should be noted that the new date of the Bering Strait first opening in the Cenozoic is inconsistent with some previous conclusions based on Arctic diatom assemblages (Zyryanov *et al.*, 1992; Polyakova, 1997). Unlike the high-latitude North Atlantic and North Pacific regions, the vast Arctic region between them is inadequately studied so far for a detailed reconstruction of Cenozoic geological history, paleoceanological changes, climatic events, and marine biota development. This is mostly a consequence of difficulties with deep-sea drilling in the Arctic Ocean covered with ice. The reliable stratigraphic data were unknown for this region, and the Arctic Ocean was like a peculiar blank spot until the recent time. However, the Arctic basin had, like now, a great influence on the Earth climate (cold water masses and the ice cover). Being connected with the North Pacific and North Atlantic basins, it determines the biota development in these oceans as well. Polyakova (1997) tried to reconstruct the Late Cenozoic history of the Arctic seas based on diatom floras known from onshore sequences and reported her conclusions on water exchange between the Arctic and the North Pacific oceans in the Cenozoic and on time of the Bering Strait first opening.

Polyakova, who analyzed the Neogene marine diatoms from lowlands of the northern Yakutia and northern Chukchi Peninsula, inferred their North Pacific origin based on taxonomic similarity between the Arctic and Pacific assemblages. The Miocene and Pliocene assemblages defined by means of correlation with the North Pacific diatom zonation allowed Polyakova to conclude that of the Arctic and Pacific oceans became connected in the Miocene. In her opinion, the Arctic biota developed under influence of the Pacific biota since the Middle Miocene, and the Arctic and Pacific oceans were connected, most likely via the Bering Strait region, in the terminal early Miocene–initial middle Miocene and periodically afterward, beginning from the terminal middle Miocene to the present time (Polyakova, 1997). However, these conclusions, which are based on a single fossil group studied in incomplete sections, seem disputable and doubtful. First, all stratigraphically important taxa Arctic diatoms listed by Polyakova are widely distributed in Subboreal and Arctic-Boreal regions, because they were recovered by the

deep-sea drilling not only in the North Pacific but also in the Norwegian–Greenland basin and the Labrador Sea of the North Atlantic (A. Gladenkov, 2001a; Marincovich and A. Gladenkov, 2001). Accordingly, these species could migrate into the Arctic from the North Atlantic basins rather than from the Pacific ones. Moreover, the early–middle Miocene taxa of unambiguously North Pacific origin have not been found in the Arctic assemblages. In the middle to high latitudes of the North Pacific, successive datum levels of Neogene diatoms are identified in relatively complete sections and calibrated with magnetostratigraphic records. In contrast, stratigraphic succession of scarce diatom assemblages from the Arctic lowlands has not been similarly substantiated and controlled by the other fossil groups. In addition, fossil diatoms, as is known, can be transported by wind from burial places over considerable distances (Burckle *et al.*, 1988; Kellogg and Kellogg, 1987, 1996; and others). Therefore, we do not exclude a possibility of wind transportation for Miocene diatoms, which could be brought from the North Pacific into the Arctic and subsequently reworked. In view of this possibility, Polyakova's supposition should be regarded with a great caution.

### Possible Causes of the Bering Strait Opening in the Late Miocene

As noted above, recent data on Neogene mollusks and diatoms suggest the first Cenozoic opening of the Bering Strait about 5.5–5.4 Ma ago. Analysis of available geological materials reveals two main causes of this event.

First, the strait opening in response to tectonic processes can be inferred from summarized data on tectonic structure of the Bering Sea–Aleutian region (Scholl *et al.*, 1992; Plafker and Berg, 1994; Mackey *et al.*, 1997; Imaev *et al.*, 2000; and others). According to suggested reconstructions, tectonic processes in eastern and northern parts of the Bering Sea–Aleutian region might induce the crustal extension in the Bering Strait area, which accelerated 6.0 Ma ago or later. It is possible that the acceleration caused by intense tectogenesis movements resulted in crustal thinning and subsidence of the crustal blocks thus giving rise to the Bering Strait formation. The modern structure of Kamchatka began to develop under influence of the tectonic activation in the second half of the late Miocene. The intense faulting and folding were characteristic of the Kamchatka region in the latest Miocene (6.0–5.5 Ma ago). In particular, large tectonic nappes were formed at that time in East Kamchatka (Yu. Gladenkov and Shantser, 1989, 1990).

