

Diatom Stratigraphy of the Gubik Formation, Arctic Alaska

Pushkar V.S.

Far East Geological Institute FEB of RAS,
159 100 Let Vladivostok Av., Vladivostok 690022, Russia
vlpushkar@mail.ru

Received: 28 April 2022/Accepted 17 May 2022/Published 29 September 2022

ABSTRACT: Diatom assemblages of marine sediments from the Gubik Formation deposit of Arctic Alaska, were used for age determination and paleoclimatic reconstruction during the Late Pliocene-middle Pleistocene. Extinct diatoms during the Late Pliocene and Middle Pleistocene, as well as the first appearance of diatoms at the Plio – Pleistocene boundary exist within the sediment. The studied deposits of Nulavik, Killi Creek and the Tuapaktushak beds correspond to the middle part *Neodenticula kamtschatica* – *N. koizumii* Zone (3.4–3.1 Ma), lower part *Thalassiosira convexa* Zone (2.58–2.4 Ma) and to lower part *Pyxidicula zabelinae* Zone (2.2–2.0 Ma) respectively, as the Karmuk beds contain a species-index of the middle *Proboscia barboi* Zone (0.43–0.38 Ma). The moderately warm climates within the described zonal age were the effect of high sea-level events (transgressions) in the Arctic Ocean basin. The first penetration of Pacific diatoms to the Chukchi Sea was likely due to the opening of the Bering Strait at ~ 3.4 Ma, or the early Colvillian age.

KEY WORDS: diatoms, Pliocene, Pleistocene, biostratigraphy, Gubik Formation, transgressions, Skull Cliff, Alaska

INTRODUCTION

The Alaska Arctic Coastal Plain is composed of widespread unconsolidated deposits of the Late Pliocene-Pleistocene age Gubik Formation (GF) (Brigham, 1985; Dinter et al., 1990; Marincovich et al., 1990; Brigham-Grette, Carter, 1992; Kaufman, Brigham-Grette, 1993). The thick marine sequence of the GF was formed during the Late Pliocene and Middle-Late Pleistocene transgressions, and are unconformably underlain near Skull Cliff by Late Cretaceous (K₂tr) in age. At least six, and possibly eight, marine transgressions are recorded within the GF. The three oldest occurred during the Late Pliocene and, from oldest to youngest, are informally named the Colvillian, Bigbendian, and Fishcreekian (Carter et al.,

ISSN 1521-9429

© Begell House, 2022

1986). The amino acid ratios estimate the age of these transgressions as 2.7–2.48 Ma, 2.48 Ma, and 2.48–2.14 Ma respectively (Brigham-Grette, Carter, 1992). Hopkins (1972) and Fyles (1991) have considered the age of the Colvillian transgression to be > 3 Ma.¹

The Middle Pleistocene transgression was named the Wainwrightian for the marine unit unconformably overlying the Late Pliocene members of the GF (Carter et al., 1986). The age of the Wainwrightian transgression was estimated by amino acid epimerization ratios together with Uranium trend measurements, yielding an age estimate between 0.475–0.540 Ma (Kaufman, Brigham-Grette, 1993).

The uppermost Walakpa and Flaxman units record traces of the youngest high sea-level events (the Pelukian and Simpsonian transgressions) which are estimated to be of the Last Interglaciation in age (Hopkins, 1972; Brigham, 1985; Carter et al., 1986).

This research discusses age determinations for the marine sequences of the GF based on diatom analysis, in correlation with diatom zones, paleoclimatic and sea-level events of the North Pacific Ocean.

MATERIALS AND METHODS

Skull Cliff (70°52'6''N, 156°38'19''W) is located near the mouth of the Tuapaktushak Creek, 50 km southwest of Point Barrow (71°17'26''N, 156°47'19''W) (Fig. 1). Brigham (1985) investigated the most critical of the GF sediments in superposition at Skull Cliff near Tuapaktushak River, and established Pliocene and Pleistocene marine units coinciding with marine transgressive events (Fig. 2).

Nulavik unit is represented by gravely sand, crossbedded, sand, silty sand up to 3–5 m thick. The sediments of the Nulavik unit lie unconformably on either sandstone of the Cretaceous Nanushuk Group or the Papigak clay unit. This stratigraphic boundary reaches altitudes of at least 8–10 m above sea level (a.s.l.). The sediments were deposited during the Colvillian transgression (Carter et al., 1986). Based on the extent of amino acid epimerization in molluscan shells Brigham-Grette and Carter (1992) suggested that the Colvillian transgression occurred sometime after 2.7 Ma, while preliminary Strontium – isotope age estimates placed a minimum age at 1.9 Ma (Kaufman et al., 1990).

¹ It should be noted that the boundary between the Pliocene and the Quaternary was considered in these works at the level of 1.79 Ma.

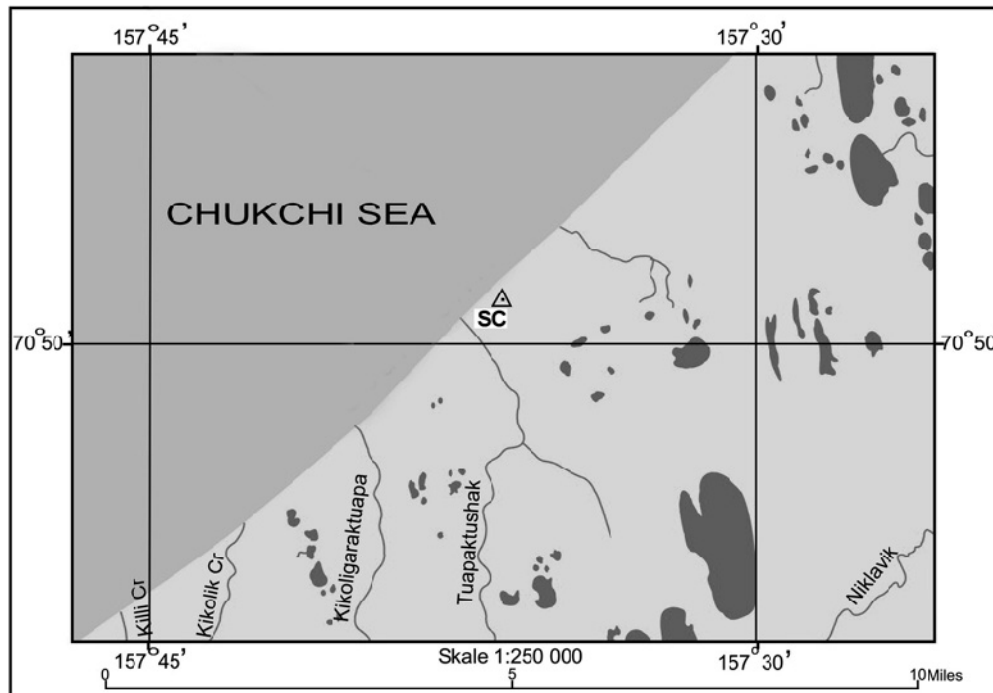


FIG. 1: Map showing Skull Cliff (SC) location in Arctic Alaska mentioned in the text

