

Improvement of the Neogene Zonal Diatom Scale of Primorye (Russia)

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Abstract—To study diatoms from some Neogene stratotype sections of Southern Primorye—the Sineutesovskaya and Novokachalinskaya formations and the Shufansky Horizon, light and scanning electron microscopy were used. The data allowed corrections to the existing Zonal Diatom Scale of the Neogene of Primorye. Studies have shown the absence of some zone index species in the deposits: *Alveolophora bifaria*, *A. jouseana*, and *A. areolata*. As a result, the subdivisions of the scale were renamed: Alveolophora hachiy-aensis—Aulacoseira elliptica Zone, Alveolophora khankaica Zone, Alveolophora khursevichiae Zone. The position of the Shufansky horizon zones has changed: the Aulacoseira praeislandica Zone now corresponds to the Early Pliocene, and the Alveolophora tscheremissinovae Zone—to the Late Pliocene. According to the International Stratigraphic Chart of the Cenozoic, the age of the upper boundary of the Alveolophora tscheremissinovae Zone is 2.58 Ma.

Keywords: diatoms, biostratigraphy, zonal scales, Neogene, Southern Primorye

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INTRODUCTION

The main problem in developing regional stratigraphic schemes is to establish a reliable stratigraphic basis for geological exploration and surveying activities, including stratification and correlation of sections, creation of predictive models, and quantitative assessment of mineral resources.

The issues of developing zonal stratigraphic scales, the principles behind their development, the criteria for distinguishing subdivisions of different levels, and the justification for their boundaries have been widely discussed [4–6, 10, 21, 27]. Attempts have been made several times to develop such scales for Neogene continental deposits in Primorye. In 1985, V.S. Pushkar and A.M. Korotkiy [19] were the first to propose a stratigraphic scale for the Miocene–Pliocene interval including three diatom beds. Later, based on this scale and new data on diatom evolution in the Neogene of Primorye and neighboring territories, other versions of the zonal diatom scale were suggested [9, 13, 47]. The zones of these scales were correlated with the Unified Stratigraphic Scheme of the Neogene and Pliocene of Primorye [22].

However, subsequent studies of Neogene–Pliocene diatoms and new insights into the taxonomy of

Bacillariophyta, and changes in the paradigm of the International Stratigraphic Chart for the Cenozoic [32] have also resulted in new ideas about index fossils used in biostratigraphic reconstructions, including their evolution and response to environmental changes. In addition, new age data on the Neogene strata in Primorye have been obtained [46]. Therefore, the present study aims at revising repeatedly Miocene–Pliocene diatom floras from some stratotype and reference sections using the advanced SEM methods and at improving the zonal diatom scale for the Neogene of Primorye.

MATERIALS AND METHODS

The newly and previously collected samples from the stratotype sections of Miocene–Pliocene deposits in Southern Primorye were used for this study (Fig. 1, Table 1).

(1) We have studied two samples (9200/55 and 9200-3/3) collected from tuff siltstones of the lower strata of the Sineutesovskaya Formation (thickness 20 m) at the sampling site 9200 near Mt. Siniy Utes (Khasansky district, southwestern Primorye). These samples were provided by B.I. Pavlyutkin and

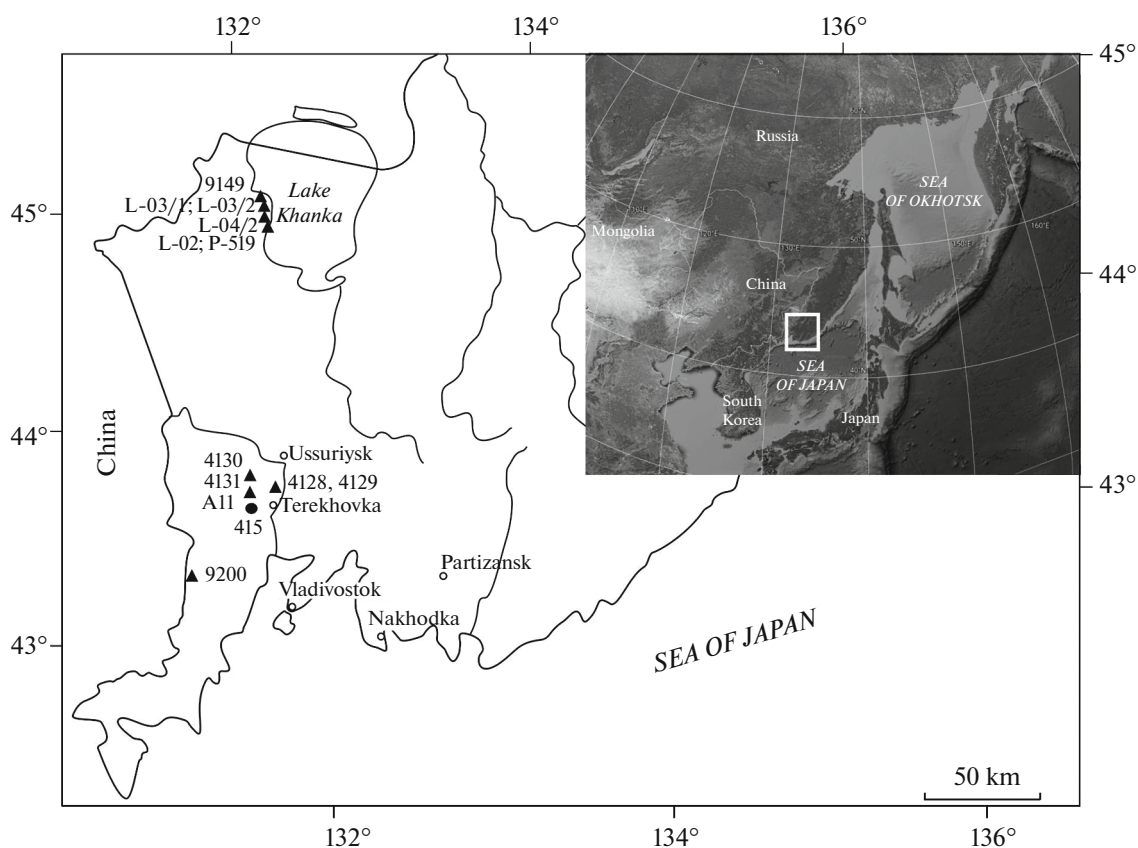


Fig. 1. Location of studied sections (black triangles) and cores (black circles).

I.Yu. Chekryzhov (Far East Geological Institute, Far Eastern Branch, Russian Academy of Sciences) in 2023. The Sineutesovskaya Formation dates to the Early Miocene [18]. The U–Pb (LA ICP-MS) dating of zircon from one of the volcanic ash layers alternating with coal seams of the Siniy Utes basin yielded an age in a range of 18–25 Ma [46].

(2) Samples from tuff diatomites of the Novokachalinskaya Formation collected by V.S. Pushkar and O.Yu. Likhacheva in the Khanka district, between settlements of Novokachalinsk and Turiy Rog (sections L-03/1, L-03/2, L-04/1, and L-02) during field works in 2008–2011 were studied repeatedly [9, 43]. We have also studied diatoms for the first time from a sample provided by V.K. Popov from section P-519 (FEGI FEB RAS). The estimated total thickness of the formation is approximately 200 m. The thickness of the studied interbeds of tuff diatomites varies from 4 to 19 m. The deposits contain imprints of leaves, leafy shoots, fructifications, spores, and pollen. The Middle Miocene age of the formation (15.97–11.63 Ma) obtained by radioisotopic methods [14] agrees with the dates obtained from micro- and macrofossils [18] and diatoms [9].

(3) Samples of the Terekhovka diatomite, collected earlier by V.S. Pushkar from section no. 4131 in a

quarry near the village of Terekhovka (Nadezhdinsky District) and core no. 415, in the western environs of the Krasny Yar village (sections nos. 4128 and 4129, where deposits of the Shufansky Horizon, composing the alluvial terrace of the Paleorazdolnaya River crop out) were studied repeatedly [18]. In addition, five new samples, collected by A.S. Avramenko and M.V. Cherepanova from the same deposits (site no. A11) in 2022, were studied. The thickness of the diatomite interbed is 4 m. Diatomite is weakly cemented, white to slightly yellowish. The diatomite age is Pliocene, according to [9, 17, 18].

