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Disturbances in the primary stratigraphy of lake sediments on the Murmansk coast (Russia): their identification and relationship with catastrophic events

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Abstract. The results of lithological, diatom analysis and radiocarbon dating of bottom sediments of small coastal lake basins along the Murmansk coast of the Barents Sea (the Kola Region, Russia) are presented. Sedimentary successions of two lakes reveal the presence of distinctive deposits, very different from the sediment above and below. These deposits are represented by erosional unconformity beds, gyttja and sand mixed with plant macrofossils, and characterized by changes in diatom flora and sand in a matrix of organic material. The sediments were deposited due to different catastrophic events: paleo-tsunami and paleo-earthquakes. According to radiocarbon analysis data, a tsunami occurred between 10,400–8200 cal yr BP and a paleo-earthquake occurred between 8200–7200 cal yr BP. We discuss various causes and mechanisms for the formation of disturbances in lake sediments, including the Storrega tsunami and paleo-earthquakes, which during and after deglaciation were strong and frequent.

Keywords*: coastal lake basins; paleo-earthquakes; tsunami deposits; seismic shaking; Kola Bay; Barents Sea; Kola region; Holocene*

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INTRODUCTION

The bottom sediments of lakes are good geological archives, which preserve information about past natural-climatic environments, including strong catastrophic events (earthquakes, tsunamis, landslides). Numerous traces of strong catastrophic events were studied in the various geological and tectonic settings in different parts of the world (Bondevik *et al.* 1997; Dawson, Smith 2000; Mörner 2005; Agnon *et al.* 2006; Guyard *et al.* 2007; Morey *et al.* 2013, etc.). In lake sequences catastrophic events are represented by stratigraphic non-conformities, changes in diatom flora and mixed sand, silt, gravel, plant macrofossils in organic matrix.

The Kola Peninsula, as an element of the north-western Baltic (Fennoscandian) Shield, is not a high-seismicity region at the present (Ahjos, Uski 1992; Godzikovskaya *et al*. 2011). However, traces of strong earthquakes were discovered in the recent decades in the different parts of Fennoscandia (Lagerbäck 1990; Lukashov 1995; Olesen *et al.* 2004; Mörner 2004; Mörner 2005; Nikolaeva 2008; Kukkonen *et al.* 2010; Mörner 2011; Shvarev, Rodkin, 2018; Nikolaeva *et al*. 2018). Seismicity was exceptionally high during and immediately after deglaciation. Strong earthquakes and large landslides could generate tsunami waves, as well as be a cause of disturbing the normal accumulation of sediments in coastal lake basins.

The giant catastrophic event, the Storegga Slide, triggered a widespread tsunami in the North Atlantic ca 8200–8000 cal yr BP (Bondevik *et al.* 1997, 2003; Dawson, Smith 2000; Romundset, Bondevik 2011). Tsunami deposits have been discovered at numerous sites (the Norwegian coast, Shetland, Scotland, Faroe Islands and Finnmark area of the Barents Sea). According to present estimates, the volume of slide material was 3000 km^3 (Hafliðason *et al.* 2004). The maximal runup of a tsunami wave was up to 20 m (on the western coast of Norway), while the minimal runup of ca. 3 m was registered on the southern Barents Sea coast. Paleo-tsunami geological records are also known along the Swedish coastline and on the shores of the Baltic Sea (Mörner 2004, 2005, 2011; Mörner, Dawson 2011; Rotnicki *et al.* 2016).

Numerous studies report subaqueous mass movement that was triggered by earthquakes both in various lacustrine and marine environments. Often, in the cores from inland lake basins one can see homogenites, turbidites, breccias, convolute structures, sand and silt formed as a result of seismic shaking (Doig 1991; Chapron *et al.* 1999; Arnaud *et al*. 2002; Nomade *et al*. 2005; Guyard *et al*. 2007; Morey *et al*. 2013; Nikolaeva *et al.* 2017). Such disturbances in the primary stratigraphy of lake sediments occur near active faults or subduction zones and are formed as a result of seiches, turbiditic flows and slumping.

No tsunami deposits have been recorded along the Russian coast of the Barents Sea for a long time. However, in ancient manuscript chronicles there are some accounts describing extremely strong storm surges or potential tsunamis. Today, there is a lot of information on seismic dislocations (Nikolaeva 2008; Spiridonov 2005; Verzilin *et al.* 2013) and possible traces of tsunami (Tolstobrov *et al.* 2018) of the Murmansk coast.

In this paper we present results of the study of disturbances in the primary stratigraphy of lake sediments on the Murmansk coast (the Kola Peninsula, Russia) and relationship with catastrophic events (tsunami and earthquakes) in two localities: near the Kola Bay and near Teriberka settlement of the Barents Sea (Fig. 1). We also revise data on known disturbances in other sedimentary successions in lakes of the Murmansk coast. The aim of this research is to describe the structure and texture of lake sediment sequences, to estimate the age and to discuss hypotheses of mechanisms of disturbance formations and their possible relationship to the seismic shaking or tsunami.

GEOLOGICAL SETTING

The 500 km long Murmansk coast is coincident with the first order tectonic boundary between the Barents plate and the Baltic Crystalline Shield. The crystalline basement, which is mostly composed of Archaean granitoids, step-by-step submerges to the north and north-east under the cover of Late Proterozoic deposits (Mitrofanov *et al*. 1995). The coastal area corresponds with "Karpinsky fault"– the newest tectonic structure, which is part of the Murmansk seismogenic zone (Godzikovskaya *et al.* 2011). Young and recent tectonic activity of the zone is proved by many scientific specialists (Nikonov, Shvarev 2015; Spiridonov 2005; Verzilin *et al.* 2013).

The Kola Peninsula and the surrounding areas were covered by the Scandinavian Ice Sheet during the local last glacial maximum (LLGM) ca. 18,000–17,000 cal yr BP (Yevzerov, Nikolaeva 2000; Svendsen *et al.* 2004). During the Holocene, this area experienced uplift, and the shoreline of the sea suffered regressive movement. The final melting of the ice occurred about 9000 cal yr BP. During the last deglaciation, the territory was uplifted, while the coastline regressively shifted. The uplift amplitude increases from the north-east to the south-west (Snyder *et al.* 1997; Corner *et al.* 2001; Tolstobrov *et al.* 2016).