Killi Creek unit corresponds to the Bigbendian transgression based on marine deposits along the big bend of Colville River near Ocean Point (Brigham, 1985; Carter et al., 1986, Brigham-Grette, Carter, 1992). The Bigbendian transgression deposits are well exposed at altitudes up to about 20 m a.s.l., and are unconformably locally underlain by Nulavik deposits. The 8 m thick Killi Creek deposits represent inner-shelf facies, and include gravel, sand, and silt with interbedding of silty sand and silty clay. There is a magnetic reversal that occurs within the Killi Creek unit which most likely represents the 2.48 Ma Gauss-Matuyama boundary (Brigham-Grette, Carter, 1992; Carter, Hillhouse, 1992).

Tuapaktushak unit is correlated with the Fishcreekian transgression on the basis of its amino acid geochemistry. With altitudes up to 20–25 m a.s.l., the 8–9 m thick Tuapaktushak deposits consist largely of inner-shelf facies of interbedded sand, silty sand, silt, and some clay layers overlying a basal gravel lag (Brigham, 1985; Brigham-Grette, Carter, 1992). The Killi Creek/Tuapaktushak boundary is unconformably marked by pebbly, gravel, erratic cobbles and boulders. The age of the Fishcreekian transgression is thought to be < 2.48 Ma. Carter and Hillhouse (1992) argue for an early Matuyama, pre-Reunion age of 2.48–2.14 Ma. At the same time, Brigham-Grette and Carter (1992) recognized that a younger age for the Tuapaktushak unit has not yet been excluded.

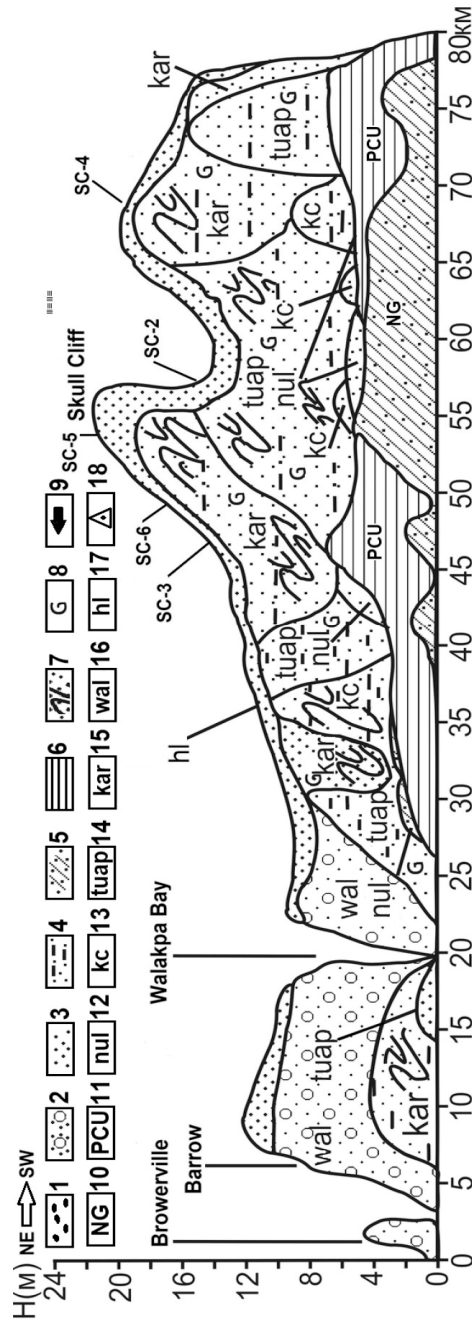


FIG. 2: Geological structure of the Gubik Formation and location of the explored outcrops (SC): 1 – pebbly and gravel; 2 – gravely sand; 3 – sand; 4 – silty sand; 5 – sandstone; 6 – siltstone; 7 – deposits with glacial destruction; 8 – molluscan shells; 9 – sampling; 10 – Cretaceous Nanushuk Group; 11 – Papigak clay unit; 12 – Nulavik unit; 13 – Killi Creak unit; 14 – Tuapaknushak unit; 15 – Karmuk unit; 16 – Walakpa unit; 17 – Holocene; 18 – triangulation point (modification from Brigham, 1985)

The **Karmuk unit** consists of marine deposits up to 10–12 m thick and of Middle Pleistocene age. These deposits are correlated with the Wainwrightian transgression, and are represented by a sequence of mainly inner-shelf sand, silty sand and a basal gravel lag. Barrier beach and lagoon facies are exposed intermittently along Skull Cliff and reach altitudes up to 23 m a.s.l. The Karmuk beds unconformably overlie the Tuapaktushak beds of Cretaceous bedrock (Dinter et al., 1990). Molluscan, ostracode, and foraminifera faunas from the Karmuk deposits are similar to those found on the Arctic shelf today (Brigham, 1985). Amino-acid epimerization ratios together with Uranium-trend determination suggest that the Karmuk sediments were deposited within the Wainwrightian transgression between 0.475–0.540 Ma (Brigham, 1985; Brigham-Grette, Carter, 1992).

The Walakpa and Flaxman units of the GF are not seen at the studied sections of Skull Cliff. Diatoms from sand, silty sand and silt of different marine units of four sections of the GF along Skull Cliff were identified. The location of the outcrops sections and lithostratigraphy are shown in Fig. 2. Although limited in species diversity (about 50 taxa) and abundance (usually less than 0.5 million valves per 1 g dry sediment), diatom sampling < all identified diatoms and their distribution along stratigraphic units, which are shown on the diagrams (Figs 3–6). Diatom levels of first evolution appearance and disappearance (Table) were used according to Pushkar (Pushkar et al., 2014) and Gladenkov (2007). The Pliocene and Quarter Diatom Zonal scale of North Pacific was applied as the age model (Pushkar et al., 2014). The boundary Pliocene/Quarter is considered at the level 2.58 Ma (Ogg, Pillans, 2008; Pillans, Gibbard, 2012).

RESULTS AND DISCUSSION

Biostratigraphy

The following Late Pliocene and Pleistocene diatom assemblages were established for marine units of the GF from oldest to youngest.