Thus, the tectonic activation of the latest Miocene took place simultaneously in different parts of the Bering Sea–Aleutian region. The crustal thinning or block subsidence in response to tectonic processes in the land area that connected Asia and North America could bring about a relative sea-level rise, and both factors
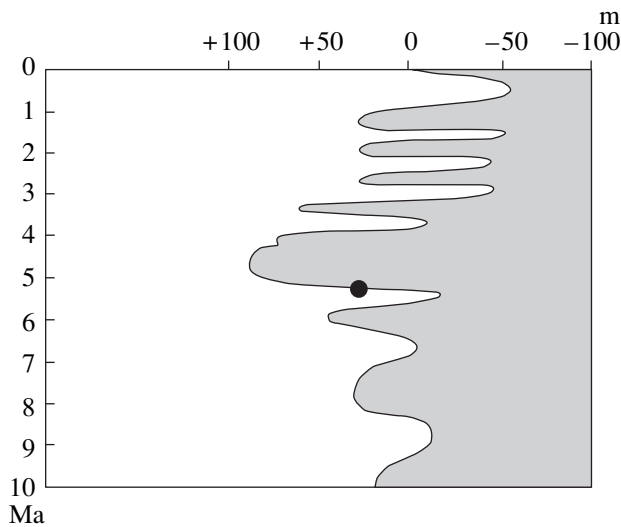
**Fig. 5.** Eustatic sea level fluctuations (Haq *et al.*, 1987) during the last 10 m.y. correlated with the geochronological scale (Berggren *et al.*, 1995); black dot denotes the supposed first opening of the Bering Strait in the Neogene as inferred from diatom data.

could together breach the Bering Strait after formation of a tectonic step in that area 6.0 Ma ago. It is apparent that the age estimated for the regional tectonic activation is well consistent with fossil records suggesting the initial strait opening approximately 5.5–5.4 Ma ago.

Second, the Bering Strait opening within the above time interval might be related to a global eustatic sea-level rise. The largest transgression in the last 12 m.y. took place 5.0 Ma ago, when sea level reached a peak value of 70 m above the modern level (Haq *et al.*, 1987; Fig. 5). That transgression started however earlier in the warming period that postdates the Messinian salinity crisis (6.0 Ma) and subsequent sea-level drop caused by cooling about 5.8 Ma ago (Haq *et al.*, 1987; Fig. 5).

It is remarkable that the Bering Strait opening was close in time to the Mediterranean transgression after the Messinian crisis. A detailed oxygen isotope analysis of the Neogene sections in the equatorial East Pacific (ODP Site 846) and northwestern Morocco (Salé Borehole) revealed a distinct trend of $\delta^{18}O$ decreasing, with rapid and extreme fluctuations, during the initial Subhron C3r of the Gilbert Polarity Zone (Shackleton *et al.*, 1995; Hodell *et al.*, 1994). The lowest $\delta^{18}O$ values correspond to the global sea-level rise during the warmest interglacial, which could be responsible for the Mediterranean flooding after the salinity crisis. The event occurred within the TG9 isotopic stage (5.46 Ma) according to one interpretation (Shackleton *et al.*, 1995) and across the TG12–TG11 boundary (5.32 Ma) according to the other one (Hodell *et al.*, 1994). This indicates that the Mediterranean transgression took place either in the latest Miocene or across the Miocene–Pliocene boundary.

Of course, the Mediterranean transgression and the Bering Strait opening could be caused by different factors responsible for disproportional sea-level rise in remote regions. Anyway, the rapid and extreme eustatic fluctuations (Shackleton *et al.*, 1995; Hodell *et al.*, 1994) approximately coincide in time with the Bering Strait opening. The date of 5.46 Ma established for the minimal $\delta^{18}O$ values (Shackleton *et al.*, 1995) is consistent with the time of the Bering Strait opening (5.5–5.4 Ma) suggested based on new paleontological data. On the other hand, as noted above, the upper age limit of 5.4 Ma for the strait opening is defined based on the index diatom species *Thalassiosira temperei* found in the lower part of the Milky River Formation of Alaska. The last occurrence level of this form in the North Pacific is dated by means of sedimentation rate extrapolation in deep-sea drilling sections. It is possible to assume therefore that *Thalassiosira temperei* disappears slightly earlier at about 5.3 Ma in the Alaska section. Correspondingly, we do not exclude that the Bering Strait opening could take place at 5.32 Ma (Hodell *et al.*, 1994), i.e., at the time of the Miocene–Pliocene boundary.

Noteworthy is the increasing abundance of warm-water taxa in the latest Miocene diatom assemblages of the North Pacific. This evidences for climatic warming at that time. The presence of some warm-water species in the diatom assemblages of the Gulf of Alaska and the Milky River Formation may be also as a response to influence of relatively warm oceanic water (A. Gladenkov, 2003). In sections of Alaska, Kamchatka, and Hokkaido, just below the lowermost *Astarte*-bearing stratigraphic level, there are hiatuses or unconformities and lithological changes indicative of a marine transgression. Consequently, the Bering Strait opening might be caused by flooding of land in that region during the latest Miocene marine transgression and significant sea-level rise.

Thus, the Bering Strait first opening at 5.5–5.4 Ma might be a consequence of either tectonic events or eustatic sea-level rise. A combined influence of both factors cannot be excluded as well.