In the early Holocene, the uplift rate was maximum ca. 40–50 mm / year. In the middle Holocene, the gradual decrease of the sea level was interrupted by the Tapes transgression (Fig. 1). On the Varanger Peninsula coast (Romundset, Bondevik 2011) and near the Dalniye Zelentsy settlement (Snyder *et al.* 1997) in a time span 9500–7500 cal yr BP, a low-amplitude (2–5 m) transgression with a maximum of 7500 cal yr BP is recorded on curves of the sea level relative displacement (Fig. 2). At the time, this transgression occurred only as a long stillstand of one sea level on the coastline in the Paatsjoki River valley, near Nikel (Corner *et al.* 1999) and near the town of Polyarny (Corner *et al.* 2001).

After the Tapes transgression, the sea is regressed at an average rate of 2 to 4 mm per year, slowly declining. According to Fjeldskaar *et al.* (2000) and Pohjola *et al.* (2014), the territory of the Murmansk coast in the present time continues uplifting with a velocity of 1 to 3 mm per year.

The coastal area is greatly dislocated and occurs as a high dissected denudation plain with a height of 150–200 m rising to the south and steeply dipping to the north.

The study areas are located along the northern Kola coast between Murmansk and Polyarny and near Teriberka settlement (Fig. 1). The bedrock is represented by a complex of granitoids and gneisses and characterized by abrupt discontinuities which control valley orientation and coastline morphology. The Quaternary deposits consist mainly of a relatively thin till cover on the bedrock (Niemelä *et al.* 1993).

Sedimentary successions in the two coastal water basins – Lake R1 (51.5 m above sea level (a. s. l.)) and Lake T1 (17 m a. s. l.), are described below. The lake basins occupy glacially eroded rock depressions of undulating relief, lying mostly below 100 m a. s. l. During the Holocene, as a result of raising the land, lake basins were isolated from the sea.

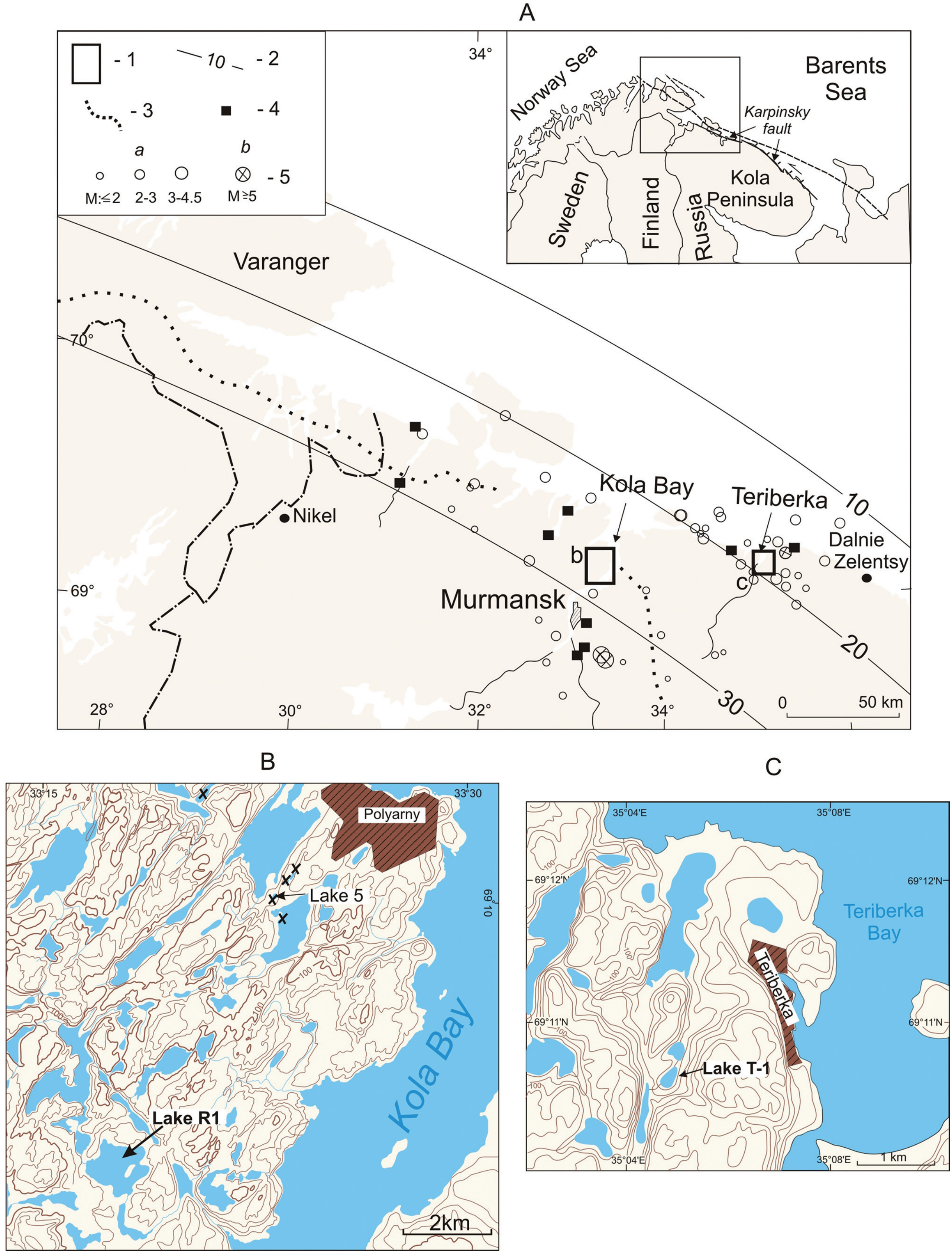

Fig. 1 Location map of the study areas on the Murmansk coast and isobases for the mid-Holocene "Tapes" shoreline (after Snyder *et al.* 1997). A: 1 – study areas; 2 – Tapes isobases (meters above present sea level); 3 – Younger Dryas and moraine zone (after Yevzerov, Nikolaeva 2000); 4 – locations of seismic events (after Nikolaeva (2008), Spiridonov (2005), Verzilin *et al.* (2013)); 5 – epicenters of earthquakes (after Ahjos, Uski (1992), Godzikovskaya *et al.* (2011)): modern (a), historical (b), M – magnitude. B, C – locations of studied lakes. Isohypses are drawn through 20 m. The crosses in the B section show lake basins studied by Corner *et al*. (2001)

