ABS ACTA BIOLOGICA SIBIRICA
A journal on the biodiversity of Siberia and the adjacent lands

Acta Biologica Sibirica 9: 403–415 (2023)
doi: 10.5281/zenodo.8192366
http://journal.asu.ru

RESEARCH ARTICLE

Morphology and population size structure of *Pantocsekiella teletskoyensis* (Bacillatiophyta) in the deep mountain lake

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Academic editor: R. Yakovlev | Received 13 March 2023 | Accepted 10 May 2023 | Published 31 July 2023

http://zoobank.org/EEBDD82B-5F88-43EC-A7D5-22AE0D27C25A

Citation: Genkal SI, Mitrofanova EYu (2023) Morphology and population size structure of *Pantocsekiella teletskoyensis* (Bacillatiophyta) in the deep mountain lake. Acta Biologica Sibirica 9: 403–415. https://doi.org/10.5281/zenodo.8192366

Abstract

The new and rare small-celled centric diatom species *Pantocsekiella teletskoyensis* Genkal et Mitrofanova was recently identified from *Cyclotella delicatula* Genkal, previously described in the phytoplankton of Lake Teletskoye (Altai, Russia). The identification of *P. teletskoyensis* was based on the analysis of numerous scanning electron microscopy images since the beginning of a recent phytoplankton study in the lake. The investigation of the species revealed a wider variability of its qualitative morphological features such as valve relief, presence of granules on valve face, rimoportula position, and structure of alveoli. As a result, new data on the morphological variation of this species allowed for the refinement of its diagnosis. In addition, a comparison of the morphological features of *P. teletskoyensis* and other small-celled centric diatoms of *Pantocsekiella* and *Cyclotella* genera found in various water bodies across Europe, Asia, and America showed that *P. teletskoyensis* is most similar to *C. minuscula*, that was previously described from the deep-water Lake Ohrid located on the border of Northern Macedonia and Albania. We also conducted numerous measurements of *P. teletskoyensis* valve diameters, which enabled us to estimate the cell size in the population ranging from 3.02 up to 7.98 μm. The study of *P. teletskoyensis* population structure revealed that the group of 4.00-4.99 μm was consistently the most numerous among size groups with a step of 1 μm in all the months studied.

Keywords
Centric diatom algae, phytoplankton, valve size, *Pantocsekiella*, *Cyclotella*, Lake Teletskoye, Altai

Introduction

In 1989, the small-sized species *Cyclotella delicatula* Genkal was described through the transmission and scanning electron microscopy study of phytoplankton collected from Lake Teletskoye (Genkal 1994). Later, the same alga was also reported under the name of *Cyclotella* species for this lake (Genkal and Mitrofanova 1995). However, it was reidentified and assigned to the new genus *Pantocsekiella teletskoyensis* Genkal et Mitrofanova in 2022 (Genkal and Mitrofanova 2022a). Several morphologically similar species were also described in the literature, causing identification problems with small-sized algae of this group. Thus, *C. gordonensis* Kling et Håkansson, *C. arctica* Genkal et Kharitonov, *C. ocellata* Pantocsek emend. Genkal et Popovskaya, *C. minuscula* (Jurilj) Cvetkoska (Kling and Håkansson 1988; Genkal and Kharitonov 1996; Genkal and Popovskaya 2007, 2008; Cvetkoska et al. 2014), were later transferred to the genus *Pantocsekiella* (Ács et al. 2016).

Long-term studies indicate that *P. teletskoyensis* is numerically dominant among other small-celled centric diatoms and is the dominant species in the phytoplankton of Lake Teletskoye. As such, it may play a key role in maintaining the stable state of the lake's ecosystem. To understand this better, the size structure of *P. teletskoyensis* population needs to be studied to identify which cell sizes are dominant. Population analysis methods are useful for studying community structures, dynamic processes, mechanisms of functioning, stability, and self-regulation under various internal and external factors (Zlobin 1989). Population analysis is also essential for predicting productivity, assessing state and dynamics, investigating anthropogenic changes, and developing protection measures and environmental management practices. This is especially important for Lake Teletskoye, a UNESCO World Heritage Site and a background water body for Siberia due to its low anthropogenic impact.