*Possible Changes in Oceanic Circulation and Marine Biota Migrations through the Bering Strait in the Early Pliocene*

According to the latest data, the deep-to-intermediate water exchange between the Pacific Ocean and Caribbean Sea via the Panama Strait ceased at 4.6 Ma, because the latter turned out to be less than 100 m deep (Haug and Tiedemann, 1998). The event significantly affected oceanic circulation, state of deep water, and climate in the Pacific and Atlantic oceans. The simulated global oceanic circulation shows that prior to this event the dominant flow through the Bering Strait could be oriented southward, from the Arctic Ocean (influenced by the North Atlantic water inflow) into the North Pacific (Maier-Reimer *et al.*, 1990), i.e., opposite

to the present-day direction. After rearrangement of the global oceanic circulation in response to the Panama Strait shoaling, stream through the Bering Strait should be oriented northward, i.e., from the North Pacific into the Arctic and farther into the North Atlantic. This suggests an increased supply of fresh cold water to the high-latitude North Atlantic. Thus, the shoaling (and subsequent closure) of the Panama Isthmus and the Bering Strait opening were significant Neogene events that brought about important hydrological and paleogeographic changes. The events had not only regional but also global effect, as they connected the Pacific and Atlantic oceans through the Arctic and resulted in transformation of oceanic circulation and climate in the Northern Hemisphere. (Maier-Reimer *et al.*, 1990; Reason and Power, 1994; Shaffer and Bendtsen, 1994; and others). All the factors must influence the marine biota development and migration ways of different organisms. According to Marincovich (2000), taxonomic composition of the Neogene high-latitude molluscan assemblages is consistent with the Pliocene reversal of marine flow through the Bering Strait. During the latest Miocene–earliest Pliocene (prior to the closure of the deep Central American seaway), mollusks predominantly migrated through the opened Bering Strait from the North Atlantic and Arctic into the North Pacific. The reversed migrations after 4.6 Ma are evidenced by appearance of the North Pacific species in the North Atlantic beginning from 3.6 Ma. However, migrations of marine benthic fauna might be more complicated. Mollusks of the Pacific origin were found in the Netherlands borehole sections at the level of 4.8 to 4.7 Ma (Meijer, 1993), while mollusks of the North Atlantic origin were discovered in the North Pacific sections at the level of 4.6 Ma and higher (Yu. Gladenkov, 1978, 1988, 1995; and others).

We should add one more consideration concerning a problem, which has not been discussed yet. Let us suppose that prochoreses in both the Pacific and Arctic oceans were simultaneous despite the asymmetrical biota migration through the Bering Strait from the Pacific into the Arctic and *vice versa*. This puts forward an important problem of relative migration rates. If the Bering Strait opened about 5.5–5.4 Ma ago and Pacific migrants appeared in the North Atlantic 4.8–4.6 Ma ago (see above), the time span more than 0.5 m.y. (up to 0.9 m.y.) was necessary for mollusks of Pacific origin to cross the Arctic Ocean and spread over its shelf zones. Data from Iceland only suggest the time span of 1.8 m.y. It is unclear therewith whether we deal with real rates of the Pacific mollusks dispersal over the Arctic shelf zones or the assessments are a consequence of incomplete geological records on the migration ways and dispersal of mollusks, which occupied the Arctic basin. These problems can considered now only in provisional aspect, but we should remember them, if we want to define whether the Arctic Ocean was occupied instantaneously or not in terms of geological time.

There is no data implying that the North Pacific diatom assemblages penetrated into high latitudes of the North Atlantic through the Bering Strait before the early Pliocene. However, the earlier interchange between the North Pacific and North Atlantic floras was possible through the Panama seaway, as suggested by the presence of common planktonic elements in the North Pacific and North Atlantic diatom assemblages, although most of their taxa are cosmopolitans. However, some transitional warm-water taxa, such as *Thalassiosira praeoestrupii* and *T. oestrupii*, appeared asynchronously in two oceanic basins.

### Climatic Events at the Bering Strait Formation Time

The ice-rafted material was found at separate levels (6.7 to 4.4 Ma) of the ODP core sections penetrated in the northwest Pacific and Gulf of Alaska (Krissek, 1995; Rea *et al.*, 1995). The oldest ice-rafted material in the Neogene Yakataga Formation exposed along the Gulf of Alaska coast is recorded at the level of about 6.2 Ma (Lagoe *et al.*, 1993). Lithology and paleontological remains from this formation imply the tidewater glaciations in the Gulf of Alaska between 6.2 and 4.4 Ma during the climate deterioration in the high northern latitudes (Lagoe *et al.*, 1993). "Floating" ice-rafted debris are also characteristic of the coeval interval of the Yununvayam and Limimtevayam formations on the Karaginskii Island, northeastern Kamchatka (*Detailed…*, 1992). In combination with paleontological data, this evidences for a cooling and water temperature drop in the Kamchatka region. Noteworthy is scarcity of ice-rafted material in the ODP cores within the interval of 6.7–4.4 Ma. Moreover, abundance of this material usually decreases away from the coast and southward. Hence, coasts of Alaska and Kamchatka could represent at that time areas of local glaciations and the ice-rafted debris transportation to the ocean (Krissek, 1995). The supposition is consistent with composition of the Neogene diatoms from the Milky River Formation, which were deposited on the Alaska shelf. The latest Miocene–earliest Pliocene diatom assemblages contain here some marine Arctic-Boreal species (*Bacterosira fragilis, Detonula confervacea, Porosira glacialis, Thalassiosira kryophila, Th. gravida*, and others) and the forms that commonly live near sea ice fields (*Fragilariopsis oceanica, Fr. cylindrus* and others), the vegetation periods of which were likely coincident with ice melting near the southwestern margin of Alaska (A. Gladenkov, 2003). On the other hand, presence of planktonic taxa characteristic of the subtropical and temperate regions (*Thalassiosira leptopus, Th. temperei, Th. oestrupii, Auliscus* sp., *Bacteriasrum varians*, and others) indicates influence of relatively warm oceanic surface water.