The samples were processed using hydrogen peroxide following the generally accepted method [5]. Diatoms were examined under Axioskop 40 Carl Zeiss light microscope (LM) on a 18 × 18 mm cover glass slide at ×1000 magnification with immersion liquid. To search for index species that could be used for the zonal diatom scale, we conducted a detailed examination of diatoms using Carl Zeiss EVO 40 and Merlin scanning electron microscopes (SEM) with magnification up to ×50000 at the Instrumental Center of Biotechnology and Gene Engineering of the Federal Scientific Center of the East Asia Terrestrial Biodiversity FEB RAS (FSCEATB FEB RAS).

Table 1. Stratotype Neogene sections of Southern Primorye

International stratigraphic unit				Regional stratigraphic units (formations)	Section location, samples examined	Sections
system	series	subseries	stage			
NEOGENE	PLIOCENE	Upper	Piacenzian	Shufansky	Terekhovka area (Nadezhdinsky district; Pushkinskaya Depression); Core 415 (43°20'25" N and 131°52'59" E), sections nos. 4131 (43°20' N and 131°52' E), 4128 and 4129 (43°41'40" N and 131°54'54" E), A11 (43.65440° N, 131.87580° E)	Key section, described by B.I. Pavlyutkin [18]
		Lower	Zanclean			
	MIOCENE	Upper	Messinian	Ust-Suifunskaya Formation	Along Razdolnoe–Kraskino Rd, Mt. Klepochnaya (Nadezhdinsky district), no. 4001 (43°32'00" N, 131°53'50" E); in the Terekhovka area (Nadezhdinsky district; Pushkinskaya Depression), no. 4130 (43°38'25" N, 131°54'50" E)	Hypostratotype, described by B.I. Pavlyutkin [18]
			Tortonian			
		Middle	Serravalian	Novokachalinskaya Formation	The western coast of Lake Khanka, between Turiy Rog and Novokachalinsk (Khankaysky district), nos. 9149, L-03/2 (45°09'14.3" N; 132°00'23.3" E), L-04/1 (45°09'11.8" N; 132°00'126.00" E), L-02 (45°01'00.0" N; 132°00'25.1" E), P-519 (45°08'25.14" N; 132°01'15.32" E)	Holostratotype, described by B.I. Pavlyutkin [18]
			Langhian			
		Lower	Burdigalian	Nezhinskaya	3 km north of Nezhino (Nadezhdinsky district; Pushkinskaya Depression), no. 9180 (43°29' N, 131°47' E)	Key section, described by B.I. Pavlyutkin [18]

The permanent slides are stored in the diatom collections of the Laboratory of Paleobotany of the Federal Scientific Center of Biodiversity and Laboratory of Cenozoic Paleocology at the Far Eastern Geological Institute of the Far Eastern Branch of the Russian Academy of Sciences (FEGI FEB RAS), Vladivostok.

The diatom systematics from Algaebase [33, 35] was used in this study. To better understand the ecological characteristics of taxa, the following publications were used: S.S. Barinova et al. [2], K. Krammer and H. Lange-Bertalot [40] and several others, which are referenced in the text. The categories of zones are defined in accordance with the Stratigraphic Code of Russia [23].

RESULTS AND DISCUSSION

The Neogene was an important turning point in the evolution of continental planktonic diatoms [30,

42], during which several important events occurred including the invasion of marine species of the genus *Actinocyclus* Ehrenberg into temperate lake systems and the replacement of non-marine *Actinocyclus* taxa with genera of the family Stephanodiscaceae Glezer et Makarova at the Middle/Late Miocene boundary [34].

The genus *Alveolophora* [53] is also considered to be one of the earliest settlers in freshwater environments, making it an interesting subject for understanding the origin, distribution, and evolution of the Aulacoseiraceae family. In terms of biostratigraphy, these events are important for the development and refinement of regional diatom scales, which serve as the basis for determining and refining the age of deposits. In this regard, a comprehensive study of Miocene–Pliocene diatom floras in some stratotype sections using the advanced SEM methods allows both taxonomic revision of zonal diatom assemblages

and the identification of index species that can be used to improve the Neogene diatom zonation of Primorye.

This paper presents the results of studying diatoms from important stratigraphic sections. In some cases, the age of the deposits of these sections is still controversial and is being revised due to applying new chronological methods. In addition, changes in diatom systematics, which have recently become widespread due to the use of scanning electron microscopy, have an impact and require changes, primarily in the names of subunits. A description of the new, changed biozones is given below.

Alveolophora hachiyaensis—Aulacoseira elliptica Zone (holostratotype of the Siniutyevskaya Formation, early Early Miocene).

Category: acme zone.

Definition: the upper boundary of the zone is determined based on the last occurrence of index species of *Alveolophora hachiyaensis* (Tanaka) Houk, Klee et Tanaka and *Aulacoseira elliptica* Tsoy.

Age: the lower part of this zone dates back to 22.0 ± 1.0 Ma, and the upper part, to 20.9 Ma [18, 46]. Zone corresponds to the Aquitanian Stage (23.03–20.44 Ma).

Authors: V.S. Pushkar, A.S. Avramenko, M.V. Cherepanova, O.Yu. Likhacheva.

Additional markers: pronounced predominance of index species with oval-shaped valves, as well as ring-shaped colonies.

The characteristic diatom assemblage of the zone (Fig. 2): dominants: *Alveolophora hachiyaensis*, *Aulacoseira praeislandica* (Jousé) Simonsen + f. *curvata* (Jousé) Moisseeva, *A. elliptica* Tsoy; associate taxa: *Actinocyclus gorbunovii* (Sheshukova-Poretskaya) Moisseeva et Sheshukova-Poretskaya, *Aulacoseira canadensis* (Hustedt) Simonsen, *Melosira undulata* (Ehrenberg) Kützing, *Ellerbeckia teres* (Brun) Crawford, *Staurosira venter* (Ehrenberg) Cleve et Möller, *S. construens* Ehrenberg, *Staurosirella pinnata* (Ehrenberg) Williams et Round, *Tetracyclus ellipticus* (Ehrenberg) Grunow, *T. lacustris* var. *elongatus* Hust. and other representatives of this genus.

Discussion: A.I. Moisseeva, who proposed the first zonal diatom scale for Neogene continental deposits in the Far East [13], used *Alveolophora bifaria* Nevretdinova et Moisseeva as a species index of a bed with the binominal name: bed with *Aulacoseira canadensis* and *Alveolophora bifaria*. This bed is distinguished from the lowest part of the Shestakovsky stratum of the Ildikilyakh Regional Stage (Penzhina Bay, North Okhotsk Region) and corresponds to the earliest Miocene.

Moisseeva has correlated this bed with that with *Aulacoseira canadensis* from the lowest part of the Kizin Formation in the Aukan Bay area of Northeastern Sikhote-Alin (Khabarovsk krai). According to age boundaries, the proposed zone is considered a com-

plete analog to the Miosira bifaria Zone proposed by O.Yu. Likhacheva et al. [9].

This zone was renamed due to the fact that *Alveolophora bifaria* has only been reliably identified in the lower part (earliest Miocene) of the Shestakov Formation in the Penzhina Bay area [11, 56]. There are reports of its occurrence in the Miocene deposits of the Yamato Formation of the Sea of Japan [52] and the Sineutesovskaya Formation [9]. None of these studies have included the results of SEM study of the valves. A repeated study of Early Miocene diatoms from Southern Primorye revealed the absence of this taxon in the deposits.

Therefore, we assume that there was a need to rename the zone, as the former index species, *A. bifaria*, is not widely distributed, which does not meet the requirements of the Stratigraphic Code [23] for the selection of index species of regional biostratigraphic subunits.

At the same time, *A. hachiyaensis* and *A. elliptica* were found not only in the Sineutesovskaya Formation, but also in the same-age continental deposits on the Yamato Rise [26, 54] and Ullyn Plateau [51] in Sea of Japan, as well as in deposits of the the Hachiya Formation (Gifu Prefecture, Japan) [48]. It seems that the active development of the oval *Aulacosira* species can be considered a stratigraphic indicator of the Early Miocene deposits in the region. In 2011, a new species *Aulacoseira iwakiensis* Tanaka, Nagumo was described from coeval deposits of the Shichiku Formation in Fukushima Prefecture (Japan) [49].