Therefore, the aim of this work is to study the morphological characteristics of valves, the size structure of *P. teletskoyensis* population based on new materials, and conduct a comparative analysis with similar species.

Materials and methods

This study is based on phytoplankton samples collected from Lake Teletskoye in 1989–2022 (Fig. 1). The lake is a deep (maximum depth – 323.3 m, average – 174 m), canyon type reservoir (77.8 km length, maximal width: 5.2 km, average one: 2.4 km) of tectonic origin with a water volume of 41.1 km^3. It is located in the Altai Mountains in the south of West Siberia (between 51°21.46' and 51°48.36'N, 87°14.40' and 87°50.54'E). The lake elevation is 434 m a.s.l. (Selegei and Selegei 1978; Selegei et al. 2001).

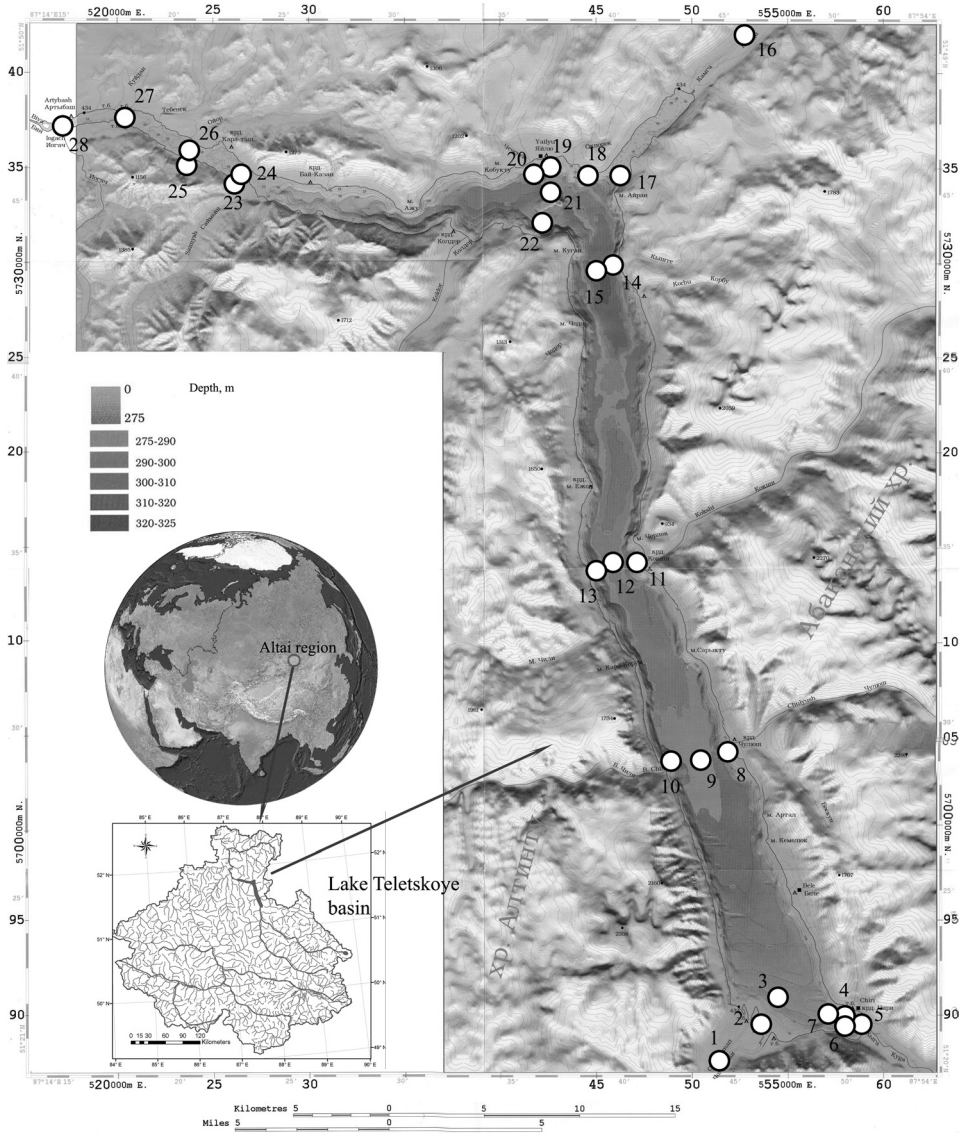

Figure 1. Location and map of Lake Teletskoye with sampling sites: 1 – mouth of Chulyshman River; 2 – Chulyshman, littoral; 3 – Chulyshman, pelagial; 4 – mouth of Chiri River; 5 – mouth of Kyga River; 6 – Kyga Bay, littoral; 7 – Kyga Bay, pelagial; 8 – mouth of Chelush River; 9 – Chelush, pelagial; 10 – mouth of Bolshiye Chili; 11 – mouth of Kokshi River; 12 – Kokshi, pelagial; 13 – mouth of Malye Chili River; 14 – mouth of Koru River; 15 – Korbu, pelagial; 16 – Kamga Bay, littoral; 17 – Kamga Bay, pelagial; 18 – mouth of Ok-Porok River; 19 – Yailu, littoral; 20 – mouth of Chechenek River; 21 – Yailu, pelagial; 22 – Koldor, littoral; 23 – mouth of Samysh River; 24 – Samysh, pelagial; 25 – Kamenny (Stone) Bay, littoral; 26 – Kamenny (Stone) Bay, pelagial; 27 – Artybash, pelagial; 28 – source of Biya River.

Diatom frustules were released from organic matter by cold burning (Balonov 1975). To study the size structure of the *P. teletskoyensis* population, samples were collected throughout the lake during the open water period in October 2021 and June, August 2022. The samples were passed through Vladipor membrane filters with a pore diameter of about 1 μm and washed with ethanol. Then the filters were dried, mounted on "specimen tables" for electron microscopy, sprayed with a gold-palladium mixture and examined in a Hitachi S-3400N SEM (IWEP