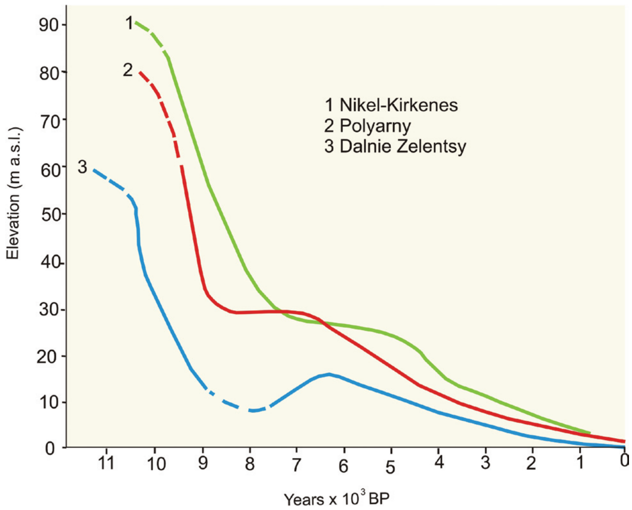

Fig. 2 Relative sea-level curves constructed for three locations along the northern Kola coast, after: 1 – Snyder *et al.* (1997), 2 – Corner *et al.* (2001), 3 – Corner *et al.* (1999)

MATERIALS AND METHODS

Field methods. Sediment cores were retrieved from ice-covered lakes in April of 2015 and of 2017. Cores were taken in 1 m length using a portable piston drill, diameter 54 mm. Drilling was carried out to bedrock or till in the deepest flat-bottomed place of the lake. Sediment cores were selected with an overlap of 10 cm. Lake elevation was obtained from 1:25 000 scale topographic maps. Threshold depth or height relative to lake level was determined locally in the field and subtracted from or added to lake elevation to give the threshold elevation. Lithological description and sampling for diatom analysis and radiocarbon dating were provided in field conditions based on the visual characteristics (colour, structure, inclusions, and mechanical composition). Retrieved sediment cores were extruded on-site, split longitudinally to reveal structure, then described, photographed and sampled. Sediment slices were collected for diatoms (2–3 cm thick) and radiocarbon dating (5–10 cm thick).

Diatom analysis was provided for a series of closely spaced samples. A technical processing of the samples was performed using standard methods (Diatomovye …, 1974). The species composition of diatoms' valves was identified and calculated, using a biological digital microscope Motic DMBA 310 with a zoom of ×400 and ×1000 and some immersion oil. The taxonomic and ecological identification of diatoms was performed according to indicators and literary sources, taking into account the latest taxonomic changes (Guiry, Guiry 2013).

Radiocarbon dating of sediment samples was made in the Laboratory of Quaternary Paleogeography and Geochronology of the Faculty of Geography and Geoecology at St. Petersburg State University (LU-samples). Radiocarbon dates were calibrated using the OxCal 4.3 program (Bronk Ramsey 2018) and the IntCal13 calibration plot (Reimer *et al.* 2013).

RESULTS

In general, sedimentary succession in lake basins of the Barents Sea coast is represented by the following facies (Snyder *et al.* 1997; Corner *et al.* 2001): fI – marine (mineragenic), fII – transitional (organic or mixed organic / mineragenic), fIII – freshwater lacustrine (organic). The formation of all these facies is due to the rise of the Earth's crust, the regression of the coastline of the sea and the general paleogeographic situation during the Late Pleistocene and Holocene. In the succession of the studied lakes there are both complete and reduced sequences, as well as lithological, stratigraphic and tectonic disturbances. We interpret these disturbances as tsunami facies (fTs) and seismogenic facies (fSg). Lake R1 shows the regressive succession in which there is a seismogenic facies (fI–fII–fIII–fSg–fIII). Lake T1 stratigraphy contains the fI–fII–fIII–fTs–fI–fSg(?)–fIII complex and tsunami facies.

Lake R1 *(51.5 m a. s. l.)*

Lake R1 (Retinskoe Lake) is located on the western side of the Kola Bay, south of Polyarny and at a distance of 15 km from the open coast of the Barents Sea (Fig. 1 A, B). The basin's range in size is 2.8 × 1.25 km. The maximum depth of the lake is more than 12 m. The basin runoff threshold is 51.5 m a. s. l. and drainage from the lake is by stream flow across the rock threshold. Deposits of the lake were studied by three cores at a distance of 0.4 km from each other. The description of lithology and diatom flora is given by core 1 (N 69°07'37.7''; E 33°18'55.4'') and is focused on defining environmental interpretations and anomalous phenomena (Figs 3, 4).

Layer 1, 550–488 cm – sandy silt and clay, non-laminated, gray. This layer contains pebbles, gravel, sand lenses and rock debris (size of up to 5 × 2.5 × 4 cm) presumably deposited by ice rafting. There are inclusions of dispersed organic material at a depth of 500–490 cm. A transition to overlying deposits is distinct.

Diatom flora of the silt sample from the bottom part of the layer 1 (540–538 cm) indicates a development of marine algae, which contains 60% of polyhalobous and mesohalobous and 24% of halophilous. The amount of freshwater indifferents is 16.4%. This composition allows making a conclusion about the diatom flora genesis in marine conditions. The main dominants on this depth were polyhalobous *Grammatophora angulosa* var. *islandica* (Ehr.) Grun. and mesohalobous *Cocconeis scutellum* Ehr., *Diploneis subcincta* (A.W.F. Schmidt) Cleve, *Diploneis inter-*

