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A refined age for the earliest opening of Bering Strait

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Biostratigraphically and chronostratigraphically important diatoms from the Milky River Formation, Alaska Peninsula, southwestern Alaska, imply an age range of 5.4–5.5 Ma for the oldest North Pacific Cenozoic occurrence of the marine bivalve mollusk *Astarte*, which migrated from the Arctic Ocean into the North Pacific when Bering Strait first flooded. The data presented here are a refinement of the age range of 4.8–5.5 Ma reported earlier and imply that Bering Strait first opened very near the end of the Miocene at 5.32 Ma.

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1. Introduction

Bering Strait is among the most globally significant regions for paleogeography and biogeography. Throughout most of the Cenozoic, a closed strait joined Eurasia and North America into one supercontinent and allowed the interchange of terrestrial animals and plants, but sealed off the only marine connection between the North Pacific and the Arctic oceans. The first opening of Bering Strait temporarily ended terrestrial migrations

(Repenning, 1967, 1980), but let marine organisms migrate between the Arctic and North Pacific oceans for the first time since the middle Cretaceous (Marinovich et al., 1990).

Despite the importance of its first opening, determining Bering Strait's age has proven difficult, mostly due to the apparent absence of a suitable onshore or offshore stratigraphic sequence bearing age-diagnostic fossils. Various authors have estimated the age of Bering Strait's first opening from the oldest appearance of cool-water boreal Pacific mollusks in Iceland (Einarsson et al., 1967) or the first appearance of migrants from the Arctic Ocean in the North Pacific (Brigham-Grette et al., 1994; Gladenkov, 1994; Nolf and Marinovich, 1994; Vermeij, 1989, 1991; Carter and Hillhouse, 1992; Repenning and Brouwers, 1992;

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Kaufman and Brigham-Grette, 1993; White et al., 1997). As summarized by Marinovich and Gladenkov (1999, 2001), these estimates have ranged from 4.1 to 3.1 Ma (when adjusted to the time scale of Berggren et al., 1995), but are imprecise because they were based on faunal events that had not been well-dated.

The migration of *Astarte* from the Arctic Ocean into the North Pacific has been cited as evidence for the earliest opening of Bering Strait (Marinovich and Gladenkov, 1997, 1999). *Astarte* has dwelled in the North Atlantic and Arctic oceans since the middle Cretaceous, but was absent from North Pacific until Bering Strait opened (Marinovich et al., 1990; Marinovich et al., in press). The opening of Bering Strait introduced *Astarte* into the middle- and high-latitude North Pacific, while it continued to dwell in the Arctic and North Atlantic oceans. The oldest North Pacific Cenozoic appearance of *Astarte* is accompanied by abundant and diverse marine diatoms of North Pacific provenance in the Milky River Formation (previously cited as the Bear Lake Formation by Marinovich and Gladenkov, 1999), on the Alaska Peninsula in southwestern Alaska (Fig. 1). Diatoms are absent or extremely rare in Cenozoic sediments in Alaska, but they are present within the shells of *Astarte* (*Tridonta*) *bo-realis* (Schumacher, 1817) and other mollusks in the basal marine beds of the Milky River Formation at a stratigraphic locality named Sandy Ridge (Fig. 2) (Detterman et al., 1996; Marinovich and Gladenkov, 1999; Marinovich et al., in press). This method of sampling the interiors of mollusk shells follows Barron and Mahood (1993), who noted that mollusk shells may provide protection from abrasion and dissolution of diatom frustules. The reassignment of most strata at Sandy Ridge from the Bear Lake Formation to the Milky River Formation is based on fieldwork conducted in 1998 and 1999 by L. Marinovich, A. Oleinik and K. Barinov.