In general, the latest Miocene–earliest Pliocene diatom assemblages of the Subarctic Pacific contain an increased amount of warm-water forms, which suggests a relatively warm period (Oreshkina, 1986; and

others). In the early Pliocene, after 5.1–5.0 Ma, cold-water taxa increased in abundance and some new species (*Thalassiosira latimarginata* and *T. tertiaria*) appeared. In the period of the second half of the early Pliocene to the initial middle Pliocene, warm-water diatom species intensely penetrated into high latitudes (Oreshkina, 1986; Barron, 1995; and others). Warm-water benthic taxa also appeared at that time in the Subarctic circum-Pacific areas (*Detailed...*, 1992; and others). The absence or reduced amount of ice-rafted material in the high-latitude North Pacific, the Gulf of Alaska included, also implies the climatic warming about 4.6–3.1 Ma ago (Lagoe *et al.*, 1993; Krissek, 1995; Rea *et al.*, 1995).

### *Diatom Productivity in North Pacific during the Late Miocene–Pliocene as Related to Climatic and Oceanographic Changes*

In the North Pacific, the time span from about 6.4 to 2.7 Ma was characterized by increasing biogenic silica mass accumulation (BSMA) and by the maximum diatom productivity during the Cenozoic (Rea *et al.*, 1993, 1995; Rea and Snoeckx, 1995; Barron, 1998). The enhanced biogenic silica deposition is recorded in the marginal basins (Sea of Okhotsk, Bering Sea, California Gulf) and in western and eastern sectors of the Subarctic Pacific. In the western sector, where the sediments are mostly represented by siliceous ooze, sedimentation rates were 4.5 times greater than before beginning from 6.4 Ma and remained high until 2.7 Ma ago with their maximum of 14 to 15 cm/ka recorded between 4.6 and 3.1 Ma (Rea *et al.*, 1993, 1995). The BSMA values increased from about 0.7 to more than 3.0 g/(cm$^2$ ka) and then, after 2.7 Ma, it sharply decreased down to the values recorded prior to 6.4 Ma. A similar trend was characteristic of the Gulf of Alaska, where after 6.4 Ma sedimentation rates increased sharply (approximately four times), reached the maximum values of more than 4 cm/ka, and the BSMA grew from about 0.6 to 1.5–2.0 g/(cm$^2$ ka). In the interval from about 3.1 to 2.7 Ma, sedimentation rates declined from 3 to 1.5 cm/ka and the BSMA values from ~1.0 to 0.2–0.3 g/(cm$^2$ ka).

According to these data, the peak of biogenic silica sedimentation and diatom productivity in the subarctic Pacific (4.6–3.1 Ma) coincides in time with a significant warming. The beginning of above period (4.6 Ma) is correlative with the Panama Strait shoaling and cessation of deep-to-intermediate water exchange between the Pacific Ocean and the Caribbean Sea (Haug and Tiedemann, 1998). The latter event should accelerate inflow of "ancient" Antarctic deep-water masses rich in nutrients into the North Pacific because of reorganized oceanic circulation. On the other hand, the Pliocene warming could trigger inflow of large masses of relatively warm saline surface water into the North Pacific from the south (Barron, 1995). A wide zone that separated warmer and cooler surface waters was likely favorable for penetration of warmer, more saline surface waters into the high-latitude North Pacific, where they diminished the vertical stratification of water masses and caused water mixing and upwelling of nutrient-rich deep waters (Barron, 1998).

### UNSOLVED PROBLEMS

A great progress has been achieved in research of the Bering Strait geological history since the 1960s. Most of the new data are summarized in three publications: "The Bering Land Bridge" (1967), "Beringia in the Cenozoic Era" (1976), and "Beringian Paleoenvironments" (2001). Some problems were attacked in monographs (Strauch, 1972; Yu. Gladenkov, 1978) and in some articles (see above). However, there is a number of problems that have not been adequately studied or solved. Some of them partially mentioned above are outlined below.

(1) Stratigraphic distribution of old astartids in the North Pacific is not very clear so far. They are known from Mesozoic (Zakharov, 1970) and Lower Paleogene deposits of the region, in particular, from the Paleocene Sinegorsk Beds of Sakhalin (Kalishevich *et al.*, 1981). Why are astartids missing from the Eocene and Miocene intervals of the North Pacific sections, except for the uppermost Miocene? There is no well-reasoned answer.