SB RAS). A total of 3,484 measurements of *P. teletskoyensis* valve diameters were made. Some preparations were examined under JSM-25S and JSM-6510LV scanning electron microscopes (IBIW RAS). To study the size structure of the *P. teletskoyensis* pelagial population, samples were taken in the 3, 12, 21 and 27 sites, littoral one – 2, 6, 16, 19 and 28 sites (Fig. 1) in October 2021 and June, August 2022.

Result

The quantitative characteristics of *P. teletskoyensis* were in line with the literature data on this species, except for the minimum and maximum valve diameters. Based on light microscopy, we determined that they corresponded to 3.0 μm and 7.9 μm, respectively. In terms of qualitative characteristics, we observed a wider range of variability in the external and internal surface of the valve. While the diagnosis of *P. teletskoyensis* indicates that the central area of the valve is flat (Fig. 2A) (Genkal and Mitrofanova 2022a), we also observed other morphotypes, such as those with small and large lacunae (Fig. 2B-F, J), and sometimes, valves with slightly protruding branching costae on the external surface (Fig. 2G-I). We also detected valves with disorderly arranged granules or their complete absence (Fig. 2B, G-I), despite the diagnosis stating that rows of small granules are radially arranged on the valve. On the interior valve surface of *P. teletskoyensis*, we observed small alveoli of two types – with clear (Fig. 2N) and blurred edges near the central area of the valve (Fig. 2K-M) (Genkal and Mitrofanova 2022a, P l. III, 11, 12). Our measurements revealed that the ratio of the diameter of the central area to the diameter of the valve varied from 0.6 to 0.8. According to the description, the only rimoportula in *P. teletskoyensis* is located on the costa, and its slit is oriented radially (Fig. 2K, M) (Genkal and Mitrofanova 2022a). However, we also observed another location of the rimoportula – in the marginal zone near the costa (Fig. 2L, N).

Our study shows that *P. teletskoyensis* exhibits a wider variability than is given in the description of this species and makes it possible to refine its diagnosis.