2. Geologic setting

The name ‘Milky River Formation’ was first used by Galloway (1974) for volcanic and sedi-

mentary rocks overlying marine beds of the lower middle Miocene Bear Lake Formation exposed in the Milky River Valley (Burk, 1965). The Milky River Formation at its type locality and reference exposures reportedly consists of non-marine deposits, volcanoclastic sediments and basalt flows (Detterman et al., 1981, 1996). However, we discovered the first outcrops of fossiliferous marine rocks in the Milky River Formation during field studies in 1998 and 1999. The well-preserved, articulated bivalves *Mya* cf. *M. truncata* and *Clino-cardium* sp. were found in situ in stringers near the base of the Milky River Formation type section, which otherwise does consist of non-marine sediments and volcanic flows. The specimens used in this study were collected from the Sandy Ridge stratigraphic section of the Milky River Formation, on the distal part of the Alaska Peninsula, southwestern Alaska, at 56°70′N 159°92′W, in August 1998 and July 1999, which lies some 15 km northeast of the Milky River Formation type locality (Fig. 1). This stratigraphic section consists almost entirely of shallow-marine sediments that contain abundant fossils, which makes it the only known Milky River marine exposure. Prior to the present study, unidentifiable fragments of presumed marine bivalves had been recovered from a borehole near Becharof Lake (Detterman et al., 1996), some 200 km northeast of the Milky River Formation type locality (Fig. 1).

The Milky River Formation was first thought to be of Pliocene age, based on its superposition above the Bear Lake Formation that was then thought to be of middle and Late Miocene age, and by potassium–argon numerical ages of a basalt flow just below the top of the Milky River Formation type section (3.53±0.27 Ma, early late Pliocene) and a basalt flow in a nearby reference section (3.87±0.06 Ma, late early Pliocene) (Detterman et al., 1996). The recently revised age of the Sandy Ridge marine strata is 4.8–5.5 Ma, spanning the Miocene–Pliocene boundary, based on the presence of diatoms within the shells of *Astarte* and other bivalves and gastropods (Marinovich and Gladenkov, 1997, 1999). Based on the lack of evidence for submarine deposition of the stratigraphically high basalt flows in the type Milky River Formation, we infer that they were

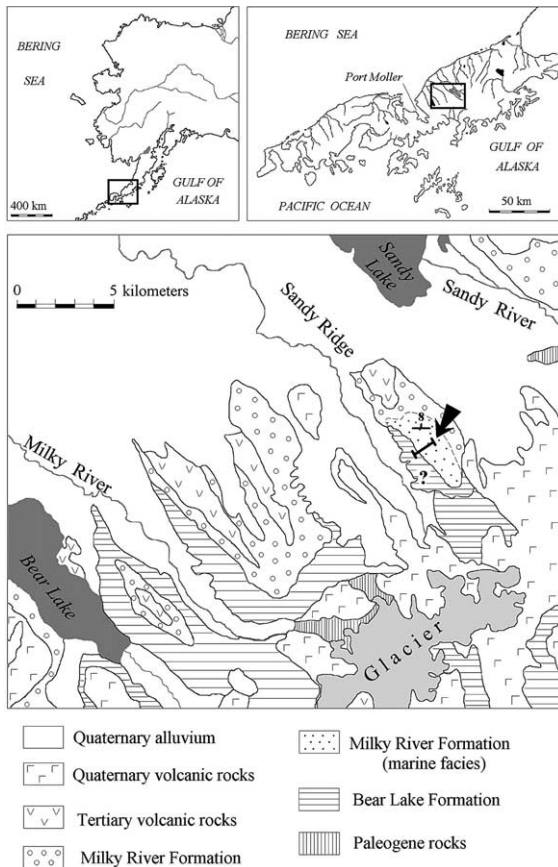


Fig. 1. Location of the study area in the Alaska Peninsula and geologic map of the Sandy Ridge area (modified after Detterman et al., 1996) with arrow showing the Sandy Ridge stratigraphic section of the Milky River Formation.

deposited on land and are significantly younger than the underlying sediments that contain the marine mollusks cited here. It seems likely that the marine mollusks in the type Milky River Formation are the same age as the identical taxa in the Sandy Ridge stratigraphic section of this formation discussed below.