Miocene freshwater oval-shaped diatoms were previously found on the Yamato Rise in Sea of Japan [25, 28, 31], North Korea [37], State Oregon, USA [58], and Japan [45]. Representatives of genus *Aulacoseira* with oval valves have not yet been found in younger sediments along the Pacific coast. However, the new species *Aulacoseira capitalina* Titova, Hassan, Usoltseva with such valves was first identified in the core 532 of Middle Miocene deposits from the Barguzin Depression in the Transbaikalia Region and described in 2022 [50].

Alveolophora khankaica Zone (the lower part of holostratotype of the Novokachalinskaya Formation, the end of Early Miocene—the first half of Middle Miocene).

Category: interval-zone.

Definition: the upper boundary is determined by the extinction of the index species and the first appearance of *Alveolophora khursevichiae* Usoltseva, Pushkar et Likhacheva. The lower boundary is defined by the last occurrence of the previous zone—*Actinocyclus lobatus* Rubina et Khursevich, as well as a series of oval-shaped species of the genus *Aulacoseira*, typical of Early Miocene [26, 48, 51, 54].

Age: a series of dates in a range of 18.1–14.9 Ma was obtained for the diatom assemblage [14, 15]. Zone corresponds to Late Burdigalian—Early Langhian.

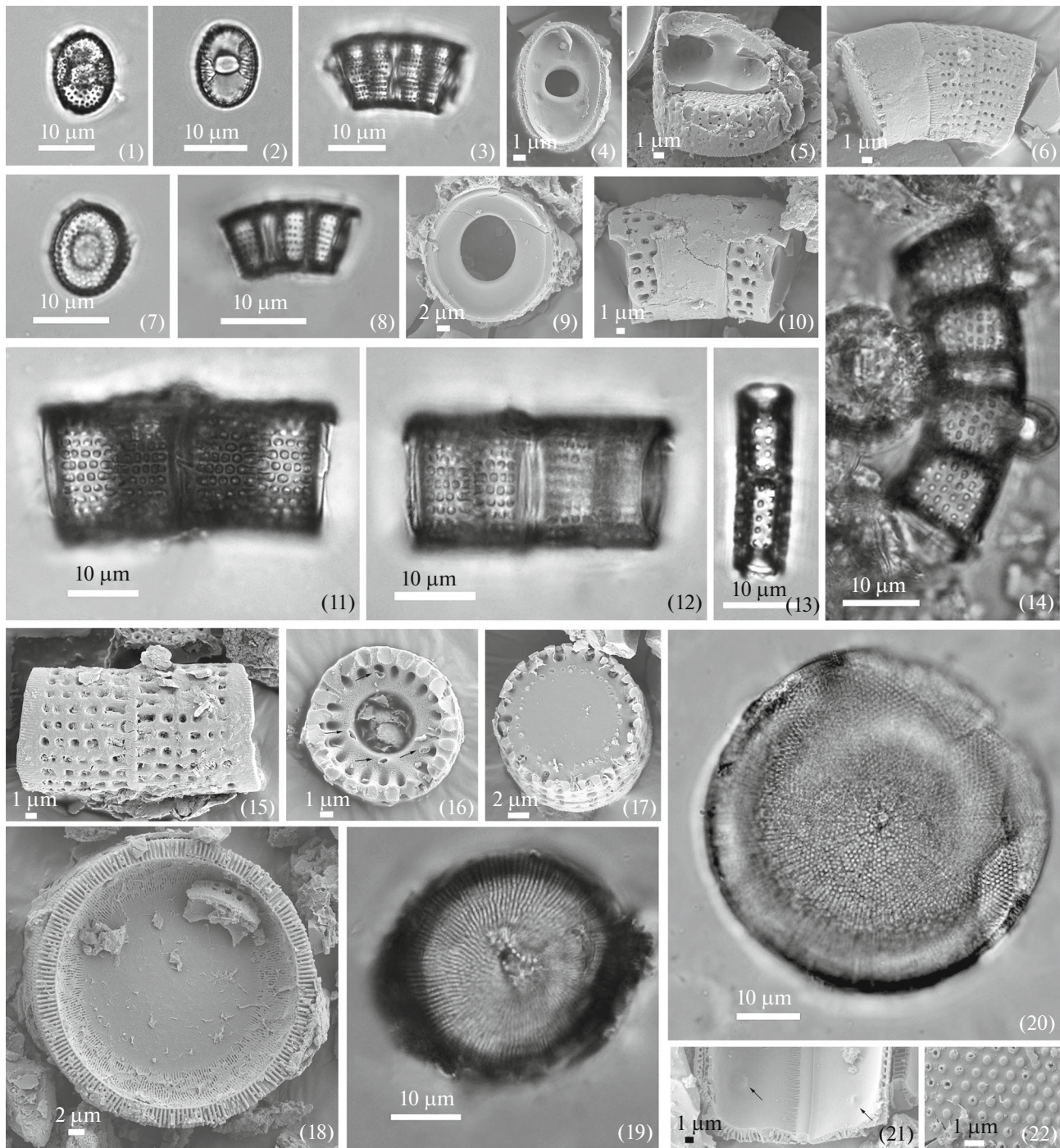


Fig. 2. Diatom assemblage of Sineutesovskaya Formation. (1–6) *Alveolophora hachiyaensis* (Tanaka) Houk, Klee et Tanaka; (7–10) *Aulacoseira elliptica* Tsoy; (11, 12, 14–17) *Aulacoseira praeislandica* (Jousé) Simonsen; (13) *Aulacoseira canadensis* (Hustedt) Simonsen; (16) internal valve mantle with rimoportulae (arrows); (18, 19, 21) *Melosira undulata* (Ehrenberg) Kützing ((21) internal valve view); (20, 22) *Actinocyclus gorbunovii* (Sheshukova-Poretskaya) Moisseeva et Sheshukova-Poretskaya ((22) valve fragment with areoles). (1–3, 7, 8, 11–14, 19, 20) LM; (4–6, 9, 10, 15–17, 21, 22) SEM.

Authors: V.S. Pushkar, A.S. Avramenko, M.V. Cherepanova, and O.Yu. Likhacheva.

Additional markers: the striking predominance and taxonomic diversity of the genus *Aulacoseira* (six taxa), including curvate forms forming ring colonies, as well

as diversity but low abundance of associated diatoms of genera *Tetracyclus*, *Eunotia*, *Achnanthes*, *Navicula*, *Pinnularia* and representatives of family Cymbellaceae can be considered an important stratigraphic feature.

The characteristic diatom assemblage (Fig. 3) includes planktonic and tychoplanktonic taxa of genus *Aulacoseira*: *A. praegratulata* (Jousé) Simonsen + f. *curvata* (Jousé) Simonsen + var. *praeangustissima* (Jousé) Moisseeva + f. *curvata* (Jousé) Simonsen, *A. praeislandica* (Jousé) Simonsen + f. *curvata* (Jousé) Moisseeva. *Alveolophora tscheremissinovae* Khursevich, *Ellerbeckia kochii* (Pantocsek) Moisseeva, *Melosira undulata* (Ehrenberg) Kützing were also found.

Discussion: the issue of correlating this area with the subdivisions of the biostratigraphic schemes proposed earlier, particularly those of V.S. Pushkar and A.M. Korotkiy [19] and A.I. Moisseeva [13], arises from the fact that, as noted by B.I. Pavlyutkin [18], there are differing views on the age and stratigraphic placement of the Novokachalinskaya Formation. Pavlyutkin has examined the existing perspectives on this matter in greater detail in his monograph [16]. In terms of taxonomic composition, the dominant group of taxa and the stratigraphically important diatom species that reflect the evolution of diatom flora of Primorye, we can correlate this zone with the diatom assemblage 6 [12], characterizing the bed with *Ellerbeckia kochii* and *Achnanthes aengimatosus* of A.Yu. Moisseeva's scheme [13] and corresponding to the lower part of the bed with *Fagus khankaica* [7]. It is interesting to note that similar diatom assemblages from this time period have been identified in both Cisbaikalia and Transbaikalia.

One of the stratigraphically important components of these assemblages is *A. gorbunovii* [13], which we found in the Sineutesovskaya Formation and then reappears in the Pliocene deposits of the Shufansky Horizon.