Pantocsekiella teletskoyensis Genkal et Mitrofanova emend. Genkal et Mitrofanova (Fig. 2).

Cells cylindrical, circular, 3.0–7.9 μm in diameter, solitary or in chains composed of 2 to 8 cells. Central area flat, sometimes with irregular depressions or with slightly raised branching ribs. Valves covered with radially or irregularly positioned bumps. Striation fine, 20–35 in 10 μm, the alveoli are small. Marginal fultoportulae

situated on every 4–12 costae, externally with simple opening, internally with short central tube surrounded laterally by two satellite pores. Single rimoportula situated on costa or in peripheral zone, with small external opening, internally with sessile labium, slit oriented radially. Single central fultoportula (sometimes missing) situated near valve center. Central fultoportula has simple external opening, internally with short central tube surrounded by 1–2 satellite pores.

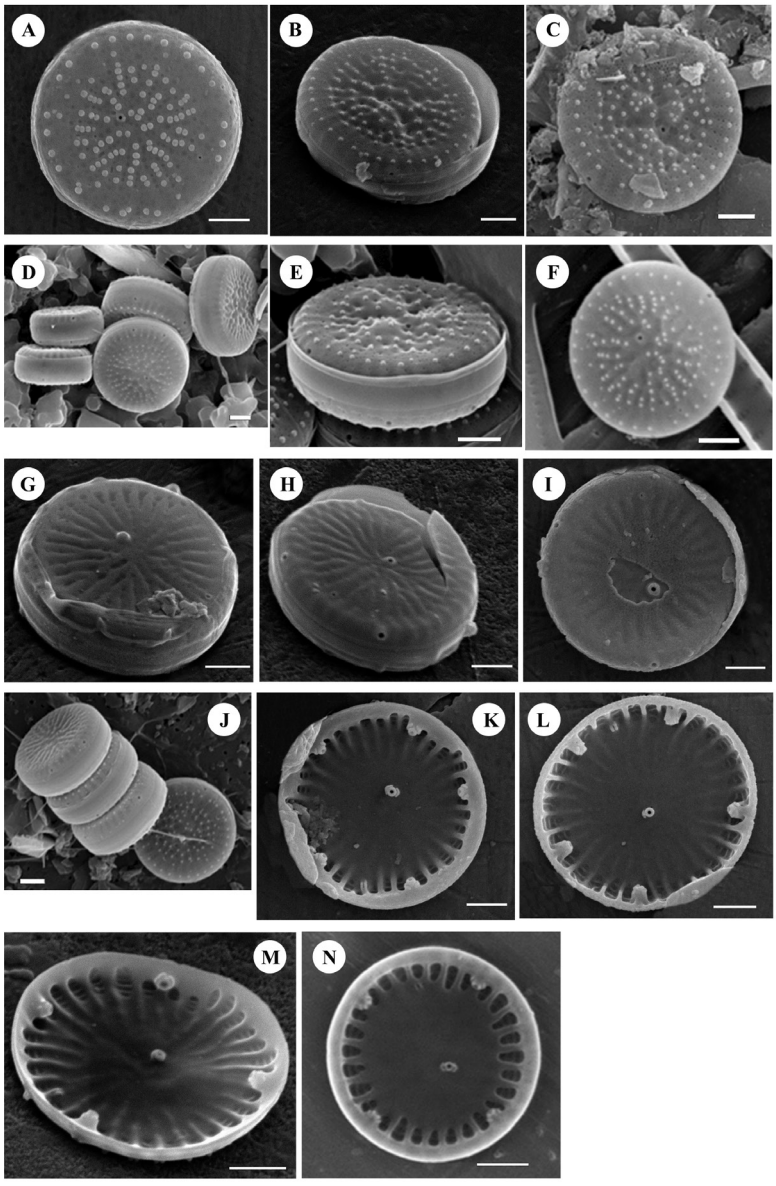

Figure 2. Images of *Pantocsekiella teletskoyensis* from phytoplankton of Lake Teletskoye. Scale bars – 1 μm.