Our measured stratigraphic section of the Milky River Formation at Sandy Ridge consists of 276 m of shallow-marine sediments. These marine beds are overlain by approximately 200 m of non-marine volcanoclastic sediments and basalt flows that crop out to the west along Sandy Ridge (Fig. 3) and are identical to the same rocks elsewhere in the Milky River Formation, including the type section (Lyle et al., 1979; Detterman et

al., 1996). The Sandy Ridge marine beds lie with angular unconformity upon a terrestrial sequence that is strongly deformed into semi-isoclinal folds. Strata below this unconformity consist of interbedded siltstone, coal and tuff that are lithologically identical to parts of the lower middle Miocene Bear Lake Formation at its type section (Lyle et al., 1979; Marinovich et al., in press). The marine and non-marine sediments that make up the nearby type section of the Bear Lake Formation are tilted but not deformed, so the deformation of the inferred Bear Lake Formation beds below the angular unconformity at Sandy Ridge evidently may be a local phenomenon. The inferred Bear Lake Formation beds below the angular unconformity lack age-diagnostic criteria. However, the abundance of coal beds supports correlation with the lower part of the type Bear Lake Formation section, which is the only other described formation in this part of the Alaska Peninsula that contains coal beds (Burk, 1965; Lyle et al., 1979; Detterman et al., 1996).

3. Discussion and conclusions

Diatom species from Sandy Ridge were assigned by Marinovich and Gladenkov (1999) to Subzone b of the North Pacific *Neodenticula kamtschatica* diatom Zone of Barron and Gladenkov (1995). Subzone b has an age range of 4.8–5.5 Ma, based on the time scale of Berggren et al. (1995). The stratigraphic record of *Astarte* in Kamchatka (Gladenkov, 1972; Gladenkov et al., 1992) and northern Japan (Uozumi et al., 1986; Suzuki and Akamatsu, 1994) suggests that the oldest Cenozoic records of *Astarte* there are of similar age, but the mollusks in those places are unaccompanied by age-diagnostic microfossils or other precise age criteria (Marinovich and Gladenkov, 2001).

The stratigraphically lowest specimens of *Astarte* (*Tridonta*) *borealis* in the Sandy Ridge section occur 28 m above its base (Fig. 3) (Marinovich, Barinov and Oleinik, in press), and the diatoms illustrated here (Fig. 4) come from the identical horizon. Further study of the Sandy Ridge diatom microflora suggests a refined age



Fig. 2. Photograph of the Sandy Ridge stratigraphic section (photo by A. Oleinik).

range for Bering Strait's first opening of 5.4–5.5 Ma, nearly at the end of the Miocene, which is significantly narrower than the age range of 4.8–5.5 Ma reported by Marinovich and Gladenkov, 1999) (the Miocene–Pliocene boundary is currently placed at 5.32 Ma by Berggren et al. (1995)). Well-preserved diatoms are present in several beds of the Sandy Ridge stratigraphic section, and all of the species noted here occur within mollusk shells collected from the horizon with the stratigraphically lowest *Astarte* specimens, 28 m above the base of this stratigraphic section. The diatom microflora from this bed (California Academy of Sciences diatom locality 608382) contains all of the age-diagnostic species typical of Subzone b (4.8–5.5 Ma) of the North Pacific *Neodenticula kamtschatica* diatom Zone of Barron and Gladenkov (1995), as reported previously by (Marinovich and Gladenkov, 1999, 2001). The base of this subzone is defined by the first occur-

rence of *Thalassiosira oestrupii* at 5.5 Ma, and its top by the last occurrence of *Cosmiodiscus insignis* at 4.8 Ma (Fig. 3). The zonal species *N. kamtschatica* is also present in sample CAS 608382, collected from the lowest stratigraphic level bearing *Astarte* in the Milky River Formation (Fig. 4). This examination of samples from the stratigraphically lowest localities cited by Marinovich and Gladenkov, 1999) confirms that *Astarte* first appeared in the age range of 4.8–5.5 Ma. However, the discovery of additional age-diagnostic diatoms, including *Thalassiosira convexa*, *T. jacksonii*, *T. marujamica* and *T. temperei*, allows us to refine this age. Of these species, the most important for biochronology is *T. temperei* (Fig. 4). The last occurrence of this species is a useful Neogene biohorizon marker in the North Pacific, including onshore sequences in Japan and Kamchatka, which occurs within the lowermost part of Subzone b of the *N. kamtschatica* diatom Zone (Aki-