(2) A problem of the first connection between the Arctic and Pacific oceans is still under discussion. The common opinion is that communication between two oceans started with the opening of the Bering Strait. However, prior to the late Miocene–Early Pliocene, they might be connected via an area situated further to the west, in northwestern Asia (northern Yakutia). An ancient strait can be outlined there based on of sporadic finds of marine diatoms (Polyakova, 1997). Although this supposition is not substantiated well, it needs to be studied and checked.

(3) The migration ways of Pacific benthic organisms from the Bering Strait to the North Atlantic, i.e., across the Arctic Ocean, are undetermined yet. It is not clear what shelf zones, Eurasian or North American, were populated predominantly by these organisms. Without relevant data, it is impossible to reconstruct the ancient sea currents and former hydrological regimes, which were essential for migrations of the North Atlantic assemblages, mollusks of the genus *Astarte* included, into the Pacific and the Pacific assemblages with *Mya* and *Neptunea* forms into the North Atlantic. Physical and climatic barriers may be also of great importance. For instance, shoal area of the New Siberian Islands is a good example of a physical barrier, which controls the biota distribution in the Arctic shelf. The specific climatic regime of this area with a low seawater temperature, pack ice sheets, and fresh water influx along them controls the biota distribution. Apparently, the Neogene climatic conditions differed from the Quaternary ones

in higher temperatures of seawater. Otherwise, Boreal mollusks of the Pacific origin could not cross the Arctic-type polar basin. What way (taking into consideration the former sea currents) was used by the North Atlantic migrants to reach the Bering Strait is unclear. Future deep-sea drilling in the Arctic basin may answer this question.

(4) There are diverging assessments of biota migration rates in the shelf zones of oceans under consideration, especially in those, where migrants arrived first after passing the straits from the basin of their origin. In the light of available data, it is unclear whether the migrations were virtually instantaneous or lasted over a period of 0.5–2 m.y.

(5) As stated above, it is difficult to estimate unambiguously the role of tectonic and eustatic factors in the Bering Strait opening. It is likely that both factors were jointly responsible for this event. The sea-level rise was likely brought about by the global warming, and the increased temperature of Arctic surface waters allowed the Boreal migrants of the Pacific origin to cross more than 6000–7000 km of the Arctic shelf and to reach the North Atlantic.

(6) The commonly recognized factors influencing the biota migrations are hydrodynamic regimes, marine currents, climatic changes, and eustatic fluctuations. As a rule, no attention is paid however to some species expansion supplanting the others in biocoenoses. Although such a competition is insufficiently clear and proved, it does exist. Similarly, competition between neighboring ecosystems in the transitional zones may lead to expansion of some ecosystems and to reduction of the others. It is the activity of the North Pacific ecosystem, as well as the relative abundance and diversity of its biotic components, that is considered as responsible for dominating direction of biota migrations from the Pacific into the Arctic (Yu. Gladenkov, 1988; Vermeij, 1991; and others).

(7) The asymmetry of biota migrations through the Bering Strait has been already mentioned. The asymmetry ratio estimated for the Pliocene is 8 : 1, meaning that for every eight species migrated from the Pacific into the Arctic, there was only one species migrated in the opposite direction (Durham and MacNeil, 1967; Yu. Gladenkov, 1974). The ratio variations can be attributed to different factors, such as changes in hydrological and climatic regimes, opening and closing of other straits, and so on (Marincovich, 2000). As it is difficult to define a general trend of these variations with geological time, the problem needs to be investigated further.

(8) We do not fully realize the influence of migrants on biocoenoses development in the Arctic and Pacific ecosystems. Occupying certain ecological niches, migrants may become important components of an ecosystem. For example, astartids play now an important role in the North Pacific assemblages and represent index-species (*Astarte rollandi, A. alaskensis, A. ioani*

and others) of modern Boreal biocoenoses. After a certain period, migrants may become intrinsic in biocoenoses and, as such, they may be considered as native elements of assemblages at the next geological stage.

Conversely, some newcomers failed to occupy a niche in new biocoenoses. They become extinct or pushed aside with time. A good example is the peculiar Arctic fauna, which was formed under the Pliocene–Quaternary climatic conditions. Foreign Boreal elements had either to move to the south or to become more resistant to cold environment. As a result, after significant cooling of the Northern Hemisphere 2.7 Ma ago and, especially, in the Quaternary time, first the Arctic-Boreal and then Arctic assemblages appeared. The molluscan assemblage with *Portlandia arctica* appeared in the Arctic basin in the Early Quaternary (the Eopleistocene of Iceland) and spread widely over all shelf zones of the region. During the periods of intense cooling, this assemblage migrated to the North Pacific through the Bering Strait. It was found in the Karaginskii Island stratigraphic section of northeastern Kamchatka.