In Lake Teletskoye, at different stations, the proportion of *P. teletskoyensis* in the group of centric diatoms in October 2021 and August 2022 varied between 88.2-95.1% and 85.9-93.3 with average values for the lake in these periods of 90.8±1.09 and 89.5±1.14, while in the late spring – early summer (June) – 53.9-73.3 and 66.9±2.95%, respectively. According to the results of measurements, the smallest and largest sizes of *P. teletskoyensis* valves were recorded in October – 3.02-7.98 μm. In June and August, a slight increase in the minimum size of the valves was observed, the maximum values decreased relative to October in June and slightly increased by August. In the pelagic zone, the range of valve sizes and the average values of their diameters were higher, while in the littoral zone, these values were smaller.

According to their size, we divided the *P. teletskoyensis* valves into groups with a step of 1 μm – 3.00-3.99, 4.00-4.99, 5.00-5.99, 6.00-6.99 and 7.00-7.99 μm. It turned out that the group of 4.00-4.99 μm was the most numerous in all the months of sampling, except for August 2022, when valves with sizes from 5.00 to 5.99 μm predominated in the pelagic zone of the Artybash station (Fig. 3). In October 2021, the share of the 4.00-4.99 μm group at different pelagic stations was 45.0-51.7% with an average value of 49.2±1.5, in June and August the percentage ranged from 44.9 to 64.0 and from 18.3 to 72.7 at an average of 53.6±4.0 and 54.2±12.3%, respectively.

Discussion

The valves of *Pantocsekiella teletskoyensis* with small and large lacunae are similar to those of *Cyclotella ocellata* (Table 1). The latter species is characterized by several morphotypes, including those with flat valves in the size range up to 20 μm (Genkal and Popovskaya 2007, 2008). At the same time, some valves of *C. ocellata* (Genkal and Popovskaya 2008, Fig.2) are very similar to those of *P. teletskoyensis* (Fig. 2A). A similar situation occurs with *C. minuscula* – flat valves (Cvetkoska et al. 2014, Figs 91, 92). Valves with large lacunae (Fig. 2B, C, E) are also very similarity to those in *C. ocellata*, but usually this species additionally has large granules between the lacunae (Genkal and Popovskaya 2008, Fig.6). As in *P. teletskoyensis*, valves with small lacunae (Fig. 2F) are also found in *C. minuscula* (Cvetkoska et al. 2014, Figs 72, 74, 87–89).

In *P. teletskoyensis*, we have observed valves with slightly protruding branching costae on the outer surface, as shown in Figure 2G–I. This relief on the external face is also characteristic of *C. arctica* (Genkal and Kharitonov 1986, Tables I, 3, 4) and *C. gordonensis* (Kling and Håkansson 1988, Fig. 99), as described in the literature. Similarly, variations in morphotype are common in other centric diatom genera, such as *Stephanodiscus* (Genkal 1996). The presence of granules on the valve is listed as a qualitative feature in the diagnosis of *C. minuscula* (Cvetkoska et al. 2014), but their presence or absence also occurs in other species of this genus, including *C. ocellata* (Genkal and Popovskaya 2007, 2008; Ács et al. 2016), *C. rossii*, *C. comensis*,

C. costei, and *C. delicatula* (Houk et al. 2010). However, we believe that this trait is highly variable and therefore not of taxonomic value.

Based on our measurements, the ratio of the central area diameter to the valve diameter in *P. teletskoyensis* varies from 0.6 to 0.8, while in the morphologically similar *C. minuscula*, this ratio is 0.45–0.7, and the alveoli have clear edges along the entire length of the chambers and are more elongated radially (Cvetkoska et al. 2014, Figs 93–99). Similar values of this ratio are typical for *C. ocellata* (Genkal and Kharitonov 1996), *C. gordonensis* (Kling and Håkansson 1988), and *C. arctica*. The latter species is also characterized by longer alveoli (Genkal and Kharitonov 1996).

Figure 3. The ratio of size groups in the *Pantocsekiella teletskoyensis* population of Lake Teletskoye in 2021-2022.