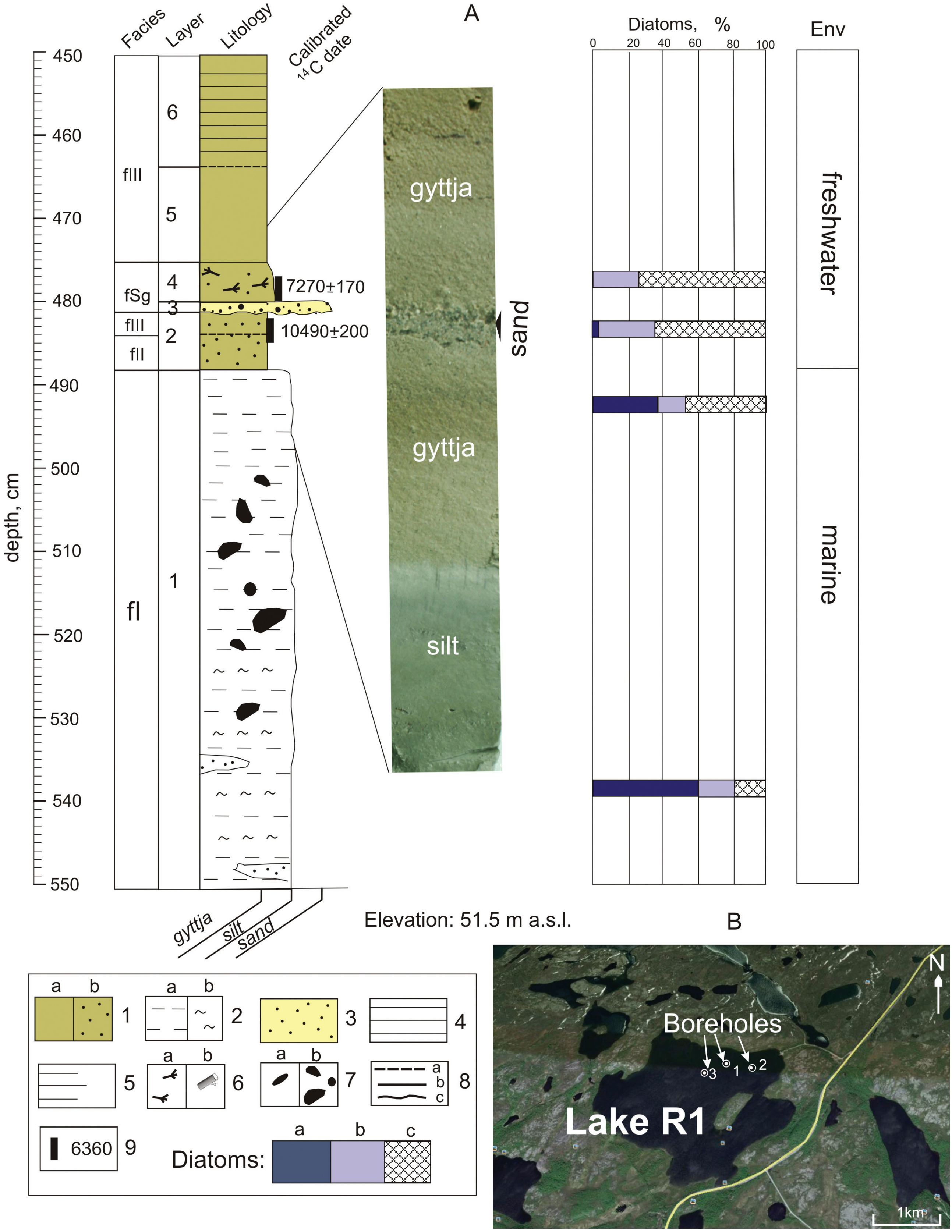

Fig. 3 Lithology, radiocarbon ages and diatom diagram (A) and boreholes location (B) from Lake R1. 1 – gyttja (a), sandy gyttja (b); 2 – silt (a), clay (b); 3 – sand; 4 – lamination; 5 – weak lamination; 6 – fragments: plant (a), wood (b); 7 – gravel/pebbles (a), rock debris (b); 8 – contacts: gradational (a), abrupt (b), erosional unconformity (c); 9 – radiocarbon dating (cal yr BP). Facies: fI – marine, fII – transitional, fIII – freshwater lacustrine, fSg – seismogenic facies. Diatoms: a – marine (polyhalobous, mesohalobous); b – halophilous; c – halophobous. Diatom analysis: T.S. Shelehova

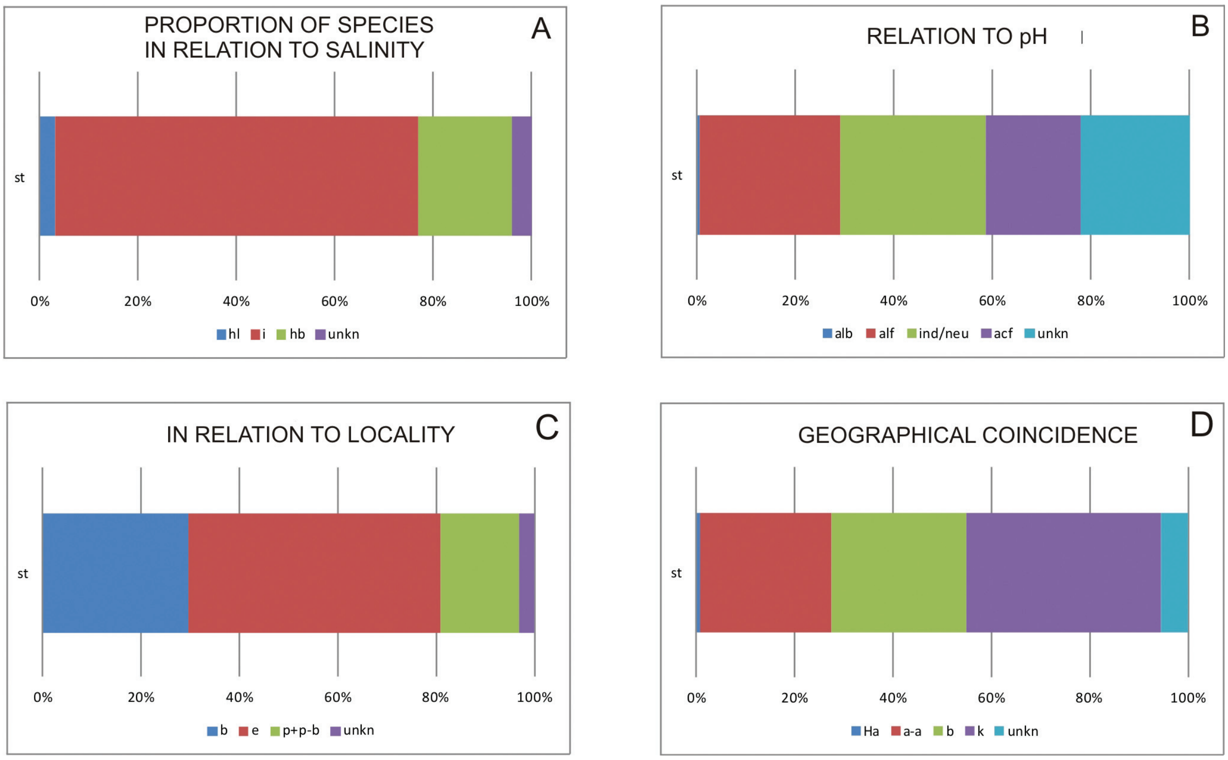

Fig. 4 Ecological characteristics of diatom complexes in the sand (layer 3 in Fig. 3). A: hl – halophilous; i – indifferent; hb – halophobous; unkn – unknown. B: alb – alkalibionts; alf – alkaliphils; ind/neu – indifferent/neutrophil; acf – acidophiles; unkn – unknown. C: b-benthic; e – planktonic; p + pb – planktonic + planktonic-benthic; unkn – unknown. D: Ha – Holarctic, a – arctoalpine; b – boreal; k – cosmopolitan; unkn – unknown. Diatom analysis: A.N. Tolstobrova