## CONCLUSION

The latest data imply that the Bering Strait formation began in the latest Miocene–earliest Pliocene (5.5–5.4 Ma ago according to diatom records). The strait first opened in the Neogene because of regional tectonic processes or sea-level eustatic fluctuations; a combined effect of these factors is also possible. Since that time the North Pacific ecosystem became intermittently unclosed in its northernmost part and greatly influenced the biota distribution in northern latitudes. The migration direction of marine biota through the Bering Strait was reversed 4.6 Ma ago probably because of the oceanic circulation reorganization induced by the paleoceanographic changes, particularly in the Panama Isthmus region.

The Bering Strait was one of the most important seaways in the Neogene history of the Pacific and Arctic Oceans. It is an interesting object for a methodical geological study. The unsolved problems listed above clearly show how important is to understand the geological history of similar objects and their influence on holarctic and global processes.

## ACKNOWLEDGMENTS

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## REFERENCES

1. D. I. Agapitov, in *Cenozoic Geology and Stratigraphy of the Northwest Pacific*, Ed. by A. Ya. Il'ev (DVO AN SSSR, Vladivostok, 1991), pp. 70–95 [in Russian].

2. D. I. Agapitov, V. V. Ivanov, V. G. Muzhikov, and I. V. Shabatin, in *Beringia in the Cenozoic Era*, Ed. by V. L. Kontrimavichus (DVNTs AN SSSR, Vladivostok, 1976), pp. 89–98 [in Russian].

3. F. Akiba, in *Initial Rep. Deep Sea Drill. Project* (Washington, US Gov. Print. Off., 1986), Vol. 87, pp. 393–481.

4. F. Akiba and Y. Yanagisawa, in *Initial Rep. Deep Sea Drill. Project* (Washington, US Gov. Print. Off., 1986), Vol. 87, pp. 483–554.

5. R. S. Allison, Veliger **21**, 171 (1978).

6. J. A. Barron, in *Initial Rep. Deep Sea Drill. Project* (Washington, US Gov. Print. Off., 1980), Vol. 56–57, Pt. 2, pp. 641–685.

7. J. A. Barron, in *Centenary of Japanese Micropaleontology*, Ed. by K. Ishizaki and T. Saito (Terra Scientific, Tokyo, 1992), pp. 413–425.

8. J. A. Barron, in *Proceedings of Ocean Drilling Program. Scientific Results* (ODP, College Station, Texas, 1995), Vol. 145, pp. 43–53.

9. J. A. Barron, J. Asian Earth Sci. **16**, 85 (1998).

10. J. A. Barron and A. Yu. Gladenkov, in *Proceedings of Ocean Drilling Program. Scientific Results* (ODP, College Station, Texas, 1995), Vol. 145, pp. 3–19.

11. J. A. Barron and A. D. Mahood, Micropaleontol. **39**, 29 (1993).

12. W. A. Berggren, D. V. Kent, C. C. Swisher III, and M.-P. Aubry, Special Publication Soc. Econ. Paleontol. Mineral., No. 54, 129 (1995).

13. *Beringia in the Cenozoic Era*, Ed. V. L. Kontrimavichus (DVNTs AN SSSR, Vladivostok, 1976) [in Russian].

14. *Beringian Paleoenvironments–Festschrift in Honour of D.M. Hopkins*, Quatern. Sci. Rev. **20** (1–3), 1 (2001).

15. L. H. Burckle, R. I. Gayley, M. Ram, and J.-R. Petit, Geology **16**, 326 (1988).

16. *Detailed Division of the Neogene of Kamchatka*, Ed. by Yu. B. Gladenkov and E. N. Devyatkin (Nauka, Moscow, 1992) [in Russian].

17. R. L. Detterman, J. E. Case, J. W. Miller, *et al.*, Bull. US Geol. Surv., No. 1969-A, 74 (1996).

18. J. W. Durham and F. S. MacNeil, in *The Bering Land Bridge*, Ed. by D. M. Hopkins (Stanford Univ. Press, Stanford, California, 1967), pp. 326–349.

19. R. N. Dzinoridze, A. P. Jousé, G. S. Koroleva-Golikova, *et al.*, in *Initial Rep. Deep Sea Drill. Project* (Washington, US Gov. Print. Off., 1978), Vols. 38, 39, 40, 41 (Supplement), pp. 289–427.

20. T. Einarsson and Yu. B. Gladenkov, Izv. Akad. Nauk SSSR, Ser. Geol., No. 5, 93 (1973) [in Russian].

21. T. Einarsson, D. M. Hopkins, and R. D. Doell, in *The Bering Land Bridge*, Ed. by D. M. Hopkins (Stanford Univ. Press, Stanford, California, 1967), pp. 312–325.

22. W. E. Galloway, Bull. Geol. Soc. Am. **83**, 379 (1974).

23. A. Yu. Gladenkov, Priroda, No. 9, 29 (1999) [in Russian].

24. A. Yu. Gladenkov, in *Ecosystem Reorganizations and the Evolution of Biosphere*, Ed. by M. A. Fedonkin, A. G. Ponomarenko, and A. Y. Rozanov (Paleontol. Inst., Moscow, 2001a), pp. 124–130 [in Russian].