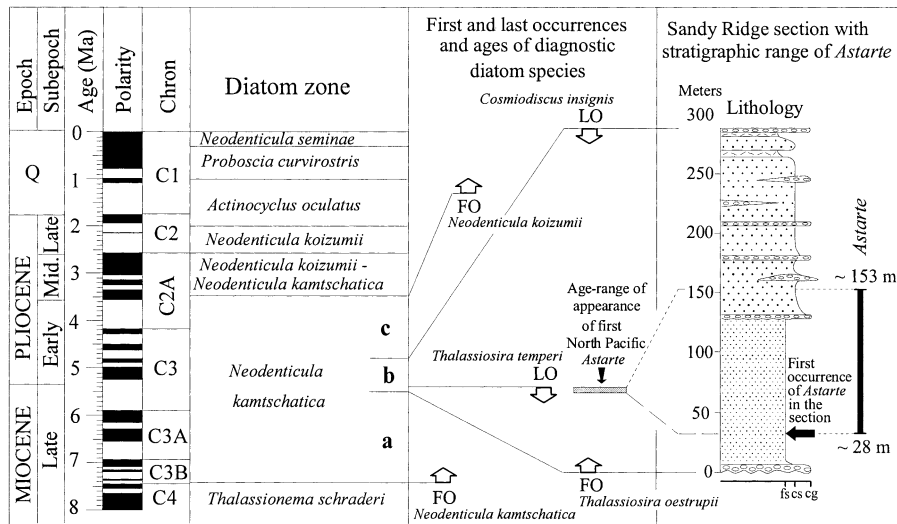


Fig. 3. North Pacific diatom zonation of Barron and Gladenkov (1995) for the last 8 Myr, correlated with the geochronologic and geomagnetic polarity scales after Berggren et al. (1995), showing first and last occurrences of the age-diagnostic diatom species, and the stratigraphic range of the earliest Cenozoic *Astarte* in the Sandy Ridge stratigraphic section. Abbreviations used: FO – first occurrence, LO – last occurrence, a–c – subzones of the *Neodenticula kamschatica* Zone, Q – Quaternary, fs – fine-grained sandstone, cs – coarse-grained sandstone, cg – conglomerate.

ba and Yanagisawa, 1986; Oreshkina, 1985; Yanagisawa, 1990; Barron, 1992). The most recent studies indicate that *T. temperei* had its last occurrence at 5.4 Ma in the middle- to high-latitude North Pacific (Yanagisawa and Akiba, 1998) (Fig. 3). Therefore, the co-occurrence of *T. temperei*, *T. oestrupii* and *C. insignis* indicates that the earliest to enter the North Pacific from the Arctic Ocean did so within the age range of 5.4–5.5 Ma. This implies that Bering Strait first opened in the very end of the Late Miocene, joining the Arctic and boreal marine realms, and separating Asia from North America for the first time since the middle Cretaceous.

Marincovich (2000) has speculated that the first opening of Bering Strait likely resulted from tectonic events that affected all of Alaska, a eustatic sea-level rise, or a combination of the two. Tectonic reconstructions of southern Alaska, westernmost Siberia, and the Bering Sea region (Scholl, 1999; Scholl et al., 1992; Plafker and Berg, 1994; Mackey et al., 1997) imply that Late Cenozoic deformation occurred throughout Alaska, owing to ongoing underthrusting of southern Alaska by the Pacific plate. The ensuing westward extrusion

of interior Alaska evidently produced extension and rifting in the Bering Strait region, which accelerated at 6.0 Ma or later in response to collision of the main body of the Yakutat terrane with southern Alaska (Mackey et al., 1997; Scholl et al., 1992; Scholl, 1999; Scholl, 1999, personal communication). Increased tectonism in the Bering Strait region at 6.0 Ma or later is associated with formation of the Bering tectonic block (Mackey et al., 1997). It is thought that enhanced extension and rifting resulted in crustal thinning and subsidence of the Bering Strait region, which may have contributed to initial submergence of Bering Strait (Scholl, personal communication, 1999). The flooding of Bering Strait may have been abetted by a eustatic sea-level rise that remained at ≥ 60 m in the interval from about 5.5 to 4.1 Ma and peaked at +75 m at 5.0 Ma (Haq et al., 1987; Marincovich, 2000). The simultaneous impact of eustasy and crustal thinning in this region at < 6.0 Ma is in accordance with the 5.4–5.4-Ma age inferred here for the first opening of Bering Strait.