Table 1 Radiocarbon dates of Lake R1 sediments

No	Relation to disturbed layer	Depth, cm	Material	^{14}C age, (yr BP)	Calibrated age (2σ interval, yr BP)	Lab. number
1	below	488–481	gyttja	9280 ± 140	10,490 ± 200	LU-7907
2	above	479–472	gyttja	6360 ± 160	7270 ± 170	LU-7908

rupta (Kütz.) Cleve. The halophilous complex was more diverse, its main dominants were *Rhoicosphenia abbreviata* (C.Agardh) Lange-Bert., *Diploneis smithi* (Bréb.) Cleve. Freshwater flora is mostly represented by numerous individual valves of different genera: *Amphora, Cymbella, Eunotia, Fragilaria, Gomphonema, Navicula, Nitzschia.*

Up in the succession, the amount of both marine polyhalobous and mesohalobous (from 60 to 38%), and halophilous (from 24 to 13.6%) markedly declined in the upper part of the silt sequence (494–492 cm). The proportion of freshwater diatoms increased from 16.4 to 48%, respectively. Furthermore, there was a replacement of polyhalobous in this complex: earlier dominating *Grammatophora angulosa* var. *islandica* were displaced by *Rhabdonema minutum* Kütz.; *Cocconeis verrucosa* J.-J.Brun, *Diploneis subcincta* dominated among mesohalobous; *Cyclotella kuetzingiana* var *radiosa* Fricke among halophilous, *Fragilariforma virescens* var. *subsalina* (Grun.) Bukht. All the others occur as isolated valves, and various freshwater organisms are species of the *Cymbella, Eucocconeis, Pinnularia, Neidium, Navicula, Frustulia.*

Layer 2, 488–481 cm – sandy gyttja, non-laminated, brown. The radiocarbon data of 10,490 ± 200 cal yr BP (Table 1) from the lowermost part of layer 2 correspond approximately to isolation of the basin.

Layer 3, 481–479 cm – sand from medium-grained to coarse-grained, gray. We traced the sand layer, 2–4 cm thick, which rests upon an erosive boundary in three cores along a ca. 310 m long transect of the lake (Fig. 3B). The diatom flora in the sand is freshwater (Fig. 3A, 4).

Layer 4, 479–475 cm – gyttja, sandy gyttja, non-laminated, dark brown. Layer 4 contains a lot of plant residues including twigs up to 3–4 cm. Samples from the layer gave radiocarbon data of 7270 ± 170 cal yr BP (Table 1).

Layer 5, 475–464 cm – gyttja, non-laminated, dark brown.

Layer 6, 464–450 cm – gyttja, laminated, light brown. Layer 6 contains lamina, 0.5–2.5 cm thick, of different colours: from light gray to dark brown.

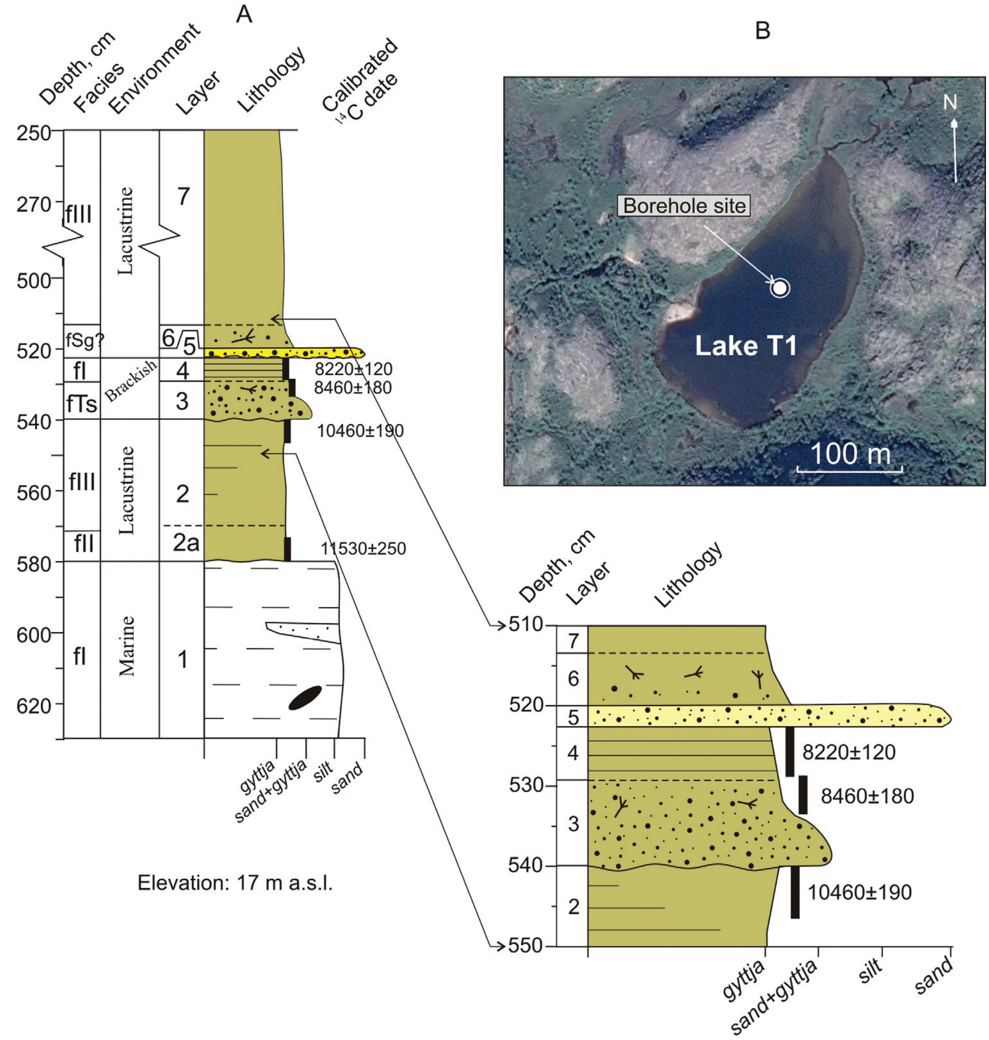

Fig. 5 Lithology and radiocarbon ages of borehole section (A) and location of borehole site (B) in Lake T1 (for legend see Fig. 3)