25. A. Yu. Gladenkov, in *Proceedings of the 2nd Symposium on Evolution of Life on the Earth, Tomsk, Russia, 12–15 November, 2001*, Ed. by V. M. Podobina (NTL, Tomsk, 2001b), p. 52 [in Russian].

26. A. Yu. Gladenkov, Proc. California Acad. Sci. **54**, 27 (2003).

27. A. Yu. Gladenkov, A. E. Oleinik, L. Marincovich, Jr., and K. B. Barinov, Palaeogeogr. Palaeoclimatol. Palaeoecol. **183**, 321 (2002).

28. Yu. B. Gladenkov, *The Neogene of Kamchatka: Problems of Biostratigraphy and Paleoecology* (Nauka, Moscow, 1972) [in Russian].

29. Yu. B. Gladenkov, Izv. Akad. Nauk SSSR, Ser. Geol., No. 7, 129 (1974) [in Russian].

30. Yu. B. Gladenkov, in *Beringia in the Cenozoic Era*, Ed. by V. L. Kontrimavichus (DVNTs AN SSSR, Vladivostok, 1976), pp. 33–39 [in Russian].

31. Yu. B. Gladenkov, *Marine Upper Cenozoic of the Northern Regions* (Nauka, Moscow, 1978) [in Russian].

32. Yu. B. Gladenkov, *Marine Neogene Stratigraphy of the Northern Part of the Pacific Belt: Review of the Stratigraphic Schemes for the Far East of the USSR, North America and Japan* (Nauka, Moscow, 1988) [in Russian].

33. Yu. B. Gladenkov, *Proceedings of Symposium on Neogene Evolution of Pacific Ocean Gateways, Kobe, 20–22 September 1994*, Ed. by S. Nishimura, T. Ohno, and T. Tagami (Kyoto Univ., Kyoto, 1995), p. 2.

34. Yu. B. Gladenkov, K. B. Barinov, and A. E. Basilian, Izv. Akad. Nauk SSSR, Ser. Geol., No. 9, 79 (1991a).

35. Yu. B. Gladenkov, K. B. Barinov, A. E. Basilian, and T. M. Cronin, Quatern. Sci. Rev. **10**, 239 (1991b).

36. Yu. B. Gladenkov, P. Norton, and G. Spaink, *Upper Cenozoic of Iceland: Stratigraphy of Pliocene-Pleistocene and Paleontological Assemblages* (Nauka, Moscow, 1980) [in Russian].

37. Yu. B. Gladenkov and A. E. Shantser, in *The Earth Sedimentary Cover in Space and Time. Reports of Soviet Geologists at XXVIII Session of International Geological Congress, Washington, July 1989* (Nauka, Moscow, 1989), pp. 127–134 [in Russian].

38. Yu. B. Gladenkov and A. E. Shantser, in *Pacific Neogene Events: their Timing, Nature, and Interrelationship*, Ed. by R. Tsuchi (Univ. of Tokyo, Tokyo, 1990), pp. 173–181.

39. B. U. Haq, J. Hardenbol, and P. R. Vail, Science **235**, 1156 (1987).

40. G. H. Haug and R. Tiedemann, Nature **393**, 673 (1998).

41. D. A. Hodell, R. H. Benson, D. V. Kent, *et al.*, Paleoceanogr. **9**, 835 (1994).

42. V. S. Imaev, L. P. Imaeva, B. M. Koz'min, *et al.*, Geotektonika **34** (4), 44 (2000) [Geotectonics **34**, 294 (2000)].

43. T. G. Kalishevich, E. D. Zaklinskaya, and M. Ya. Serova, *Development of the Organic World of the Pacific Belt at the Mesozoic–Cenozoic Boundary (Foraminifers, Mollusks and Palynoflora of the Northwestern Sector)* (Nauka, Moscow, 1981) [in Russian].

44. D. E. Kellogg and T. B. Kellogg, Palaeogeogr. Palaeoclimatol. Palaeoecol. **60**, 77 (1987).

45. D. E. Kellogg and T. B. Kellogg, Geology **24**, 115 (1996).

46. L. Krissek, in *Proceedings of Ocean Drilling Program. Scientific Results* (ODP, College Station, Texas, 1995), Vol. 145, pp. 179–194.

47. M. B. Lagoe, C. H. Eyles, N. Eyles, and C. Hale, Bull. Geol. Soc. Am. **105**, 1542 (1993).

48. K. G. Mackey, K. Fujita, L. V. Gunbina, *et al.*, Geology **25**, 979 (1997).

49. F. S. MacNeil, Special Volume Tohoku Univ. Sci. Rep., 2nd Ser. (Geol.) **6** (Hatai Memorial Volume), 55 (1973).

50. E. Maier-Reimer, U. Mikolajewicz, and T. Crowley, Paleoceanogr. **5**, 349 (1990).

51. L. Marincovich, Jr., Geology **28**, 551 (2000).

52. L. Marincovich, Jr., K. B. Barinov, and A. E. Oleinik, J. Paleontol. **76**, 239 (2002).

53. L. Marincovich Jr., E. M. Brouwers, D. M. Hopkins, and M.C. McKenna, in *The Geology of North America*, Ed. by A. Grantz, L. Johnson, and J.F. Sweeney (Geol. Soc. Am., Boulder, Colorado, 1990), Vol. L: *The Arctic Ocean Region*, pp. 403–426.