In the zonal diatom scale proposed by O.Yu. Likhacheva et al. [9], the age range of this subunit corresponds to the *Miosira jouseana* Zone. By the way, the index species of this zone appeared in the composition of the genus *Miosira* Krammer, Lange-Bertalot et Schiller due to the relocation of some species of the genus *Alveolophora* Moisseeva et Nevretdinova to this genus [41]. Subsequently, a more detailed study of the morphological features of species from the genus *Miosira*, as well as newly discovered diatoms with similar characteristics [53, 55–57], allowed us to return some of the species, including *M. jouseana* (Moisseeva) Krammer, Lange-Bertalot et Schiller, back to the genus *Alveolophora*.

As a result of our repeated study of diatoms from the lower stratum of the Novokachalinskaya Formation, *A. jouseana* (Moisseeva) Moisseeva was not found in the deposits. However, a new species to the genus *Alveolophora* was found out, which we describe below. This gave us grounds for renaming this subunit as *Alveolophora khankaica* Zone. The ecological structure of the diatom community, which is dominated by planktonic and tychoplanktonic species, and the small quantitative representation of diatoms from

different habitats, testify to the formation of the assemblage in a rather large lake, both in area and depth, with pronounced ecological zones. A high concentration of valves in the deposits [9] is evidence of favorable habitat conditions for diatoms. Most likely, this assemblage formed during the optimal phase of the Miocene, when a monsoon climate settled in Primorye, resulting in the formation of a large number of both large and small lakes. A relatively warm winter could lead to a long vegetative period for algae development, which would increase due to favorable temperatures during the spring, winter, and autumn [1, 29]. High productivity of diatoms could also have been promoted by active volcanism and high carbon concentrations in the atmosphere, which is correlated with the Monterey Event [20].

Systematic Description

Order AULACOSEIRALES Crawford

Family Aulacoseiraceae Crawford

Genus *Alveolophora* Moisseeva et Nevretdinova, 1990

Alveolophora khankaica M. Cherepanova et A. Avramenko sp. nov. (Fig. 4). The cells are connected by spikes to form filamentous colonies. Frustules low-cylindrical in valve views, with or without a girdle band, straight along the central axis. Valves are thick-walled, flat, and round, 9.86–20.15 µm in diameter, and 2.79–7.12 µm in height.

On the external valve face, the areoles are located loosely and irregularly, the central part of the valve is structureless. In the marginal zone, there are 14–16 areoles in short radial rows per 10 µm. In the peripheral zone of the valve, there are weakly expressed pseudo-alveolae and pseudosepta. The center of the valve is structureless. Rimoportulae (9–11), in the form of short tubes or small tubercles with a slit, form a ring in the peripheral zone of the valve on the septa of pseudoseptae.

The mantle consists of small areolae arranged in straight vertical rows, 26–27 rows per 10 µm, 18–20 areolae per 10 µm, one areola in each row. On the border between the frontal part of the valve and the mantle are blade-shaped linking spines (15–16 linking spines per 10 µm).

The holotype is stored in the diatom collection at the Laboratory of Cenozoic Paleocology of FEGI FEB RAS, Vladivostok, slides L-03/1, L-03/2, L-04/1.

Remarks. *A. khankaica* is similar to *A. tscheremissinovae* [38] in terms of the structure of the frontal part of the valve and small size when viewed under a light microscope. However, they differ in a number of areoles per 10 µm on the mantle and arrangement of rimoportulae (located on pseudoseptae; in *A. tscheremissinovae*, directly on a valve), which is clearly visible on a scanning electron microscope.

Freshwater, planktonic extinct species.

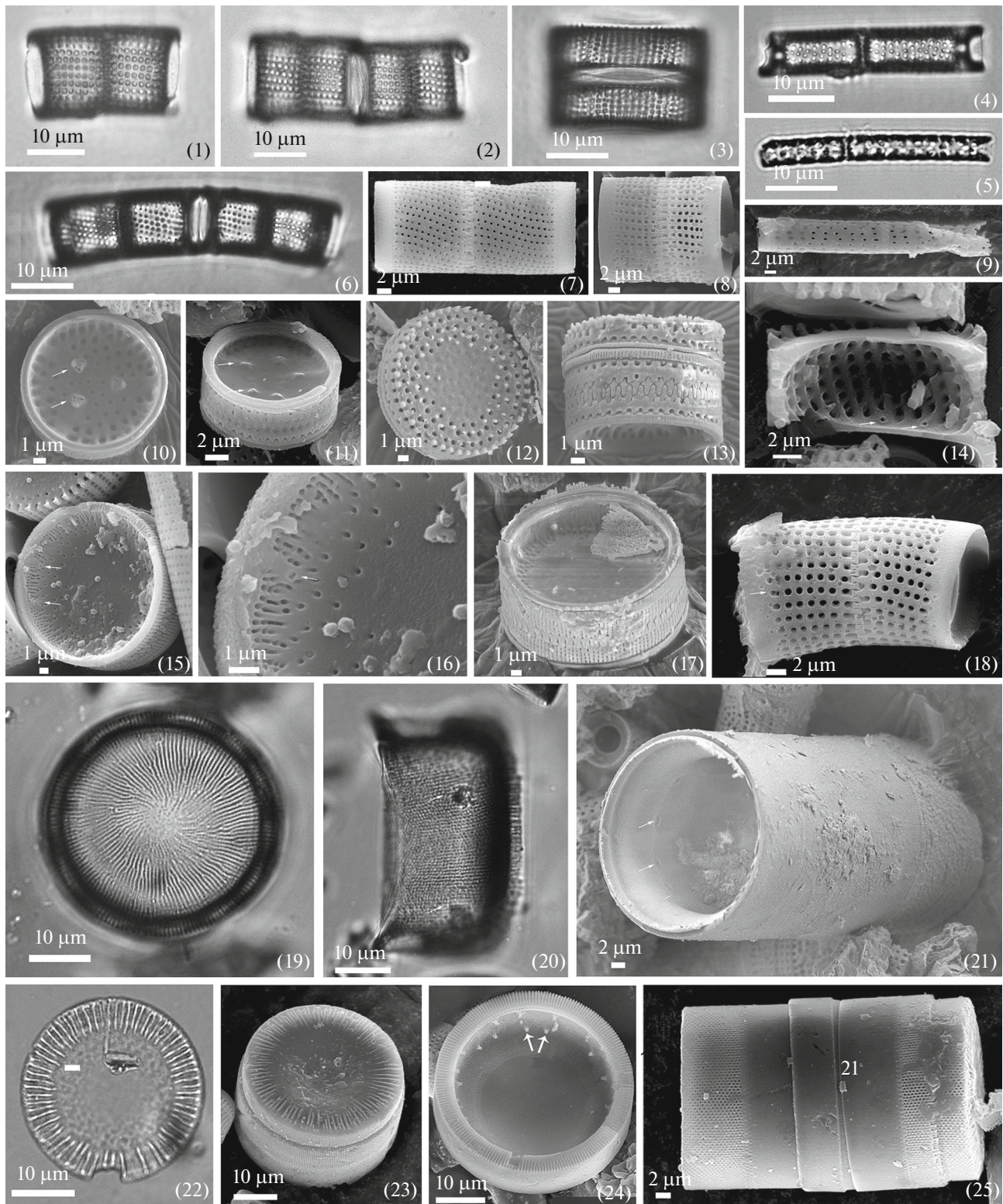


Fig. 3. Diatom assemblage from lower part of Novokachalinskaya Formation. (1–3, 7, 8, 14) *Aulacoseira praeislandica* (Jousé) Simonsen ((14) internal valve views with rimoportulae (arrows)); (4) *Aulacoseira praegranulata* (Jousé) Simonsen; (5, 9) *Aulacoseira praegranulata* var. *praeangustissima* (Jousé) Moisseeva; (6, 18) *Aulacoseira praeislandica* f. *curvata* (Jousé) Moisseeva; (10–13) *Alveolophora tsheremissinovae* Khursevich ((10–11) internal valve views with rimoportulae (arrows)); (15–17) *Alveolophora khankaica* M. Cherepanova et A. Avramenko sp. nov. ((15–16) internal valve views with rimoportulae (arrows)); (19–21) *Melosira undulata* (Ehrenberg) Kützing; (22–25) *Ellerbeckia kochii* (Pantocsek) Moisseeva. (1–6, 19, 20, 22) LM; (9–18, 21, 23–25) SEM.