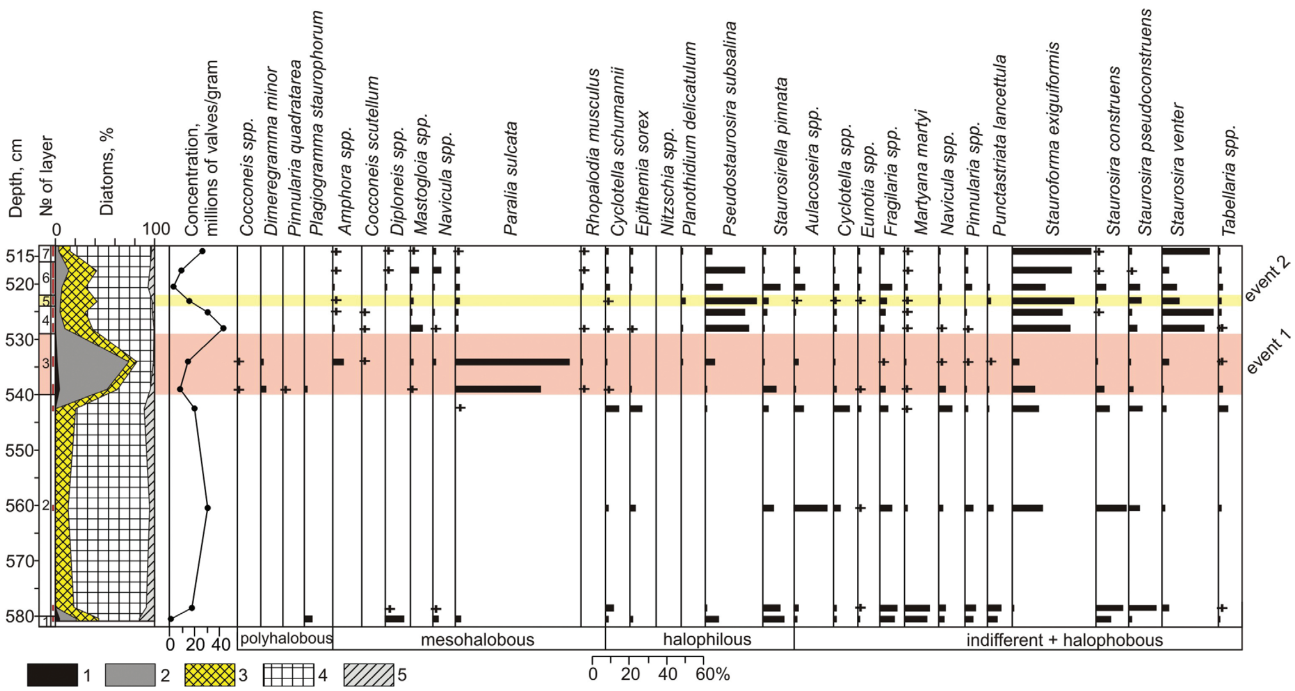

Fig. 6 Diatom diagram of core from Lake T1. Diatoms: 1 – polyhalobous; 2 – mesohalobous; 3 – halophilous; 4 – indifferent; 5 – halophobous. Diatom analysis: A.N. Tolstobrova

According to the results of diatom analysis, the silt with sand of layer 1 accumulated in marine conditions. The samples from the layers 2–6 are freshwater facies (Fig. 3). It is proved by dominant freshwater diatoms, although a sample taken from the depth of 486–484 cm has a relatively high content of halophilous (30.8%) and a minimum of mesohalobous and polyhalobous occurred as individual species (2.8%). In sandy gyttja, halophilous are represented by *Staurosirella pinnata* (Ehr.) D.M. Williams et Round*, Fragilariforma virescens* var. *subsalina, Cyclotella kuetzingiana* Thwaites*, C. kuetzingiana* var. *schumanii* Grun.*, C. kuetzingiana* var. *radiosa, Navicula radiosa* Kütz.*, N. tenella* Brébisson ex Kütz. They are accompanied by the *Nitzschia* genus, which are more common in shallow waters and soils, in homogeneous gyttja. In the layer 3, there are 30% of halophilous species with an admixture of some individual mesohalobous in sand (Fig. 4). These halophilous are more typical of freshwater basins.

Stratigraphy and diatom flora from the investigated lake basin shows rapid isolation of the lake from the sea about 10,490 ± 200 cal yr BP. Since that time, a freshwater regime has been established in the basin and started to accumulate of organic material.

Layers 3 and 4 reflect a sharp change in the hydrodynamic situation and a disturbance in the normal accumulation of organic. The diatom flora of sand (layer 3) indicates its formation in a deeper reservoir than layer 2. After this event, the basin became shallowing and deposits (layers 5 and 6) accumulated in a stable hydrodynamic environment.

Lake T1 *(17 m a. s. l.)*

Lake T1 is located on the Murmansk coast to the west of the Teriberka settlement (Fig. 1, A, C). The lake is small (300 × 130 m), surrounded by hard rock; the maximum depth of the water is 2.5 m. A stream joins it in the south-west, and the lake runs off through a stream in the north. In the central part of the basin there is a core site (N69°10’37.1”; E35°04’53.6”). Lithology of the sediment core is described below (Fig. 5).

Layer 1, 634–580 cm – silt and sandy silt, non-laminated, gray. Layer 1 contains gravel grains and sand lenses. There is a 1–2 mm wide sand interlayer at the boundary with overlaying sediments. According to the diatom analysis, a sample from the upper part of the layer 1 is ca. 20% valves of marine and brackishwater (polyhalobous and mesohalobous) diatoms, among which *Diploneis didyma* (Ehr.) Cl., *Navicula vaneei* Lange-Bert., *Paralia sulcata* (Ehr.) Kütz., *Plagiogramma staurophorum* (Greg.) Heib., *Rhabdonema minutum* etc. occur (Fig. 6). Oligohalobous dominate in the diatom complex, and ca. 20% of them are halophilous, in particular, small benthic diatoms – *Staurosirella pinnata* (10% of the total number of species) and *Pseudostaurosira subsalina* (Hust.) Morales (7%). The upper part of the layer formed in settings of brackishwater basin.