Nulavik unit. The transgressive Colvillian diatom assemblages are described for samples from sections SK-2 and SK-5 (Fig. 4). In both sections assemblages are represented by the Late Pliocene extinct planktonic diatoms: *Neodenticula kamtschatica*, *Thalassiosira nativa*, *T. convexa*, *T. antiqua*, *Pyxidicula zabelinae*, *Coscinodiscus pustulatus*, *Stephanopyxis schenckii* as well as the following diatoms that went extinct during the Pleistocene: *N. koizumii*, *T. gravida* var. *fossilis*, *T. sheshukovae*, *T. nidulus* var. *nidulus*, *T. jouseae*, *Porosira punctata*, *C. marginatus* var. *fossilis*, *Proboscia barboi*, *Actinocyclus oculatus*, *C. ochotensis*.

Most of the diatom taxa are transitional from the Pliocene to recent. The diagnostic zonal *Neodenticula kamtschatica* directly indicates assemblages belonging to the North Pacific *N. kamtschatica* – *N. koizumii* Zone 3.70–2.58 Ma.

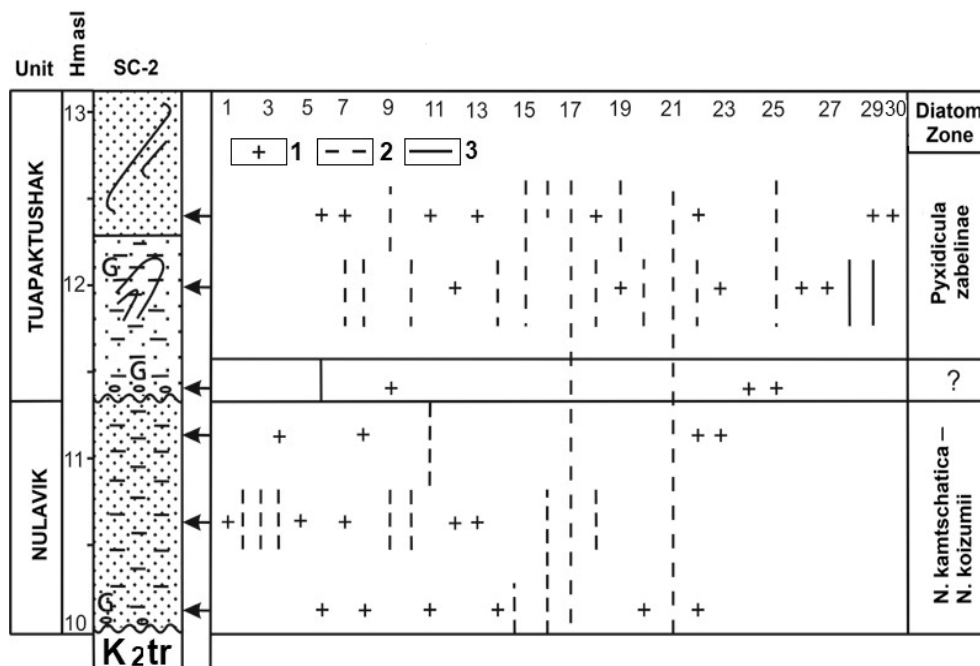


FIG. 3: Diatom diagram in the outcrop SC-2 of the Gubik Formation Grades of diatom abundance: 1 – single (1–10 valves per slide); 2 – rare (11–79 valves per slide), few – 1–2 valves in each horizontal traverse (X400) 18 mm length. Diatoms: 1 – *Grammatophora arcuata* Ehr.; 2 – *Neodenticula kamtschatica* (Zabelina) Akiba et Yanag.; 3 – *Proboscia barboi* (Brun.) Jordan et Priddle; 4 – *Thalassiosira nativa* Sheshukova-Poretzkaya; 5 – *T. convexa* Muchina; 6 – *Actinocyclus curvatus* Janisch; 7 – *A. ochotensis* var. *fossilis* Pushkar; 8 – *A. senarius* Ehr.; 9 – *Bacterosira bathyomphala* (Cleve) Syvertsen & Hasle; 10 – *Coscinodiscus marginatus* var. *fossilis* Jouse?; 11 – *Pyxidicula pustulatus* (Mann) Streln. et Nikolaev; 12 – *Coscinodiscus asteromphalus* Ehr.; 13 – *Diploneis subcineta* (A.S.) Cl.; 14 – *Grammatophora oceanica* (Ehr.) Grun.; 15 – *Navicula marina* Ralfs; 16 – *Neodenticula koizumii* Akiba et Yanag.; 17 – *Paralia sulcata* (Ehr.) Cl.; 18 – *Pyxidicula zabelinae* (Jouse?) Makar. et Moiss.; 19 – *Stephanopyxis horridus* Koizumi; 20 – *Thalassiosira antiqua* (Grun.) Cl.-E.; 21 – *T. gravida* var. *fossilis* Jouse?; 22 – *T. eccentrica* (Ehr.) Cl.; 23 – *Shionodiscus latimarginatus* (Makarova) A.J.Alverson, S.H.Kang et E.C.Theriot; 24 – *Odontella aurita* (Lyng.) Ag.; 25 – *Chaetoceros* spp. (spores); 26 – *Diploneis interrupta* (Kuetz.) Cl.; 27 – *Lyrella hennedyi* (W.Sm.) Kar.; 28 – *Stephanopyxis schenckii* Kanaya; 29 – *Diploneis smithii* (Breb.) Cl. 30 – *Thalassiosira nidulus* (Temp. et Brun.) Jouse?