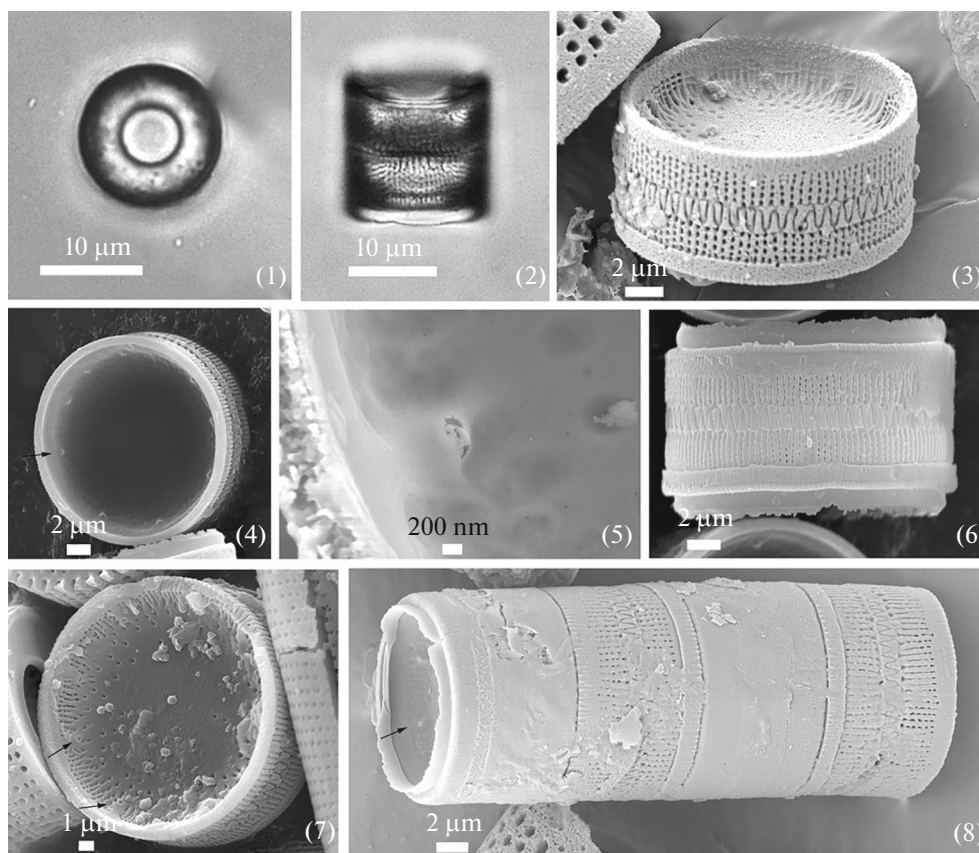


Fig. 4. New species *Alveolophora khankaica* M. Cherepanova et A. Avramenko sp. nov. (1) external valve face; (2, 6) valve mantle view; (3, 4, 7) internal valve face; (5) rimoportulae on internal valve face; (8) chain consisting of eight valves. (1–2) LM; (3–8) SEM.

The first half of the Middle Miocene: Russia, Pri-morye (the lower part of the Novokachalinskaya Formation, the western shore of Lake Khanka).

***Alveolophora khursevichiae* Zone** (upper part of holostratotype of the Novokachalinskaya Formation, the second half of Middle Miocene).

Category: interval-zone.

Definition: the upper boundary is determined by the last occurrence of index species.

Age: 14.9–11.8 Ma, that corresponds to the end of Langian–Serravallian. The diatom assemblage of the zone should be dated to the Late–Middle Miocene.

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Additional markers: the predominance of the species *Aulacoseira praeislandica* (Jousé) Simonsen and its curvate forms, the presence of the Late Miocene index species—*Ellerbeckia kochii* (Pantocsek) Moisseeva, and the diversity of *Tetracyclus ellipticus* (Ehrenberg) Grunow varieties.

Diatom assemblage (Fig. 5) is characterized by predominance of *A. praeislandica* with participation of curvate forms. Associated diatoms are *Alveolophora khursevichiae* Usoltseva, Pushkar et Likhacheva,

Aulacoseira praegrnulata var. *praeangustissima* (Jousé) Moisseeva, *M. undulata*, *E. kochii*, *Tetracyclus clypeus* (Ehrenberg) Li, *Tetracyclus ellipticus* var. *lancea* (Ehrenberg) Hustedt, *Tetracyclus ellipticus* var. *latissimus* Hustedt.

Discussion: the identified zone is correlated with the assemblage 7 [12] and the bed with *Aulacoseira praegrnulata* var. *praeislandica* and *Fragilaria mioce-nica* from A.I. Moisseeva's diatom zonation [13] that corresponds to the upper part of the bed with *Fagus khankaica*. Based on the age range, this zone corresponds to the *Miosira areolata* Zone in the scale of O.Yu. Likhacheva et al. [9]. The search for the index species *Miosira areolata* (Moisseeva) Khursevich, which is now included in the composition of genus *Alveolophora* Moisseeva et Nevretdinova, has not been successful. Additionally, another species of this genus *A. khursevichiae* was identified. These findings have allowed us to rename the zone without changing its age interval.

A high percentage of benthic species in the diatom assemblage of the zone, in particular, representatives of genus *Tetracyclus*, likely indicates a decrease in water level in the waterbody. In addition to representatives of species *T. ellipticus*, there is also *T. lacustris* var.