It is interesting that Bering Strait flooded at about the same time as did the Mediterranean

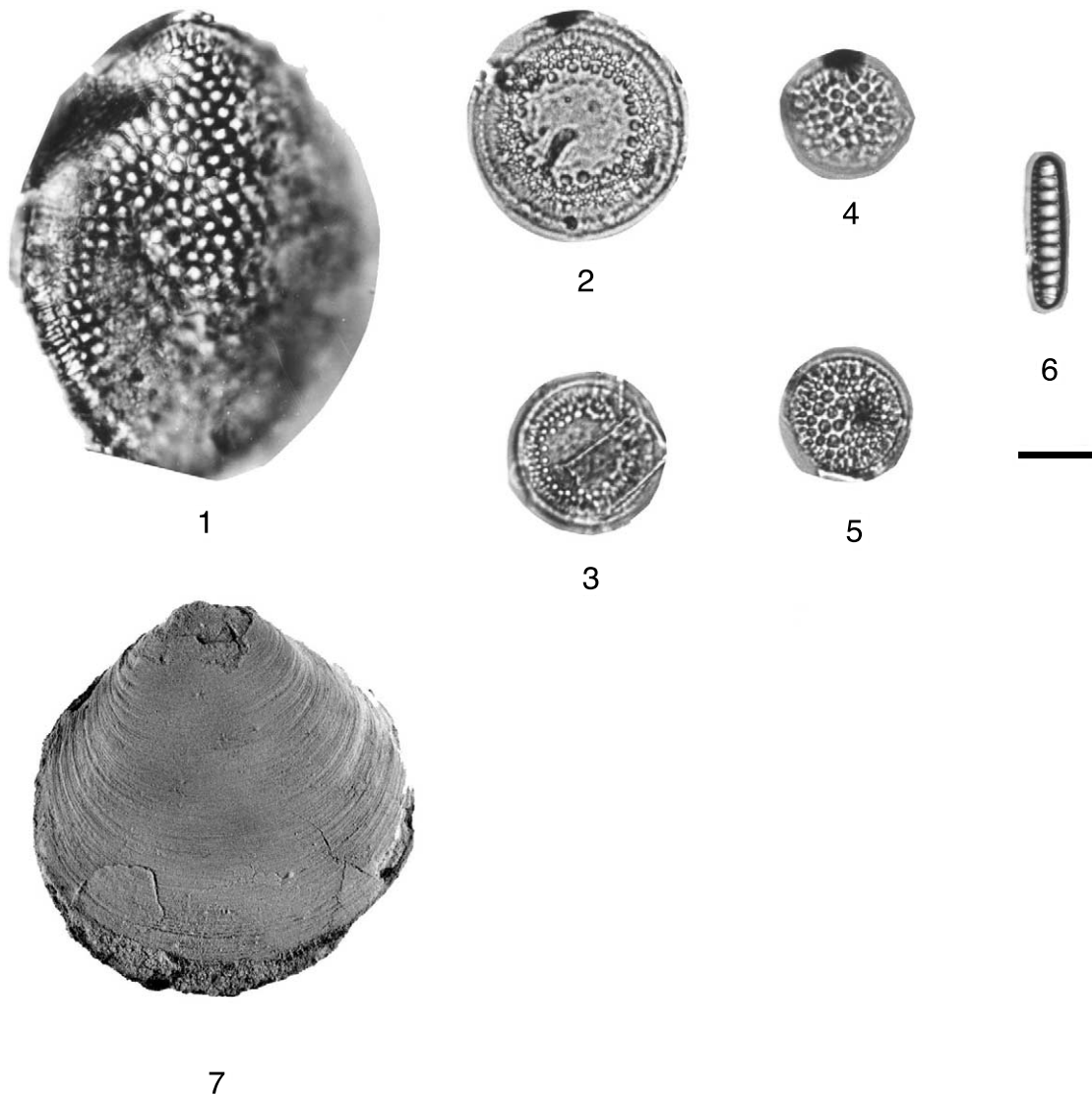


Fig. 4. The stratigraphically lowest *Astarte* and the most important age-diagnostic diatoms occurring together in the Sandy Ridge stratigraphic section of the Milky River Formation (all diatoms are from the sample CAS 608382). (1) *Thalassiosira temperei* (Brun) Akiba et Yanagisawa; (2, 3) *Cosmiodiscus insignis* Jouse; (4, 5) *Thalassiosira oestrupii* (Ostenfeld) Proshkina-Lavrenko; (6) *Neodenticula kamtschatica* (Zabelina) Akiba et Yanagisawa. Scale bar = 10 mm; (7) *Astarte* (*Tridonta*) *borealis* Schumacher, 1817; right valve, CAS Geology 68531, length – 36.03 mm, height – 35.57 mm.