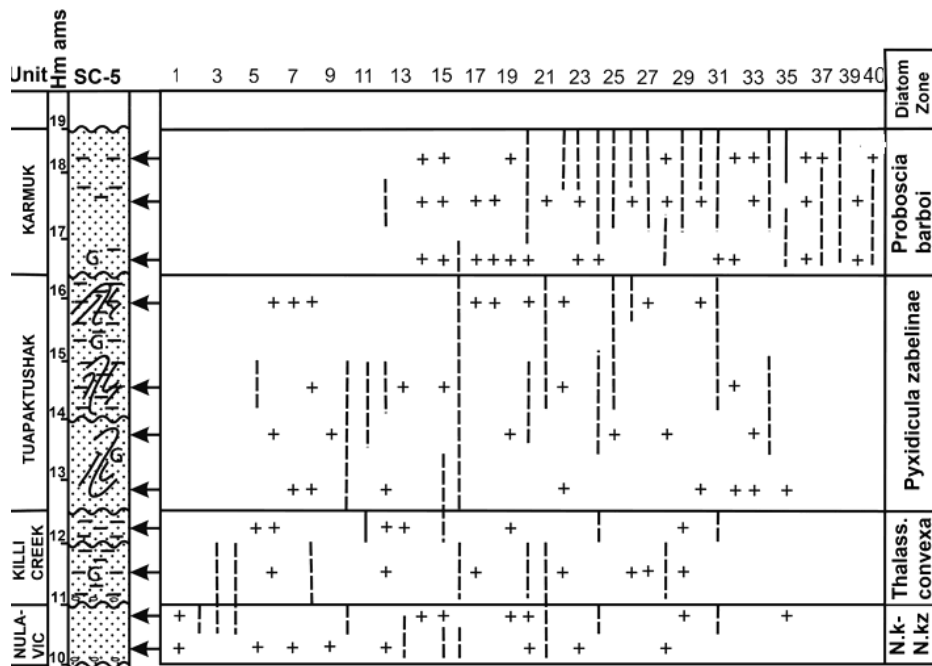


FIG. 4: Diatom diagram in the outcrop SC-5 of the Gubik Formation. Diatoms: 1 – *Neodenticula kamschatica* (Zabelina) Akiba et Yanag.; 2 – *Thalassiosira nativa* Sheshukova-Poretzkaya; 3 – *T. convexa* Muchina; 4 – *T. sheshukovae* Makar.; 5 – *Pyxidicula zabelinae* (Jouse') Makar. et Moiss.; 6 – *Stephanopyxis horridus* Koizumi; 7 – *Thalassiosira antiqua* (Grun.) Cl.-E.; 8 – *Porosira punctata* (Jouse') Makar.; 9 – *Coscinodiscus pustulatus* Mann; 10 – *C. marginatus* var. *fossilis* Jouse'; 11 – *Stephanopyxis schenckii* Kanaya; 12 – *Actinocyclus ochotensis* var. *fossilis* Pushkar; 13 – *Neodenticula koizumii* Akiba et Yanag.; 14 – *Proboscia barboi* (Brun.) Jordan et Priddle; 15 – *Thalassiosira nidulus* (Temp. et Brun.) Jouse'; 16 – *T. gravida* var. *fossilis* Jouse'; 17 – *T. jouseae* Akiba; 18 – *Proboscia curvirostris* (Jouse') Jordan et Priddle; 19 – *Actinocyclus curvatulus* Janisch; 20 – *A. senarius* Ehr.; 21 – *Bacterosira bathyomphala* (Cleve) Syvertsen & Hasle; 22 – *Coscinodiscus asteromphalus* Ehr.; 23 – *Chaetoceros mitra* (Bail.) Cl.; 24 – *Chaetoceros* sp. (spores); 25 – *Diploneis smithii* (Breb.) Cl.; 26 – *D. subcincta* (A.S.) Cl.; 27 – *Grammatophora oceanica* (Ehr.) Grun.; 28 – *G. arctica* Ehr.; 29 – *Thalassiosira eccentrica* (Ehr.) Cl.; 30 – *Shionodiscus latimarginatus* A.J.Alverson, S.H.Kang et E.C.Theriot; 31 – *Thalassiosira nordenskioldii* Cl.; 32 – *Diploneis interrupta* (Kuetz.) Cl.; 33 – *Lyrella hennedyi* (W.Sm.) Kar.; 34 – *Navicula marina* Ralfs; 35 – *Paralia sulcata* (Ehr.) Cl.; 36 – *Actinoptychus senarius* var. *tamanicus* Jouse'; 37 – *Coscinodiscus marginatus* Ehr.; 38 – *Chaetoceros compressus* Laud.; 39 – *Neodenticula seminae* (Sim. et Kan.) Akiba et Yanag.; 40 – *Odontella aurita* (Lyng.) Ag.