Layer 2, 580–540 cm – gyttja, non-laminated, brown. At a depth of 566–540 cm it is weakly laminated. Transition to the upper sediment layer is abrupt. There are no marine species, but an absolute domination of freshwater species. Indifferents prevail (up to 80%), with widespread benthic diatoms, including *Martyana martyi* (Hérib.-Joseph) Round, *Punctastriata lancettula* (Schum.) P.B. Hamilton et Siver, *Stauroforma exiguiformis* (Lange-Bert.) Flower, Jones et Round, *Staurosira construens* Ehr., *Staurosira pseudoconstruens* (Marciniak) Lange-Bert (Fig. 6). The radiocarbon data of 11,530 ± 250 cal yr BP and 10,460 ± 190 cal yr BP are obtained from the lowermost and upper part of layer 2, respectively (Table 2).

Layer 3, 540–529 cm – a mixture of sand, gyttja and plant remains. The layer 3 overlies with erosional unconformity on gyttja of layer 2. The amount of gray sand decreases from the bottom to the uppermost part from ~90% to 30–20%; brown gyttja with sand (ca. 20%) with plant macrofossils residues in the top of the interval at a depth of 535–529 cm. There are a number of marine and brackishwater diatom species, the amount of which markedly rises in sediments. The planktonic-benthic *Paralia sulcata* species (up to 50–70% of the total number of species) prevail. Besides, there are bottom-living forms and benthic diatoms among mesohalobous *Amphora commutata* Grun., *Navicula peregrina* (Ehr.) Kütz., *Mastogloia elliptica* (Ag.) Cl. et al.). Such benthic species as *Dimeregramma minor* (Greg.) Ralfs, *Diploneis subcincta* (A.Schmidt) Cl., *Plagiogramma staurophorum* et al. are defined among polyhalobous.

Samples from the upper of this layer gave radiocarbon age of 8460 ± 180 cal yr BP (Table 2).

Layer 4, 529–524 cm – gyttja, sandy gyttja, brown, laminated. Diatom analysis indicates that mesohalobous

Table 2 Radiocarbon dates of Lake T-1 sediments. Compiled by Tolstobrov *et al*. (2018)

No	Depth, cm	Material	^{14}C age, (yr BP)	Calibrated age (2σ interval, yr BP)	Lab. number
1	520–528	gyttja	7410 ± 120	8220 ± 120	LU-8250
2	528–535	gyttja	7630 ± 150	8460 ± 180	LU-8249
3	540–548	gyttja	9240 ± 140	10,460 ± 190	LU-8251
4	580–573	gyttja	9960 ± 150	11,530 ± 250	LU-8248

(5–9%) are represented by *Amphora commutata*, *Cocconeis scutellum*, *Halamphora coffeaeformis* (C.Agardh) Levkov, *Navicula peregrina*, *Mastogloia* spp., *Paralia sulcata*, *Rhopalodia musculus* (Kütz.) O.Müll., etc. The dominant complex is represented by halophilous (25–27%) and indifferents (60–67%). Notably, there is a marked burst in the development of the *Fragilaria* sensu lato species. Data obtained from the layer is 8220 ± 120 cal yr BP (Table 2).

Layer 5, 524–522 cm – sand, gray. The diatom flora composition is similar to sediments of the layer 4.

Layer 6, 522–516 cm – gyttja, dark brown. The layer contains sand, plant and gravel grains. The diatom flora is generally consistent with its composition of sediments in the layer 4. However, compared to the underlaying deposits, there was a small increase of the halophobous content up to 5%, due to apprising and/or appearing of the *Tabellaria flocculosa* (Roth) Kütz., *Neidium ampliatum* (Ehr.) Kramm. species, species of the *Eunotia* spp. genus.

Layer 7, 516–250 cm – gyttja, non-laminated, brown. Diatom analysis was undertaken for the bottom part of this layer deposits. Indifferents constitute the prevalent group (80%), within which *Stauroforma exiguiformis* and *Staurosira venter* (Ehr.) Kobayasi are dominant. A number of halophilous decreased to 11%. Valves of *Pseudostaurosira subsalina*, *Staurosirella pinnata*, *Planothidium delicatulum* (Kütz.) Round et Bukht., *Nitzschia frustulum* (Kütz.) Grun. etc. are found.

Sediment analysis shows that after the retreat of the ice this area was flooded by the sea. Layer 1 began to accumulate in the lake basin T1. At the top of layer 1 (silt and sand) there are about 20% of marine and brackishwater diatoms. The age of the lowermost part of layer 2 is 11,530 cal yr BP, which corresponds to a time of isolation of basin T1 from the sea. At that time, the freshwater regime was established and gyttja started to accumulate (Fig. 5, layer 2). Later, as a result of the Tapes transgression, the lake was filled up with sea water and marine deposits started to accumulate there again.

Layer 3 contains a distinctive deposit, very different from the sediments above and below. Yet, there is an abrupt increase of marine and brackish water diatoms (up to 73%). The amount of sand decreases upwards along the section from 90% to 20% and plant residues appear (Fig. 6). At the time of the Tapes transgression, this area was flooded by waters of a small bay that penetrated deep into the continent, closed and protected from the wave breaking activity of the sea waters. At that time, layer 4 (laminated gyttja) was accumulated. The sea level during the Tapes transgression increased to 22 m, since approximately at this level there were coastal formations.

Above these marine sediments there is a layer of sand (layer 5), which is covered by a mix of gyttja, sand and plant residues (layer 6) (Fig. 5). The formation of these deposits was due to changes in hydrodynamic conditions in the reservoir. At the same time, there was no inflow of seawater within the limits of the studied basin, as indicated by the diatom flora (Fig. 6). After an event there is a gradual accumulation of organic material in the lake basin.

Other observations

Investigations of relative sea-level history on the Murman coast have been documented earlier (Snyder *et al.* 1997; Corner *et al*. 1999, 2001). In small lake basins, which were isolated from the sea during the continental uplift, various deformations in sedimentation were found near the cities of Nikel and Polyarny (Fig. 1 A, B). The disturbances are mostly represented by anomalous thicknesses of transition zones related to landslides and other stratigraphic non-conformities. Corner *et al.* (1999, 2001) interpreted these phenomena as sea level fluctuations on the lakes runoff threshold, in result of storms or climate changes.