Sea after the Messinian salinity crisis. The latter event was inferred to have taken place at 5.46 Ma by Shackleton et al. (1995) or 5.32 Ma (the Miocene/Pliocene boundary) by Hodell et al. (1994). These studies were based on oxygen-isotope stratigraphy from cores in the equatorial eastern Pacific (Shackleton et al., 1995) and Morocco (Ho-

dell et al., 1994), and conclusions differ owing to the quality of age control and the correct identification and extrapolation of 41-kyr oxygen-isotope cycles. Even though Shackleton et al.'s (1995) and Hodell et al.'s (1994) conclusions differ in the age assigned to flooding of the Mediterranean, both record rapid and extreme eustatic fluc-

tuations that were approximately coeval with Bering Strait's opening. Such eustatic fluctuations included high-stands that may have contributed to Bering Strait's initial submergence. However, despite the similarity in timing and sea-level relationship between the flooding of the Mediterranean Sea and the opening of Bering Strait, it is not yet known if these events were due to the same sea-level rise.

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References

- Akiba, F., Yanagisawa, Y., 1986. Taxonomy, morphology and phylogeny of the Neogene diatom zonal marker species in the middle-to-high latitudes of the north Pacific. In: Kagami, H., Karig, D.E., Coulbourn, W.T. et al. (Eds.), *Init. Rep. DSDP 87*. US Gov. Printing Office, Washington, DC, pp. 483–554.
- Barron, J.A., 1992. Neogene diatom datum levels in the Equatorial and North Pacific. In: Ishizaki, K., Saito, T. (Eds.), *Centenary of Japanese Micropaleontology*. Terra Scientific, Tokyo, pp. 413–425.
- Barron, J.A., Gladenkov, A.Yu., 1995. Early Miocene to Pleistocene diatom stratigraphy of Leg 145. In: Rea, D.K., Basso, I.A., Scholl, D.W., Allan, J.F. (Eds.), *Proc. ODP Sci. Results 145*. ODP, College Station, TX, pp. 3–19.
- Barron, J.A., Mahood, A.D., 1993. Exceptionally well-preserved early Oligocene diatoms from glacial sediments of Prydz Bay, East Antarctica. *Micropaleontology* 39, 29–45.
- Berggren, W.A., Kent, D.V., Swisher, C.C., III, Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. *Soc. Econ. Paleontol. Mineral. Spec. Publ.* 54, 129–212.
- Brigham-Grette, J., Carter, L.D., Marincovich, L., Jr., Browsers, E., Hopkins, D.M., 1994. Warm Pliocene high sea-level records from Arctic Alaska and possible implications for Antarctic ice volume 2.8–2.2 Ma. In: Ishman, S.E. (Ed.), *Pliocene High-latitude Climate Records*. US Geol. Surv. Open-file Rep. 94-588, pp. 5–6.
- Burk, C.A., 1965. Geology of the Alaska Peninsula-island arc and continental margin. *Geol. Soc. Am. Mem.* 99, 250 pp.
- Carter, L.D., Hillhouse, J.W., 1992. Age of Late Cenozoic Bigbendian marine transgression of the Alaskan Arctic Coastal Plain: significance for permafrost history and paleoclimate. *US Geol. Surv. Bull.* 1999, 44–51.