54. L. Marincovich, Jr., and A. Yu. Gladenkov, Nature **397**, 149 (1999).

55. L. Marincovich, Jr., and A. Yu. Gladenkov, Quatern. Sci. Rev. **20**, 329 (2001).

56. T. Meijer, Scripta Geol., Special Issue 2, 297 (1993).

57. K. Ogasawara, Monograph Mizunami Fossil Museum, No. 6, 183 (1986).

58. K. Ogasawara, J. Asian Earth Sci. **16**, 45 (1998).

59. T. V. Oreshkina, Izv. Akad. Nauk SSSR, Ser. Geol., No. 11, 27 (1986) [in Russian].

60. Yu. A. Pavlidis, in *Problems of Geomorphology, Lithology and Lithodynamics of a Shelf*, Ed. by A. A. Aksenov (Nauka, Moscow, 1982), pp. 47–76 [in Russian].

61. Yu. A. Pavlidis and F. A. Shcherbakov, Okeanologiya **40** (1), 137 (2000) [in Russian].

62. G. Plafker and H. C. Berg, in *Geology of North America*, (Geol. Soc. Am., Boulder, Colorado, 1994), Vol. G-1: *The Geology of Alaska*, pp. 989–1021.

63. E. I. Polyakova, *The Eurasian Arctic Seas during the Late Cenozoic* (Nauchnyĭ Mir, Moscow, 1997) [in Russian].

64. D. K. Rea, I. A. Basov, L. A. Krissek, *et al.*, in *Proceedings of Ocean Drilling Program. Scientific Results* (ODP, College Station, Texas, 1995), Vol. 145, pp. 577–596.

65. D. K. Rea, I. A. Basov, T. R. Janacek, *et al.*, in *Proceedings of Ocean Drilling Program. Initial Reports* (ODP, College Station, Texas, 1993), Vol. 145.

66. Rea, D.K., and Snoeckx, H., in *Proceedings of Ocean Drilling Program. Scientific Results* (ODP, College Station, Texas, 1995), Vol. 145, pp. 247–256.

67. C. J. C. Reason and S. B. Power, Climate Dynamics **9**, 363 (1994).

68. T. Sagayama, K. Hoyanagi, and S. Miyasaka, J. Geol. Soc. Jpn. **98**, 309 (1992).

69. D. W. Scholl, A. J. Stevenson, S. Mueller, *et al.*, in *Southeast Asia Structure, Tectonics, and Magmatism*, Ed. by M. Flower (Texas A & M University, College Station, Texas, 1992), pp. 57–63.

70. N. J. Shackleton, M. A. Hall, and D. Pate, in *Proceedings of Ocean Drilling Program. Scientific Results* (ODP, College Station, Texas, 1995), Vol. 138, pp. 337–355.

71. G. Shaffer and J. Bendtsen, Nature **367**, 354 (1994).

72. F. Strauch, Geol. Rundschau **60** (1), 381 (1970).

73. F. Strauch, Senckenberg. Naturforsch. Ges. Abh., No. 531, 211 (1972).

74. A. Suzuki and M. Akamatsu, Palaeogeogr. Palaeoclimatol. Palaeoecol. **108**, 353 (1994).

75. S. Uozumi, M. Akamatsu, and T. Takagi, Special Paper Paleontol. Soc. Jpn., No. 29, 211 (1986).

76. *The Bering Land Bridge*, Ed. by D. M. Hopkins (Stanford Univ., Stanford, California, 1967).

77. *The History of the Microplankton of the Norwegian Sea (on the Deep Sea Drilling Materials)*, Ed. by O. A. Skarlato (Nauka, Leningrad, 1979) [in Russian].

78. G. L. Vermeij, Paleobiology **17**, 281 (1991).

79. Y. Yanagisawa, Bull. Geol. Surv. Jpn. **41**, 1 (1990).

80. Y. Yanagisawa and F. Akiba, J. Geol. Soc. Jpn. **104**, 395 (1998).

81. V. A. Zakharov, in *Late Jurassic–Early Cretaceous bivalve mollusks of the north Siberia and their inhabit environments* (Nauka, Moscow, 1970), Pt. 2: *Family Astartidae*, p. 1 [in Russian].

82. L. S. Zhidkova, G. S. Mishakov, T. L. Neverova, *et al.*, *Biofacial Peculiarities of the Mesozoic–Cenozoic Basins of Sakhalin and Kuril Islands* (Nauka, Novosibirsk, 1974) [in Russian].

83. E. V. Zyryanov, S. A. Laukhin, and E. I. Polyakova, Izv. Akad. Nauk SSSR, Ser. Geol., No. 4, 97 (1992).