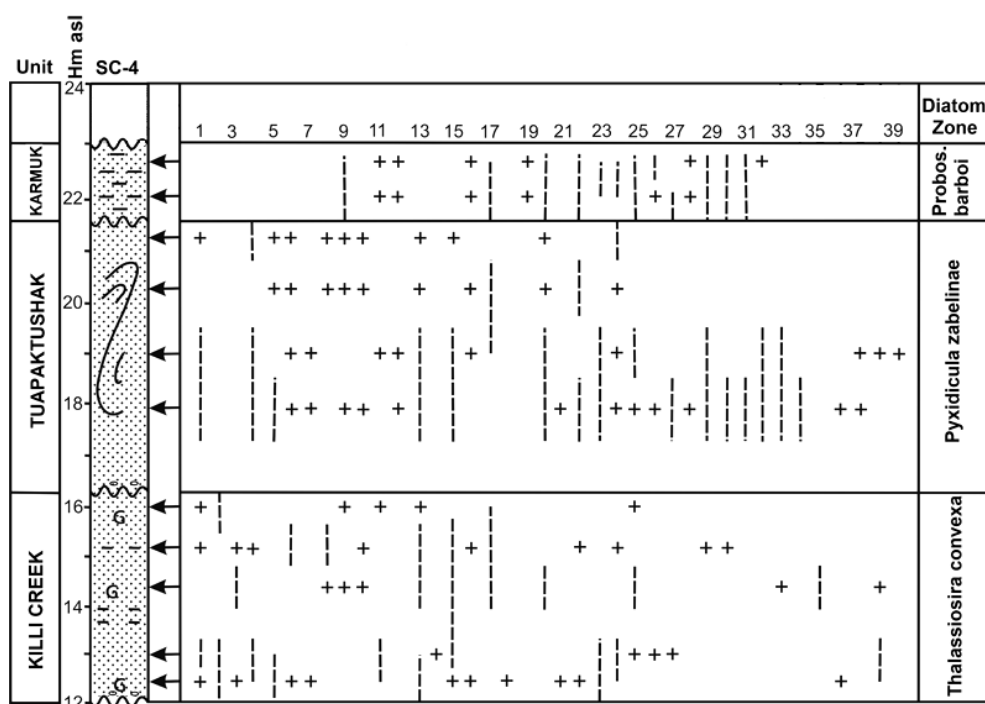


FIG. 5: Diatom diagram in the outcrop SC-4 of the Gubik Formation. Diatoms: 1 – *Porosira punctata* (Jouse') Makar.; 2 – *Thalassiosira sheshukovae* Makar.; 3 – *T. convexa* Muchina.; 4 – *Pyxidicula pustulatus* (Mann) Streln. et Nikolaev; 5 – *Neodenticula koizumii* Akiba et Yanag.; 6 – *Pyxidicula zabelinae* (Jouse') Streln. et Nikolaev; 7 – *Stephanopyxis schenckii* Kanaya; 8 – *S. horridus* Koizumi; 9 – *Thalassiosira nidulus* (Temp. et Brun.) Jouse'; 10 – *T. antiqua* (Grun.) Cl.; 11 – *Proboscia barboi* (Brun.) Jordan et Priddle; 12 – *P. curvirostris* (Jouse') Jordan et Priddle; 13 – *Thalassiosira gravida* var. *fossilis* Jouse'; 14 – *Actinocyclus ochotensis* var. *fossilis* Pushkar; 15 – *Coscinodiscus marginatus* var. *fossilis* Jouse'; 16 – *Actinoptychus senarius* Ehr.; 17 – *Bacterosira bathyomphala* (Cleve) Syvertsen & Hasle; 18 – *Stellarima microtrias* (Ehr.) Hasle et Sims; 19 – *Chaetoceros mitra* (Bail.) Cl.; 20 – *Chaetoceros* spp. (spores); 21 – *Grammatophora oceanica* (Ehr.) Grun.; 22 – *Odontella aurita* (Lyng.) Ag.; 23 – *Thalassiosira eccentrica* (Ehr.) Cl.; 24 – *T. nordenskioldii* Cl.; 25 – *Shionodiscus latimarginatus* A.J.Alverson, S.H.Kang et E.C.Theriot; 26 – *Actinocyclus curvatulus* Janisch.; 27 – *Diploneis smithii* (Breb.) Cl.; 28 – *D. interrupta* (Kuetz.) Cl.; 29 – *D. subcineta* (A.S.) Cl.; 30 – *Grammatophora arcuata* Ehr.; 31 – *Navicula marina* Ralfs; 32 – *Lyrella hennedyi* (W.Sm.) Kar.; 33 – *Aulacoseira praegrnulata* (Jouse') Sim.; 34 – *Ellerbeckia arenaria* var. *teres* (Brun.) Crawford; 35 – *Eunotia praerupta* Ehr. and its vars; 36 – *Pinnularia viridis* (Nitzsch.) Ehr.; 37 – *P. brevicostata* Cl.; 38 – *P. lata* (Breb.) W.Sm.; 39 – *Navicula amphibola* Cl.

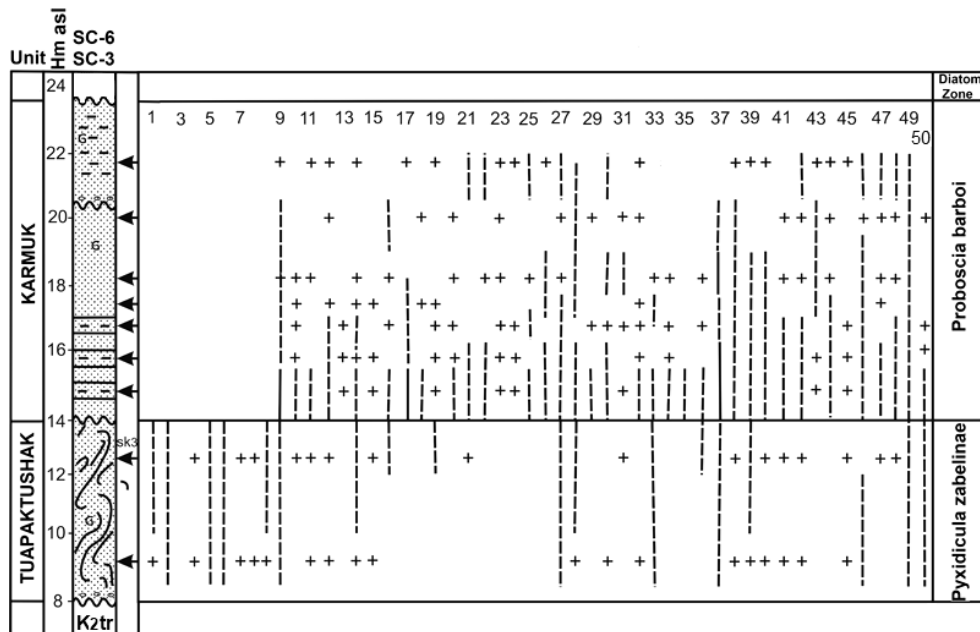


FIG. 6: Diatom diagram in the outcrop SC-3,6 of the Gubik Formation. Diatoms: 1 – *Coscinodiscus marginatus* var. *fossilis* Jouse[?]; 2 – *C. pustulatus* Mann; 3 – *Neodenticula koizumii* Akiba et Yanag.; 4 – *Porosira punctata* (Jouse[?]) Makar.; 5 – *Pyxidicula zabelinae* (Jouse[?]) Makar. et Moiss.; 6 – *Stephanopyxis horridus* Koizumi; 7 – *S. schenckii* Kanaya; 8 – *Thalassiosira antiqua* (Grun.) Cl.-E.; 9 – *T. gravida* var. *fossilis* Jouse[?]; 10 – *T. nidulus* (Temp. et Brun.) Jouse[?]; 11 – *Proboscia barboi* (Brun.) Jordan et Priddle; 12 – *P. curvirostris* (Jouse[?]) Jordan et Priddle; 13 – *Stephanopyxis dimorpha* Schrader; 14 – *Actinocyclus ochotensis* var. *fossilis* Pushkar; 15 – *Thalassiosira jouseae* Akiba; 16 – *Actinocyclus curvatulus* Janisch; 17 – *Actinoptychus senarius* Ehr.; 18 – *A. senarius* var. *tamanicus* Jouse[?]; 19 – *Bacterosira fragilis* (Cleve) Syvertsen & Hasle; 20 – *Coscinodiscus marginatus* Ehr.; 21 – *Stellarima microtrias* (Ehr.) Hasle et Sims; 22 – *Coscinodiscus asteromphalus* Ehr.; 23 – *Coscinodiscus radiatus* Ehr.; 24 – *C. perforatus* Ehr.; 25 – *Chaetoceros compressus* Laud.; 26 – *C. mitra* (Bail.) Cl.; 27 – *Chaetoceros* spp. (spores); 28 – *Diploneis smithii* (Bréb.) Cl.; 29 – *D. interrupta* (Kuetz.) Cl.; 30 – *D. subcincta* (A.S.) Cl.; 31 – *Grammatophora oceanica* (Ehr.) Grun.; 32 – *Grammatophora arcuata* Ehr.; 33 – *Navicula marina* Ralfs; 34 – *Lyrella hennedyi* (W.Sm.) Kar.; 35 – *Neodenticula seminae* (Sim. et Kan.) Akiba et Yanag.; 36 – *Odontella aurita* (Lyng.) Ag.; 37 – *Paralia sulcata* (Ehr.) Cl.; 38 – *Thalassiosira gravida* var. *fossilis* Jouse[?]; 39 – *T. eccentrica* (Ehr.) Cl.; 40 – *Shionodiscus latimarginatus* A.J.Alverson, S.H.Kang et E.C.Theriot; 41 – *Thalassiosira nordenskioldii* Cl.; 42 – *T. kryophila* (Grun.) Jorg.; 43 – *Porosira glacialis* (Grun.) Joerg. et Forti; 44 – *Actinocyclus ochotensis* Jouse[?]; 45 – *Asteromphalus brookei* Bail.; 46 – *Nitzschia cylindra* (Grun.) Hasle; 47 – *N. grunowii* (Cl.) Hasle; 48 – *N. sicula* (Castr.) Hust.; 49 – *Rhizolenia hebetata* f. *hiemalis* Gran; 50 – Freshwater diatoms (in sum)