- Detterman, R.L., Miller, J.W., Yount, M.E., Wilson, F.H., 1981. Geologic map of the Chignik and Sutwik Islands quadrangle, Alaska. US Geological Survey Miscellaneous Field Investigations Map I-1229, 1 sheet, scale 1:250 000.
- Detterman, R.L., Case, J.E., Miller, J.W., Wilson, F.H., Yount, M.E., 1996. Stratigraphic framework of the Alaska Peninsula. *US Geol. Surv. Bull.* 1969-A, 74 pp.
- Einarsson, T., Hopkins, D.M., Doell, R.D., 1967. The Stratigraphy of Tjörnes, northern Iceland, and the history of the Bering Land Bridge. In: Hopkins, D.M. (Ed.), *The Bering Land Bridge*. Stanford University Press, Stanford, CA, pp. 312–325.
- Galloway, W.E., 1974. Deposition and diagenetic alternation of sandstone in northeast Pacific arc-related basins – Implication for graywacke genesis. *Geol. Soc. Am. Bull.* 83, 379–390.
- Gladenkov, Yu.B., 1972. The Neogene of Kamchatka (Problems of biostratigraphy and paleoecology). *Geol. Inst., USSR Acad. Sci., Trans.* 214. Nauka, Moscow, 252 pp. (in Russian).
- Gladenkov, Yu.B., 1994. Some consequences of Bering Strait opening in the Neogene: solved and unsolved problems. *Proc. International Symposium on Neogene Evolution of Pacific Ocean Gateways*, 20–22 September, Kobe, pp. 2–8.
- Gladenkov, Yu.B., Barinov, K.B., Basilian, A.E. et al., 1992. Detailed Division of the Neogene of Kamchatka. Nauka, Moscow, 208 pp. (in Russian).
- Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science* 235, 1156–1167.
- Hodell, D.A., Benson, R.H., Kent, D.V., Boersma, A., Rakić-El Bied, K., 1994. Magnetostratigraphic, biostratigraphic, and stable isotope stratigraphy of an Upper Miocene drill core from the Sale Briquetrie (northwestern Morocco): a high resolution chronology for the Messinian stage. *Paleoceanography* 9, 835–855.
- Kaufman, D.S., Brigham-Grette, J., 1993. Aminostratigraphic correlations and paleotemperature implications, Pliocene–Pleistocene high sea-level deposits, northwestern Alaska. *Quat. Sci. Rev.* 12, 21–33.
- Lyle, W.M., Morehouse, J.A., Palmer, I.F., Jr., Bolm, J.G., 1979. Tertiary formations and associated Mesozoic rocks in the Alaska Peninsula area, Alaska, and their petroleum-reservoir and source-rock potential. *Alaska Div. Geol. Geophys. Surv. Geol. Rep.* 62, 65 pp.
- Mackey, K.G., Fujita, K., Gunbina, L.V., Kovalev, V.N., Imaev, V.S., Koz'min, B.M., Imaeva, L.P., 1997. Seismicity of the Bering Strait region: Evidence for a Bering block. *Geology* 25, 979–982.
- Marincovich, L., Jr., 2000. Central American paleogeography controlled Pliocene Arctic Ocean molluscan migrations. *Geology* 28, 551–554.
- Marincovich, L., Jr., Gladenkov, A.Yu., 1997. New paleontological information about the first opening of Bering Strait.