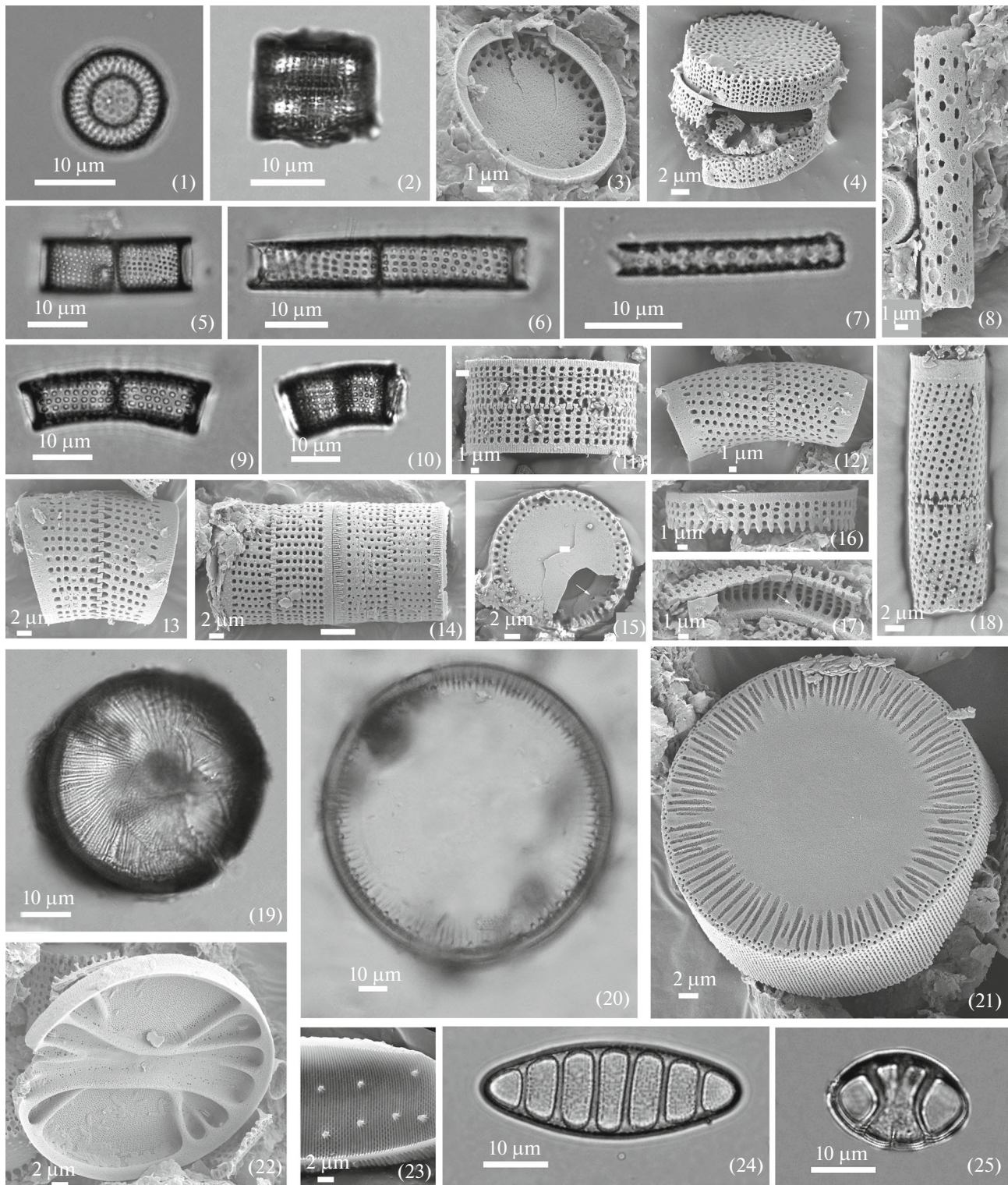


Fig. 5. Diatom assemblage of upper part of Novokachalinskaya Formation. (1–4) *Alveolophora khursevichiae* Usoltseva, Pushkar et Likhacheva; (5, 11, 14–17) *Aulacoseira praeislandica* (Jousé) Simonsen (15, 17) internal valve views with rimoportulae (arrows); (6, 18) *Aulacoseira praegranulata* (Jousé) Simonsen; (7, 8) *Aulacoseira praegranulata* var. *praeangustissima* (Jousé) Moisseeva; (9–10, 12–13) *Aulacoseira praeislandica* f. *curvata* (Jousé) Moisseeva; (19) *Melosira undulata* (Ehrenberg) Kützing; (20–21, 23) *Ellerbeckia kochii* (Pantocsek) Moisseeva ((23) valve mantle view with tube processes); (22) *Tetracyclus clypeus* (Ehrenberg) Li; (24) *Tetracyclus ellipticus* var. *lancea* (Ehrenberg) Hustedt, (25) *Tetracyclus ellipticus* var. *latissimus* Hustedt. (1, 2, 5–10, 19, 20, 24, 25) LM; (3, 4, 8, 11–18, 21–23) SEM.

lanceolatus Moisseeva. According to A.I. Moisseeva [12], it is a transitional form between the extinct *T. ellipticus* and *T. glans* (Ehrenberg) Mills, the inhabitant of modern oligotrophic lakes of the North Alpine type. A low productivity of diatoms [9] and possibly more cryophilic diatoms likely indicate cooling that started after the climatic optimum. Apparently, at this time, the difference between the summer and winter monsoon intensified due to activation of the summer monsoon, which is indirectly confirmed by findings of leaf flora [16].

Aulacoseira praeislandica Zone (Shufansky Horizon, Lower Pliocene).

Category: acme zone.

Definition: the upper boundary of the zone is determined by a sharp decrease in the morphological diversity and abundance of index species.

Age: 5.3–3.6 Ma. Zone corresponds to the Zanclean Stage.

Authors: V.S. Pushkar, A.S. Avramenko, M.V. Cherepanova, O.Yu. Likhacheva.

Additional markers: the presence in of valves of the index species with high mantle and small diameter, as well as low mantle and large diameter, which could be attributed to *Melosira praedistans* Jousé that no longer exists according to the current classification of diatoms. High species diversity is observed among limnetic taxa; there are rare occurrences of the thermophilic *Actinella brasiliensis* Grunow.

Diatom assemblage (Fig. 6) is characterized by predominance of *Aulacoseira praeislandica* (Jousé) Simonsen with associated taxa: *Actinocyclus gorbunovii* (Sheshukova-Poretskaya) Moisseeva et Sheshukova-Poretskaya, *Aulacoseira canadensis* (Hustedt) Simonsen, *Fragilariforma bicapitata* (Mayer) Williams et Round, *Gomphosphenia grovei* var. *lingulata* (Hustedt) Lange-Bertalot, *Ellerbeckia teres* (Brun) Crawford ex Houk et al., *Khursevichia jentschii* (Grunow) Kulikovskiy, Metzeltin et Lange-Bertalot, *Melosira undulata* (Ehrenberg) Kützing, *Navicula radiosa* Kützing, *Placoneis amphibola* (Cleve) Cox, as well as representatives of genus *Tetracyclus* Ralfs, characterizing by a high species diversity. In addition, there are *Tetracyclus lacustris* var. *elongatus* Hustedt, *T. glans* (Ehrenberg) Mills, as well as some other species present.

Discussion: the zone corresponds to the Miosira tscheremissinovae Zone according to the scale of O.Yu. Likhacheva et al. [9] and *Actinocyclus gorbunovii* Zone previously identified by A.I. Moisseeva [13], which at the time of the publication of the original scheme was dated to Late Miocene. At present, deposits of the section near the Terekhovka village, diatoms from which were studied by A.I. Moisseeva and reexamined by us, are now believed to be of Pliocene age. The rather rare occurrence of the index species in the assemblage used by Likhacheva et al. [9] in the name of the subunit gives grounds for renaming

the zone. It should also be noted that at present, this taxon is included in the restored genus *Alveolophora* Moisseeva and Nevretdinova (1990) [56]. A high taxonomic diversity and the presence of organisms from different lacustrine zones (profundal, sublittoral, and littoral zones) suggest the development of diatom assemblage in a rather large waterbody with numerous habitats during the Pliocene warming, when sea level and temperature were higher than they are today [36]. It should be noted that similar coeval assemblages with a predominance of species of genus *Aulacoseira* Thwaites and diversity of genus *Tetracyclus* Ralfs are observed in waterbodies of the Far East and Siberia [13]. A distinctive feature of the Pliocene diatom flora of Siberia and the northeasternmost Russia is the presence of representatives of genus *Stephanodiscus* Ehrenberg [13]. According to T. Hayashi et al. [34], genera of family Stephanodiscaceae replaced the genus *Actinocyclus* Ehrenberg, which was an important component of lacustrine phytoplankton during the Early–Middle Miocene. These changes were confirmed in many regions around the world. The authors suggest that the formation of the current assemblages of non-marine planktonic diatoms in the temperate zone occurred during the Middle/Late Miocene period. According to our data, representatives of the genus *Stephanodiscus* are absent in the Pliocene diatom flora of Primorye. However, species of the genus *Actinocyclus* continued to exist at least until the end of the Early Pliocene. Based on results of studying Late Cenozoic diatoms of Lake Baikal, it was established that rapidly disappearing small species *Stephanodiscus* appeared only in the Pliocene [39]. Their stable presence in the flora is noted starting from 1.25 Ma [8].

Alveolophora tscheremissinovae Zone (Shufansky Horizon, Upper Pliocene).

Category: interval-zone.

Definition: upper boundary corresponds to the extinction level of index species.

Age: 3.6–2.58 Ma that corresponds to the Piacentian Stage.

Authors: V.S. Pushkar, A.S. Avramenko, M.V. Cherepanova, O.Yu. Likhacheva.

Additional markers: a high morphological diversity of *Melosira undulata* (Ehrenberg) Kützing, the presence of *Tetracyclus ellipticus* (Ehrenberg) Grunow in the dominant group.

Diatom assemblage (Fig. 7), which reflects the evolutionary stage of diatom development, is represented by the dominant *Alveolophora tscheremissinovae* Khursevich, *A. praeislandica*, *E. teres*, *M. undulata*, *T. ellipticus* and associated *Cymbella australica* (A.W.F. Schmidt) Cleve, *Eunotia polyglyphoides* Sheshukova-Poretskaya, *Gomphonema subclavatum* (Grunow) Grunow, *Orthoseira* sp., *Pinnularia viridis* (Nitzsch) Ehrenberg.

Discussion: the age range of the zone corresponds to the *Aulacoseira praegrnulata* var. *praeislandica* f.