TABLE: Diatom levels of first evolutionary appearance and disappearance

Diatom level	Taxon	Index	Age (Ma)
1	<i>Proboscia curvirostris</i>	L	0.095
2	<i>Thalassiosira gravida</i> var. <i>fossilis</i>	L	0.13
3	<i>T. nidulus</i> var. <i>nidulus</i>	L	0.2
4	<i>T. jouseae</i>	L	0.23
5	<i>Stephanopyxis (Pyxidicula) dimorpha</i>	L	0.2
6	<i>Actinocyclus ochotensis</i> s.str.	F	0.22–0.23
7	<i>A. ochotensis</i> var. <i>fossilis</i>	L	0.22–0.23
8	<i>Proboscia barboi</i>	L	0.28
9	<i>Nitzschia reinholdii</i>	L	0.525–0.55
10	<i>N. fossilis</i>	L	0.65
11	<i>Actinocyclus oculatus</i>	L	0.90–0.92
12	<i>Proboscia matuyamai</i>	L	0.90–0.92
13	<i>Neodenticula koizumii</i>	L	0.90–0.92
14	<i>Coscinodiscus marginatus</i> var. <i>fossilis</i>	L	0.90–0.92
15	<i>Proboscia matuyamai</i>	F	0.97
16	<i>Thalassiosira antiqua</i>	L	1.66–1.7
17	<i>Proboscia curvirostris</i>	F	1.88–2.0
18	<i>Stephanopyxis (Pyxidicula) horridus</i>	L	1.7
19	<i>Pyxidicula zabelinae</i>	L	1.88
20	<i>Coscinodiscus pustulatus</i>	L	1.88
21	<i>Thalassiosira convexa</i>	L	2.3
22	<i>Stephanopyxis (Pyxidicula) horridus</i>	F	2.6
23	<i>Neodenticula kamschatica</i>	L	2.58 ?
24	<i>Thalassiosira nativa</i>	L	3.1
25	<i>Actinocyclus oculatus</i>	F	~ 3.4
26	<i>A. ochotensis</i> var. <i>fossilis</i>	F	~ 3.4
27	<i>Neodenticula koizumii</i>	F	~ 3.7

F – first appearance in the North Pacific; L – last appearance in the North Pacific.

The occurrence of the stratigraphic taxa *Thalassiosira nativa* with an extinction level in the North Pacific about 3.1 Ma, as well as *Actinocyclus oculatus* – *A. ochotensis* var. *fossilis* group with high morphological diversity of valve elements and level of the first appearance at about 3.5–3.4 Ma is very important for dating the Nulavik deposits. The true age suggested for the Colvillian transgressions is Late Pliocene, or 3.4–3.1 Ma. This age is correlative with the first Beringian transgression of Hopkins (1972). Correlative to the Nulavik beds, the numerical ages of the Beringian aminozones are not known with certainty but can be estimated using an empirical model of parabolic epimerization kinetics, reasonable temperature reconstruction, and an assumed age of about 3.2 Ma for the Beringian I aminozone (Kaufman, Brigham-Grette, 1993), that approximately coincides with the opening of Bering Strait (Marincovich, Gladenkov, 1999).

Killi Creek unit. The transgressive Bigbendian diatom assemblages are characterized by the same extinction species (Figs 4 and 5) as founded in the Nulavik deposits, except *Neodenticula kamtschatica*, whose level of extinction, probably, marks the top of Nulavik unit.

The first appearance of *Stephanopyxis horridus* was established only in this stratigraphic unit. Similar to the Nulavik deposits, the Killi Creek unit is deprived of species whose first evolutionary appearance is near the Pliocene-Pleistocene boundary namely planktonic *Stephanopyxis dimorpha*, *Coscinodiscus marginatus*, *Proboscia curvirostris* (Table).

The Killi Creek marine diatom assemblages are dominated by extinct planktonic *Pyxidicula zabelinae* and *Thalassiosira gravida* var. *fossilis*. The presence of *Thalassiosira convexa*, *Stephanopyxis horridus* and *Neodenticula koizumii*, and the absence of *N. kamtschatica* suggests that this unit might be correlated with the marine assemblage *T. convexa* Zone (Pushkar et al., 2014). The top of the *T. convexa* Zone is 2.3 Ma and the base is 2.58 Ma, coinciding with the age-interval from the uppermost part of the normal-polarity event of the Gauss Chron to, probably, the Reunion Normal-Polarity Subchron of the reversed Matuyama Chron. Additionally, the stratigraphically significant diatom *S. horridus*, first appearing in the North Pacific at 2.58 Ma, was found in the Killi Creek deposits (Pushkar, Cherepanova, 2001). The disappearance of *T. convexa* in the Chukchi Seas took place earlier, about 2.4 Ma (Pushkar, Cherepanova, 2001). Other floral elements of the *Thalassiosira convexa* Zone include the extinct planktonic *T. antiqua*, *T. nidulus*, *T. sheshukovae*, *Coscinodiscus pustulatus*, *C. marginatus* var. *fossilis*, *Porosira punctata*, and *P. barboi*. The Bigbendian transgression, which followed the Colvillian transgression on the Arctic Coastal Plain, was correlative with the Beringian II aminozone on the Nome coastal plain (Kaufman, 1992; Kaufman, Brigham-Grette, 1993). Furthermore, the polarity change of normal to reversed within the Killi Creek deposits is most likely the Gauss-

Matuyama boundary, the age of which dates to about 2.58 Ma (Brigham-Grette, Carter, 1992; Carter, Hillhouse, 1992).

Tuapaktushak unit (Figs 3–6). This marine unit, formed during the Fishcreekian transgression, does not contain diatom assemblages with the extinct zonal species *Thalassiosira convexa*, disappearing at 2.3 Ma in high latitudes (Pushkar, Cherepanova, 2001). Diatoms first of the Pliocene-Pleistocene, include such species as planktonic *Proboscia curvirostris*, *Thalassiosira latimarginata*, *T. kryophila*, *Coscinodiscus marginatus*, *Neodenticula seminae*, *Asteromphalus brookei* and *Nitzschia cylindra*, are established within the Tuapaktushak beds (Table). Other marine planktonic species include the Pleistocene extinct *Thalassiosira gravida* var. *fossilis*, *T. nidulus*, *T. jousea*, *Proboscia barboi*, *Actinocyclus oculatus*, and *A. ochotensis* var. *fossilis*. The assemblage of this interval includes sublittoral *Diploneis smithii*, *D. interrupta*, *Grammatophora oceanica*, *Paralia sulcata*, *Navicula marina*, *Lyrella hennedyi*, the partly neritic *Chaetoceros compressus*, *Chaetoceros* spp. (spores), *Odontella aurita*, *Actinoptychus senarius* and others (Figs 5 and 6). This unit is also characterized by the abundant and extinct *Pyxidicula zabelinae*, as well as *Coscinodiscus pustulatus*, extinct in the northern Pacific near the base of the normal Olduvai Event within the reversed Matuyama Chron (Pushkar, Cherepanova, 2001; Pushkar et al., 2014). Species bearing a level of extinction within or just above the top of the normal Olduvai Event such as *Stephanopyxis horridus* and *Thalassiosira antiqua*, can be identified.