Table 1. Morphological characteristics of *Pantocsekiella teletskoyensis* and related species of the genera

Diameter of valve, µm	Number of striae in 10 µm	Number of central fultoportulae	Number of satellite pores at the central fultoportulae	Location of marginal fultoportulae	Number of satellite pores at the marginal fultoportulae	References
			Pantocsekiella teletskoyensis			
3.5–5.8	25–35	1 (rare 0)	1–2	2–5 on the frustule	2	Genkal 1994 (as *Cyclotella delicatula*)
3.5–5	20–25	1*	2*	3*	–	Genkal and Mitrofanova 1995 (as *Cyclotella species*)
3.5–5.8	25–35	1	1(2)	on the each 4–12 interstriae'	2	Genkal and Mitrofanova 2022a
			Pantocsekiella arctica			
3.8–10.6	24–32	1 (rare 2)	2	on the each 4–8 interstriae'	2	Genkal and Kharitonov 1996 (as *Cyclotella arctica*)
2.7–14.8	2.7–14.8	1–3	2 (rare 0 or 3)	on the each 4–8 interstriae'	2	Genkal et al. 2020 (as *Cyclotella arctica*)
			Pantocsekiella minuscula			
3–7	25–30	1	1–2	on the each 4–10 interstriae'	2	Cvetoska et al. 2014 (as *Cyclotella minuscula*)
			Pantocsekiella gordonensis			
3–8	25*	1	2*	2*	2*	Kling, Håkansson, 1988 (as *Cyclotella gordonensis*)
			Pantocsekiella ocellata			
5.6–25	14–20	1–5	2 (rare 1)	on the each 2–6 interstriae'	2	Kiss et al. 1999 (as *Cyclotella ocellata*)
						Håkansson 2002 (as *Cyclotella ocellata*)
2.5–44.2	10–30	1–13 (rare absent)	2	on the each 1–8 interstriae'	2	Genkal and Popovskaya 2008 (as *Cyclotella ocellata*)

*– according to measurements or calculations in published photographs.

In *P. teletskoyensis*, the only rimoportula on the internal valve face is located on a costa, with its slit oriented radially, as depicted in Figure 2K, M (Genkal and Mitrofanova 2022a). However, we have also observed another location of the rimoportula in the marginal zone near the costa, as shown in Figure 2L, N. In *C. minuscula*, the rimoportula is also located on the interalveolar septum (Cvetkoska et al. 2014, Figs 93–99), whereas in *C. arctica* and *C. ocellata*, it is typically situated in the marginal zone or closer to the center (Genkal and Kharitonov 1996; Genkal and Popovskaya 2007, 2008; Houk et al. 2010; Genkal et al. 2020). Based on our morphological analysis, *P. teletskoyensis* is most similar to *C. minuscula* in quantitative and qualitative characteristics (Table 1), with the exception of the constant presence of lacunae on the valve face and the longer clearly bounded alveolar chambers on the inner side. *C. minuscula* was described from the deep–water Lake Ohrid, a deep-water body on the border of Northern Macedonia and Albania (Cvetkoska et al. 2014).

P. teletskoyensis is a small-sized species of centric diatom. Three more species from the same group were identified in Lake Teletskoye: *Stephanodiscus minutulus* (Kütz.) Cl. et Möll., *S. makarovae* Genkal, and *Stephanocostis chantaicus* Genkal et Kuzmina (Genkal 1994; Mitrofanova 2011). Later it was found that this lake is inhabited by *S. binatus* Håkansson et H.J. Kling, but not *S. makarovae* (Genkal and Mitrofanova 2022b). *P. teletskoyensis* is the most abundant among small-celled centric diatoms in the lake both in the pelagic and littoral zones, with over 50% representation all year round, and dominating in numbers during certain periods of the year. Additionally, it is the dominant species in phytoplankton in general, competing with the cryptophytic algae *Chroomonas acuta* Uterm. (Mitrofanova 2010).