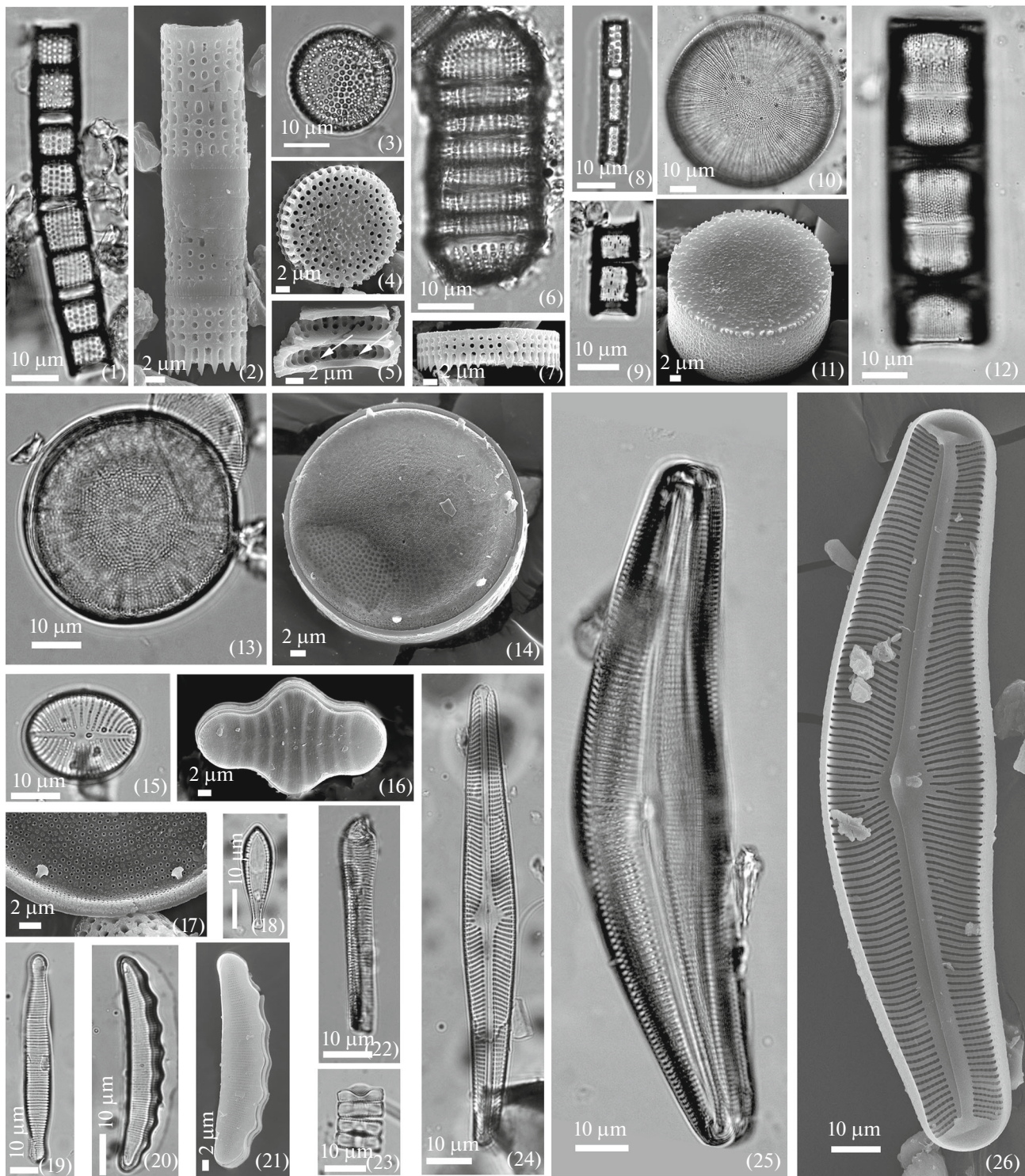


Fig. 6. Diatom assemblage of lower part of Shufansky Horizon. (1–7) *Aulacoseira praeislandica* (Jousé) Simonsen; (8) *Aulacoseira praegr anulata* (Jousé) Simonsen; (9) *Aulacoseira italica* (Ehrenberg) Simonsen; (10–12) *Melosira undulata* (Ehrenberg) Kützing; (13–14, 17) *Actinocyclus gorbunovii* (Sheshukova-Poretskaya) Moisseeva et Sheshukova-Poretskaya ((17) internal valve mantle with rimoportulae (arrows)); (15) *Cavinula scutelloides* (Smith ex Gregory) Lange-Bertalot; (16) *Tetracyclus glans* (Ehrenberg) Mills; (18) *Gomphosphenia grovei* var. *lingulata* (Hustedt) Lange-Bertalot; (19) *Fragilariforma bicapitata* (Mayer) Williams & Round; (20–21) *Eunotia polyglyphoides* Sheshukova-Poretskaya; (22) *Actinella brasiliensis* Grunow; (23) *Staurosira venter* (Ehrenberg) Cleve et J.D. Möller; (24) *Navicula radiosa* Kützing; (25–26) *Cymbella australica* Grunow. (1, 3, 6, 8–10, 12, 13, 15, 18–20, 22–25) LM; (2, 4, 5, 7, 11, 14, 15, 17, 19, 25) SEM.

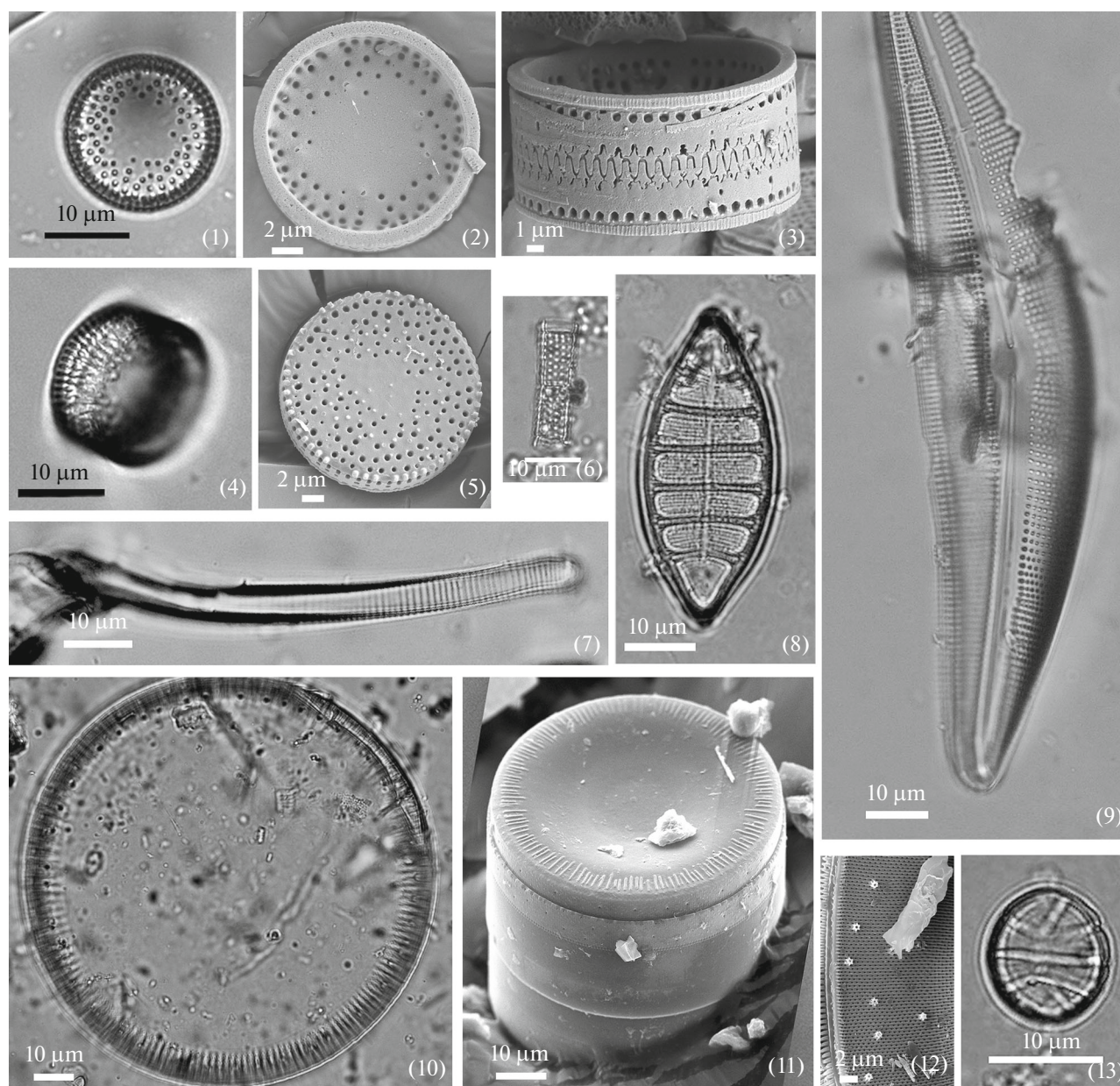


Fig. 7. Diatom assemblage of upper part of Shufansky Horizon. (1–5) *Alveolphora tscheremissinovae* Khursevich; (6) *Aulacoseira granulata* (Ehrenberg) Simonsen; (7) *Eunotia glacialis* F. Meister; (8) *Tetracyclus ellipticus* var. *lancea* (Ehrenberg) Hustedt; (9) *Cymbella lanceolata* var. *grandipunctata* Moisseeva; (10–12) *Ellerbeckia teres* (Brun) Crawford (12) valve mantle view with tube processes; (13) *Tetracyclus ellipticus* (Ehrenberg) Grunow. (1, 4, 6–10, 13) LM; (2, 3, 5, 11, 12) SEM.