Using the last occurrence of *Thalassiosira convexa*, *Pyxidicula zabelinae* and *Coscinodiscus pustulatus*, and the low frequency of Pleistocene species (Table), it is clear that the described diatom assemblage should be assigned to the *Pyxidicula zabelinae* Zone with an age-interval 2.3–1.95 (Pushkar et al., 2014), which is correlated with Gelasian Stage of Quarter (Gibbard, Head, 2010). Brigham-Grette and Carter suggest that the reversal of the magnetized Fishcreekian sediments were deposited prior to the Olduvai, or before 1.95 Ma (Kaufman, 1992; Brigham-Grette, Kaufman, 1992; Kaufman, Brigham-Grette, 1993).

Karmuk unit (Figs 4–6). The transgressive Wainwrightian diatom assemblages are dominated by *Thalassiosira gravida* var. *fossilis*, *Actinoptychus senarius* and *Paralia sulcata* (Figs 6–8). Only several of these are extinct within the middle Pleistocene, namely *Proboscia barboi*, *P. curvirostris*, *T. gravida* var. *fossilis*, *T. nidulus*, *T. jouseae* and *Actinocyclus ochotensis* var. *fossilis* (Table). The described diatom assemblages should be assigned to the *Proboscia barboi* Zone, 0.55–0.28 Ma in age. This assumption is strengthened by the absence of *Actinocyclus oculatus* and other species with early and mid-Pleistocene extinction levels in the North Pacific (Pushkar, Cherepanova, 2001). The paleoecological structure of the described assemblage allows us to determine the age at about 0.43–0.38 Ma, which coincides with warm MIS 11 (Pushkar, Cherepanova, 2001).

Evidence for the rise of the annual average surface water temperature in the Chukchi Sea during the Wainwrightian transgression is the presence of the relatively warm-water diatoms planktonic *Actinoptychus senarius*, *Coscinodiscus asteromphalus*, *C. radiatus*, *C. perforatus*, and sublittoral benthonic *Navicula marina*, *Lyrella hennedyi*. This assumption is confirmed by the regional correlation of the Wainwrightian diatom assemblages with those of Anvilian beds of Baldwin Peninsula, Northwestern Alaska (Pushkar et al., 1999).

Palaeoclimatic and sea-level changes

Clear traces of both palaeoclimatic and sea-level fluctuations during the Late Pliocene and Quarter are recorded in the deposits of the Gubik Formation along Skull Cliff.

The Nulavik diatom assemblages containing the Pacific warm-water *Thalassiosira convexa*, *Coscinodiscus asteromphalus*, *Navicula marina*, *Actinoptychus senarius*, are evidence of the warmer-than-present paleoclimatic conditions during the Colvillian transgression (on average +6 °C). These assemblages, which mostly contain more than 50% sublittoral and neritic species, as well as lithological data indicate an inner-shelf facies about 40–50 m in depth. The first perceptible influence of the Pacific taxa on the Chukchi Sea diatom composition correlates with the beginning of the Colvillian transgression at 3.4 Ma. There is evidence that eustatic sea-level 3.2 Ma rose between 35 and 50 m above modern sea level (a.m.s.l.) (Basilyan et al., 1991), and diatom flora does not contradict this.

A relatively warmer-than-present climate during the Bigbendian transgression is suggested by the presence of the relatively warm Pacific diatoms *Thalassiosira convexa*, *Coscinodiscus asteromphalus* (up to 17.5%). Additionally, the presence of the holoplanktonic diatom *C. asteromphalus* and *T. convexa* infer the absence of thick sea ice that occurs nearly year-round in northern Alaska. According to pollen analysis of Late Pliocene sediments of the Gubik Formation, the landscape of Arctic Alaska was represented by spruce and birch boreal forest with minor amounts of alder in adjacent terrestrial areas (Brigham, 1985; Dinter et al., 1990; Marincovich et al., 1990; Brigham-Grette, Carter, 1992; Kaufman, Brigham-Grette, 1993). As is the case with the Colvillian diatom assemblages, the ecological diatom composition of the Bigbendian beds records inner-shelf sedimentation. According to the diatom neritic-sublittoral ecological structures and the elevation of the marine units, the high eustatic sea-level position during the Bigbendian transgression was similar to that of the Colvillian age.

The Fishcreekian transgressive deposits (Tuapaktushak unit) contain the relatively warm-water holoplanktonic diatoms *Coscinodiscus asteromphalus*, whose modern limit is 45°–50°N, and the north-boreal species *Actinocyclus curvatulus*, *Neodenticula seminae*, and *Coscinodiscus marginatus* with northern limits in the Bering Sea (Pushkar,

Cherepanova, 2001). In addition to the northern species, the presence of the moderate sublittoral *Navicula marina* and *Lyrella heneddyi* are evidence for higher than present annual surface water temperatures in the Chukchi Sea at +3 °C.

The predominance of cold endemic taxa such as *Bacterosira bathyomphala*, *Porosira glacialis*, *Thalassiosira hyalina*, *T. kryophila*, *T. gravida*, and *T. nordenskiöldii* indicates that the period of seasonal ice cover was shorter than present, because the abundance of the cryophilic diatoms was less than that of the modern Bering Sea (Pushkar, Cherepanova, 2001). The ecological structure of the Fishcreekian diatom assemblages, which are represented by the predominance of planktonic neritic and benthic sublittoral species, suggest that Tuapaktushak deposits may be the inner-shelf facies. Warmer than present sea surface temperatures during the Fishcreekian are also indicated for the Bigbendian age. The marine diatom evidence contrasts with floral evidence of shrub-herb tundra indicating cold air temperatures (Kaufman, Brigham-Grette, 1993). Based on the ecological structure of the diatom assemblages along with the altitude of the Tuapaktushak beds the sea-level was higher than present, up to +20 m without invoking substantial glaciotectonic uplift of the shoreline.