- Program and Abstracts, Beringian Paleoenvironments Workshop, Florissant, CO, pp. 103–104.
- Marincovich, L., Jr., Gladenkov, A.Yu., 1999. Evidence for an early opening of Bering Strait. *Nature* 397, 149–151.
- Marincovich, L., Jr., Gladenkov, A.Yu., 2001. New evidence for the age of Bering Strait. *Quat. Sci. Rev.* 20, 329–335.
- Marincovich, L., Jr., Brouwers, E.M., Hopkins, D.M., McKenna, M.C., 1990. Late Mesozoic and Cenozoic paleogeographic and paleoclimatic history of the Arctic Ocean Basin, based on shallow-water faunas and terrestrial vertebrates. In: Geological Society of America, *The Geology of North America, L, The Arctic Ocean Region*, pp. 403–426.
- Marincovich, L., Jr., Barinov, K.B., Oleinik, A.E., in press. *The Astarte* (Bivalvia, Astartidae) that document the earliest opening of Bering Strait. *J. Paleontol.*
- Nolf, D., Marincovich, L., Jr., 1994. First record of fossil *Merlangius* (Pisces, Gadiformes) from Arctic Alaska and chronostratigraphic implications. *Contrib. Tert. Quat. Geol. (Leiden)* 31, 9–13.
- Oreshkina, T.V., 1985. Diatom assemblages and stratigraphy of the upper Cenozoic off Kamchatka region of the Pacific Ocean (in Russian). *Izv. Akad. Nauk SSSR Geol. Ser.* 5, 60–73.
- Plafker, G., Berg, H.C., 1994. Overview of the geology and tectonic evolution of Alaska. In: Plafker, G., Berg, H.C. (Eds.), *The Geology of Alaska. Geology of North America, Vol. G-1*. Geological Society of America, Boulder, CO, pp. 989–1021.
- Repenning, C.A., 1967. Palearctic–Nearctic mammalian dispersal in the Late Cenozoic. In: Hopkins, D.M. (Ed.), *The Bering Land Bridge*. Stanford University Press, Stanford, CA, pp. 289–311.
- Repenning, C.A., 1980. Faunal exchanges between Siberia and North America. *Can. J. Anthropol.* 1, 37–44.
- Repenning, C.A., Brouwers, E.M., 1992. Late Pliocene–early Pleistocene ecological changes in the Arctic Ocean borderland. *US Geol. Surv. Bull.* 2036, 37 pp.
- Scholl, D.W., 1999. Plate-boundary driven tectonism of the northern rim of the Pacific Basin forms the Aleutian-Bering region in the early and middle Eocene. *Geol. Soc. Am. Abstr. Progr.* 31, 92.
- Scholl, D.W., Stevenson, A.J., Mueller, S., Geist, E.L., Engbretson, D.C., Vallier, T.L., 1992. Exploring the motion that southeast Asian-type escape tectonics and trench clogging are involved in regional-scale deformation of Alaska and the formation of the Aleutian-Bering Sea region. In: Flower, M. et al. (Eds.), *Southeast Asia Structure, Tectonics, and Magmatism*. Proc. Geodynamics Research Institute Symposium. Texas A&M University, College Station, TX, pp. 57–63.
- Shackleton, N.J., Hall, M.A., Pate, D., 1995. Pliocene stable isotope stratigraphy of ODP site 846. In: Pisias, N.G., Janacek, T.R., Palmer-Julson, A., van Angel, T.H. (Eds.), *Proc. ODP Sci. Results 138*. ODP, College Station, TX, pp. 337–355.
- Schumacher, C.F., 1817. *Essai d'un Nouveau Système des Habitations de Vers Testaces*. Schultz, Copenhagen, 287 pp., 22 pls.
- Suzuki, A., Akamatsu, M., 1994. Post-Miocene cold-water molluscan faunas from Hokkaido, Northern Japan. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 108, 353–367.
- Uozumi, S., Akamatsu, M., Takagi, T., 1986. Takikawa-Honbetsu and Tatsunokuchi faunas (*Fortipecten takahashii*-bearing Pliocene faunas). In: Kotaka, T., Marincovich, L., Jr. (Eds.), *Japanese Cenozoic Mollusks – their Origin and Migration*. *Palaeontol. Soc. Jpn. Spec. Pap.* 29, pp. 211–226.
- Vermeij, G.J., 1989. Geographical restriction as a guide to the causes of extinction: the case of cold northern oceans during the Neogene. *Paleobiology* 15, 335–356.
- Vermeij, G.J., 1991. Anatomy of invasion: the trans-Arctic interchange. *Paleobiology* 17, 281–307.
- White, J.M., Ager, T.A., Adam, D.M., Leopold, E.B., Liu, G., Jette, H., Schweger, C.E., 1997. An 18 million record of vegetation and climate change in northwestern Canada and Alaska: tectonic and global climatic correlations. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 130, 293–306.
- Yanagisawa, Y., 1990. Diatom biostratigraphy of the Neogene Sendai Group, northeast Honshu, Japan (in Japanese with English abstract). *Bull. Geol. Surv. Jpn.* 41, 1–25.
- Yanagisawa, Y., Akiba, F., 1998. Refined Neogene diatom biostratigraphy for the northwest Pacific around Japan with an introduction of code numbers for selected diatom biohorizons. *J. Geol. Soc. Jpn.* 104, 395–414.