praeislandica Zone as proposed by O.Yu. Likhacheva et al. [9, 47]. The predominance of *A. tscheremissinovae* in the assemblage allows us to rename this zone. In addition, in accordance with the current International Chronostratigraphic Chart for the Cenozoic [32], which accepts the Neogene/Pleistocene boundary at 2.58 Ma, the age of the upper boundary of the zone has been changed to 2.58 Ma, respectively.

The taxa that form the dominant group of the diatom assemblage are found in waterbodies with shallow depths and swampy biotopes. This may indicate a

decrease in the water level in these waterbodies due to cooling [44]. Previously, the species was also found in small amounts in Middle Miocene and Pliocene deposits of the Novokachalinskaya Formation (Primorye) and Middle and Late Miocene deposits of the Tunka Basin (Cisbaikalia) [24]. The proposed zone corresponds to a diatom assemblage containing the species *Aulacoseira baicalensis* and *Stephanodiscus*, identified in the upper part of the Chinin Formation (Upper Pliocene) on the Vitim Plateau [13].

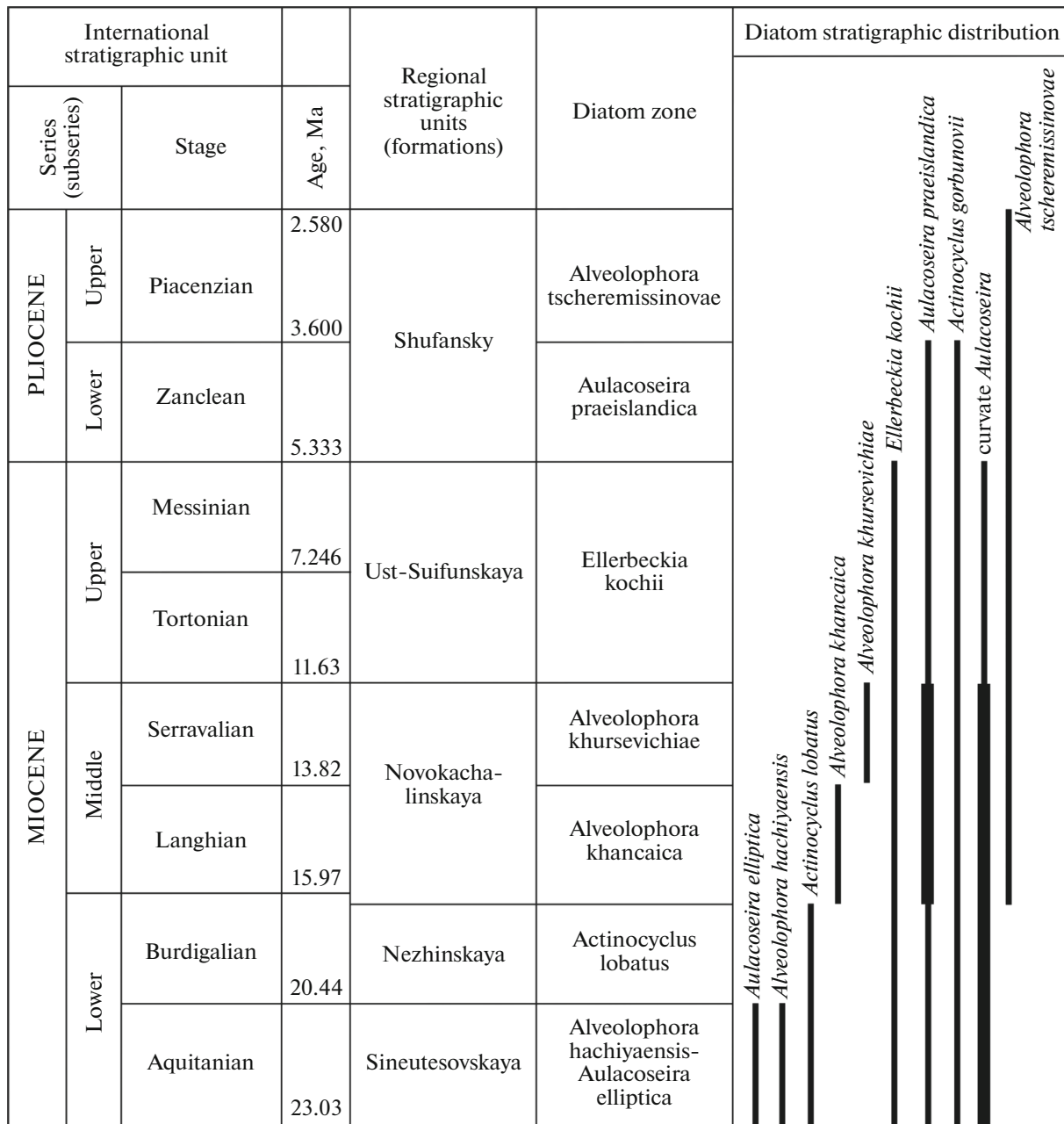


Fig. 8. Improved diatom zonal scale and stratigraphic distribution of index species.

CONCLUSIONS

A comprehensive study of diatom algae from a series of Neogene stratotype sections of Southern Primorye (Sineutesovskaya and Novokachalinskaya formations, Shufansky Horizon) using light and scanning electron microscopy has allowed us to refine the existing zonal diatom scale [9] for the Neogene of Primorye (Fig. 8).

(1) The discovery of a new species, *Alveolophora khankaica* M. Cherepanova et A. Avramenko sp. nov. with a narrow age range of distribution (18.1–

14.9 Ma), allowed us to use it as an index species for the diatom zone.

(2) SEM studies revealed the absence of several index species from the former diatom scale in the deposits: *Miosira* (= *Alveolophora*) *bifaria*, *Miosira* (= *Alveolophora*) *jouseana*, *Miosira* (= *Alveolophora*) *areolata*. They have been replaced by other taxa. As a result, the subdivisions of the zonal diatom scale have been renamed: *Miosira bifaria* Zone → *Alveolophora hachiyaensis*-*Aulacoseira elliptica* Zone; *Miosira jouseana* Zone → *Alveolophora khankaica* Zone; *Miosira areolata* Zone → *Alveolophora khursevichiae* Zone.

(3) Detailed studies of diatoms from the Shufansky Horizon, using newly collected material, have allowed us to identify the ecological characteristics of two diatom assemblages corresponding to the Pliocene stratigraphic units. These changes were primarily caused by the cooling climate trend, which led to a decrease in the morphological diversity of planktonic diatoms and an increase in the diversity of benthic diatoms. In addition, recent changes in the systematics of diatom algae have also been taken into account. This gave grounds for renaming the zones of the scale by O.Yu. Likhacheva et al. [9] developed at that time: the *Aulacoseira praeislandica* Zone has been attributed to the Lower Pliocene, and the *Alveolophora tscheremissinova* Zone, to the Upper Pliocene.

(4) New data on the age of the Sineutesovskaya Formation [46] has confirmed the age range for the *Alveolophora hachiyaensis*–*Aulacoseira elliptica* Zone (formerly the *Miosira bifaria* Zone).

(5) According to the recent changes in the International Stratigraphic Chart made for the Cenozoic, the upper boundary for the *Alveolophora tscheremissinova* Zone has been dated at 2.58 Ma.

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CONFLICT OF INTEREST

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

ADDITIONAL INFORMATION

The article is from a collection on the 65th anniversary of the founding of the Far Eastern Geological Institute, Far Eastern Branch, Russian Academy of Sciences.

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