Warmer-than-present annual surface sea-water temperatures of the Chukchi Sea were recorded by the ecological structures of the Karmuk diatom assemblages. Despite the fact that arcto- and north-boreal diatom taxa are relatively common, the warm-water and moderate elements include such infrequent Pacific endemics as planktonic *Coscinodiscus asteromphalus*, *C. radiatus*, and *C. perforatus*. The appearance of these taxa in the Chukchi Sea is evidence for higher than present average annual surface water temperatures by at least 2–3 °C. Existence of the warm and moderate elements were likely caused by both increased surface water temperature and penetration of warm currents from the northeastern Pacific through the Bering Strait and into the Chukchi Sea.

In the diatom associations there are many neritic and sublittoral elements such as *Paralia sulcata* and a species of the genus *Diploneis* that indicate a shallow water environment (< 30 m). Taking into account the elevation of the Karmuk deposits, 13 m of tectonic uplift of the northwestern Alaskan Middle Pleistocene transgressive deposits (Kaufman et al., 1991) and paleoecological analysis of diatom assemblages allows us to estimate a maximum magnitude of sea-level rise up to 20–25 m a.m.s.l. during OIS 11. This estimate correlates with values from Baldwin Peninsula (Kotzebue Sound) (Pushkar et al., 1999).

CONCLUSIONS

The Gubik Formation diatom flora of Skull Cliff was studied. The stratigraphic units consisting of marine sediments were deposited by the Colvillian, Bigbendian, Fishcreekian,

and Wainwrightian transgressions. Based on the biostratigraphic distribution of the diatoms in comparison with the diatom datum level of the North Pacific and Zonal Scale, it is suggested that the diatom zonal stratigraphy for the marine sequences is in superposition. The oldest Nulavik unit is characterized by diatom assemblages of the *Neodenticula kamschatica* – *N. koizumii* Zone, about 3.7–2.58 Ma in age. The Killi Creek deposits correlate with the *Thalassiosira zabelinae* Zone, 2.58–2.3 Ma in age, and the Tuapaktushak unit – correlates with the *Pyxidicula zabelinae* Zone, 2.3–1.88 (1.95) Ma. The Middle Pleistocene Karmuk unit contains the diatom assemblages of the *Proboscia barboi* Zone with an age-interval from 0.52–0.28 Ma. The more accurate ages are based upon the sequences of global warming correlated with the Colvillian (3.4–3.1 Ma), Bigbendian (2.5–2.4 Ma), Fishcreekian (2.2–2.0 Ma), and Wainwrightian (0.43–0.38 Ma) transgressions. The highest sea-level was recorded during the Colvillian transgression, up to 50 m above modern s.l. (msl), while sea-level during the Fishcreekian and Wainwrightian transgressions rose 20–25 m a.m.s.l. The Fishcreekian and Wainwrightian deposits contain the pollen assemblages of a shrub-herb tundra, which indicate a severe terrestrial climate during the transgressions. It seems, that the contrast in ocean and land temperatures, and abundant moisture were favorable for the buildup of ice sheets.

REFERENCES

- Basilyan A.E., Barinov K.B., Oreshkina T.V., Trubikhin V.M. 1991. In: *Paleogeography and biostratigraphy of the Pliocene and Pleistocene*. Moscow: GIN RAS. Pp. 5–24. [Rus.]
- Brigham G. 1985. *Marine stratigraphy and amino acid geochronology of the Gubik Formation, western Arctic Coastal Plain, Alaska*: PhD Diss. Menlo Park, California. USGS Open-File Report 85-381. 218 p.
- Brigham-Grette J., Carter L.D. 1992. Pliocene Marine Transgressions of Northern Alaska: Circumarctic Correlations and Paleoclimatic Interpretations. *Arctic*. 45(1): 74–89.
- Carter L.D., Hillhouse J.W. 1992. Age of the Late Cenozoic Bigbendian marine transgression of the Alaskan Arctic Coastal Plain; significance for permafrost history and paleoclimate. *Geol. Surv. Bull.* Pp. 44–51.
- Carter L.D., Brigham-Grette J., Marincovich L., Pease V.L., Hillhouse J.W. 1986. Late Cenozoic Arctic Ocean sea ice and terrestrial paleoclimate. *Geology*. 14: 675–678.
- Dinter D.A., Carter L.D., Brigham-Grette J. 1990. In: *The Arctic Ocean region*. Boulder, CO: Geol. Soc. Am. Pp. 459–490.
- Fyles J.G., Marincovich L.Jr., Matthews J.V.Jr., Barendregt R. 1991. Unique mollusk find in the Beaufort Formation (Pliocene) Meighen Island, Arctic. *Geol. Sur. Canada Paper*. 91-B: 105–112.
- Gibbard Ph.L., Head M.J., Walker M.J.C. 2010. Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. *J. Quarter. Sci.* 25(2): 96–102.
- Gladenkov A.Yu. 2007. *Detailed stratigraphy and marine ecosystems of the Late Cenozoic North Pacific region (according to diatoms)*. Moscow: GEOS. 296 p. [Rus.]

- Hopkins D.M. 1972. The paleoecology and climatic history of Beringia during late Cenozoic time. *Inter-Nord*. 12: 121–150.
- 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.
- Marincovich L.Jr., Brouwers E.M., Hopkins D.M., McKenna M.C. 1990. In: *The Geology of North America*. Vol. L. *The Arctic Ocean region*. Boulder: U.S. Geol. Pp. 403–426.
- Marincovich L.Jr., Gladenkov A.Yu. 1999. Evidence for an early opening of the Bering Strait. *Nature*. 397: 149–151.
- Ogg J., Pillans B. 2008. Establishing Quaternary as a formal international Period/System. *Episodes*. 31(2): 230–233. <https://doi.org/10.18814/epiiugs/2008/v31i2/008>
- Pillans B., Gibbard P. 2012. In: *The Geological Time Scale*. Amsterdam: Elsevier. Pp. 979–1010. <https://doi.org/10.1127/0078-0421/2012/0020>
- Pushkar V.S., Roof S.R., Cherepanova M.V., Hopkins D.M., Ivanov V.F., Brigham-Grette J. 1999. Paleogeographic and Paleoclimatic Significance of Diatoms from Middle Pleistocene Marine and Glaciomarine Deposits on Baldwin Peninsula, Northwestern Alaska. *Palaeogeogr., Palaeoclim., Palaeoecol.* 152: 67–85.
- Pushkar V.S., Cherepanova M.B. 2001. *Diatoms of Pliocene and Anthropogene of North Pacific (stratigraphy and paleoecology)*. Vladivostok: Dalnauka Press. 228 p. [Rus.]
- Pushkar V.S., Cherepanova M.V., Likhacheva O.Yu. 2014. Detailization of the Pliocene – Quaternary North Pacific Diatom Zonal Scale. *Int. J. Algae*. 16(3): 284–306. <https://doi.org/10.1615/InterJAlgae.v16.i3.80>