The valve diameter of *P. teletskoyensis* was found to range from 3.5 to 5.8 μm in a study conducted by Genkal and Mitrofanova in 2022, as well as in the present study. However, in 2021-2022, larger valves were detected, with a maximum size of 7.98 μm. The size of this species was found to vary seasonally, with the smallest and largest values recorded in autumn (October). This suggests that the range of valve sizes is larger during this period compared to spring and summer (Table 2). The first study conducted on this species in 1989 collected phytoplankton samples during summer, when the valve diameters were not at their maximum. Therefore, fall may be the most favorable period for the development of larger forms of this species. The end of September-beginning of October is the autumn period when the lake's water begins to get colder, but there is still no complete mixing of the water column due to homeothermy, strong winds, and storms. Additionally, in August, many representatives of the summer community of non-diatomic plankton stop vegetating, go dormant, or die. This decreases competition between diatoms and other algae for biogenic elements, making it more likely for larger forms to develop, especially given the low nutrient content characteristic of Lake Teletskoye (Tretyakova 2012). The study also found differences in valve dimensions by habitat, with the pelagic zone having higher average values and a wider range of sizes compared to the littoral zone.

We registered that the size structure of the phytoplankton community is affected by factors such as thermal stratification, mixing regime, and sinking rate of cells, but most importantly by the availability of nutrients. Larger phytoplankton can maintain a higher specific rate of metabolism and biomass growth when resources are abundant, and are less likely to be eaten by predators. However, both very small and very large cells can maintain the same biomass-specific metabolic rate, while the highest growth rate is achieved by medium-sized cells, which is what was recorded in the population of *P. teletskoyensis* in Lake Teletskoye. When dividing the revealed sizes of *P. teletskoyensis* valves into groups with a step of 1 μm, the group of 4.00-4.99 μm was consistently the most numerous, with slightly more of this group in June and August, and slightly less in October (Fig. 3).

Table 2. Minimal, maximal and mean frustule diameter of *Pantocsekiella teletskoyensis* in pelagial and littoral zones of Lake Teletskoye in 2021-2022, μm

Sampling period		Frustule diameter	Zone of the lake	
			pelagial	littoral
2021	October	min	3.02	3.17
		max	7.98	7.94
		mean	4.55±0.03	4.33±0.04
2022	June	min	3.12	3.64
		max	5.93	5.97
		mean	4.83±0.02	4.79±0.05
	August	min	3.31	3.62
		max	6.60	6.64
		mean	4.85±0.02	4.71±0.03

Conclusions

A rare species of small-celled centric diatom, named *Pantocsekiella teletskoyensis* Genkal et Mitrofanova emend. Genkal et Mitrofanova, was recently identified from *Cyclotella delicatula* Genkal, which was previously described in the phytoplankton of Lake Teletskoye (Altai, Russia). To better understand the morphological features of *P. teletskoyensis*, numerous scanning electron microscopy images were analyzed during a recent phytoplankton study in Lake Teletskoye. The investigation revealed a wider range of qualitative morphological characteristics, including valve relief, granules on the valve face, rimoportula position, and alveolar structure. These new findings helped refine the species' diagnosis.

Furthermore, a comparative morphological analysis of *P. teletskoyensis* and other small-celled centric diatoms from the *Pantocsekiella* and *Cyclotella* genera, found in various waterbodies across Europe, Asia, and America, showed that *P. teletskoy-*

ensis is most similar to *C. minuscula*. The latter was described from the deep-water Lake Ohrid, located on the border of Northern Macedonia and Albania.

To estimate the size of the *P. teletskoyensis* population, numerous measurements of valve diameters were taken, revealing a range from 3.02 to 7.98 μm. Among the different size groups, the 4.00–4.99 μm group was consistently the most abundant throughout all the months studied.

Overall, this study provides new insights into the morphological features and population structure of *P. teletskoyensis*, and its relationship to other small-celled centric diatoms from the *Pantocsekiella* and *Cyclotella* genera.

Acknowledgements

This study was conducted under support of the RSF No.21-17-00135 (some sample processing on SEM Hitachi S-3400N, IWEP SB RAS, and analysis of results) and partially in the framework of state assignments, projects No. 121031200178-8 (some phytoplankton sample processing on LM Laboval 4 (Carl Zeiss), IWEP SB RAS) and No.121051100099-5 (SEM JSM-25S and JSM-6510LV, IBIW RAS).

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