The succession of the Lake 5 (threshold 28.5 m a. s. l.) among the previously studied basins near the Kola Bay is of greater interest (Fig. 7). The basin (range in size 150 × 100 m) is located 0.3 km from the Pala Bay of the Kola Bay near Polyarny (Fig. 1 B). The depth of the water is 1.5 m. The core thickness is 4.4 m.

The stratigraphy contains complicated succession: an unusually thick I–II–III–II–III core and highly variable diatom flora that fluctuates between dominantly polyhalobous to dominantly indifferent oligohalobous around the unit I–II contact (Corner *et al.* 2001). The fluctuating marine/brackish to freshwater diatom flora in units I and II, the occurrence together of polyhalobous and halophobous diatoms, and evidence of deformational folding in unit II–la, suggest that the lower part of the succession is not conformable (Fig. 7). More details on stratigraphy of Lake 5 are described in Corner *et al*. (2001).

These disagreements could be due to slumping causing thickening and repetition of units, a low rate of emergence followed later by a minor ingression and new isolation, or tsunami. Radiocarbon data of the disturbed layer at the point II–1a (8610–8420 cal BP) show the same age as for deposits from Storrega tsunami (Bondevik *et al.* 2003; Romundset, Bondevik 2011).

Other cores from coastal lakes also near Polyarny and Nikel described various deformations and anomalous thickness in the sections (Corner *et al.* 1999, 2001). They indicate a rapid change of the environment and a stratigraphic unconformity.

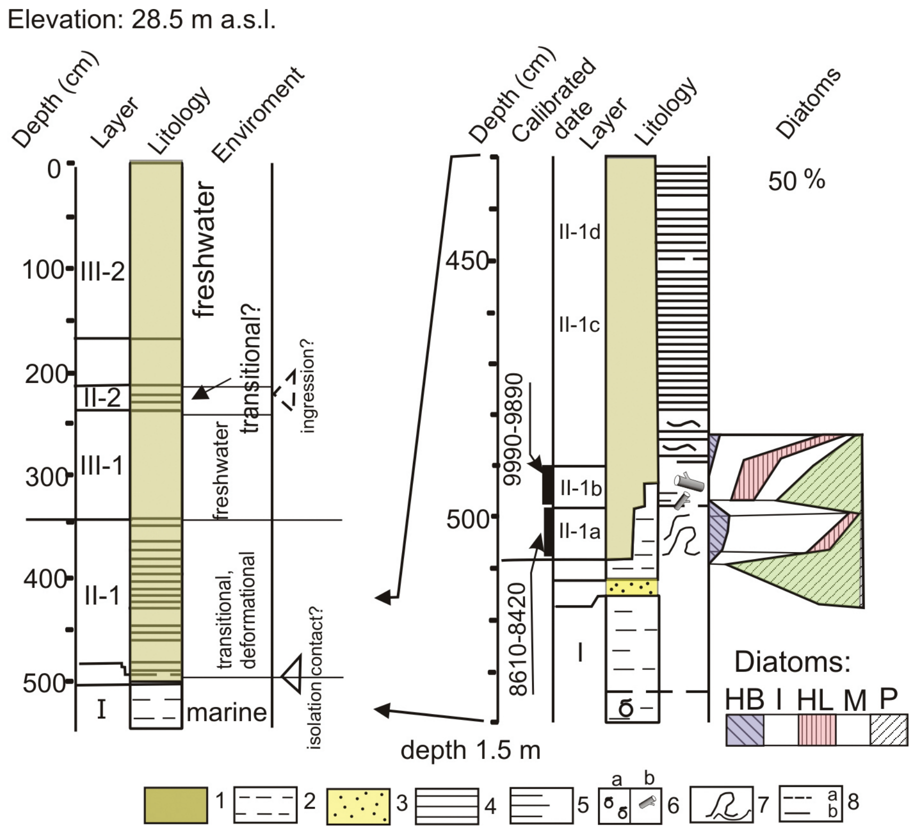

Fig. 7 Lithology of core from Lake 5 near Polyarny showing the full succession and recovered core levels (left) and detailed stratigraphy around the unit I–II transitional (right) and deformations (after Corner *et al.* (2001), simplified). 1 – gyttja; 2 – silt; 3 – sand; 4 – lamination; 5 – weak lamination; 6 – fragments: shell (a), wood (b); 7 – deformed lamination; 8 – contacts: gradational (a), sharp (b). Diatoms: I – oligohalobous indifferent; HB – oligohalobous halofilous; M – mesohalobous; P – polyhalobous

DISCUSSION

Disturbances of the primary stratigraphy of lake sediments were associated with various catastrophic events. We have considered several processes for the formation of disturbances in cores of lakes R1, T1 and 5.

Lake R1. The appearance of a layer of sand in the organic matrix (layer 3) may be explained by: (1) Tapes transgression, (2) tsunami or storm, (3) slumping, (4) seiche, (5) local tectonic factor or earthquake. We exclude the formation of sand as a result of 1–2 cases. The lake is located at a very high level (51.5 m) and the sea wave should be gigantic. There was no inflow of sea waters into the lake at that time. Diatom flora of the sand sample indicates freshwater conditions. The sea level was significantly lower in the time span of 8500–7000 cal yr BP near Polyarny on the height of 27 m (Corner *et al.* 2001).

Seismic shaking from a fault zone could cause a seiche or a landslide. The Earth's vibration (earthquake) could have caused the movement of the water column and a rise in the water from the underlying uncompacted soft sediment. It is known that seismic waves can cause mechanic instability in sediments, remove pore fluid, and bring sediments into a suspended state (Doig 1991; Alsop, Marco 2012; Morey *et al.* 2013). We suggest the apparent correlation between the mechanism of the formation of a tsunami deposits, seiche deposits and the offshore cores is due to a common trigger mechanism from subduction zone earthquakes. However, it is unlikely that seiche could occur on Lake R1. The most realistic explanation for the appearance of sand in the gyttja matrix is increased sediment transport from sources external to the lake. The sand was deposited from the coastal part of the lake. Scenarios for the mechanism of sediment formation are shown in Fig. 8.

Similar deposits formed by earthquakes have been documented in the different geological settings. For example, earthquake-induced historical homogenites are reported from Lake Lucerne, Switzerland (Siegenthaler *et al.* 1987). Doig (1991) reported that the earthquake of 1935 with a magnitude of 6.3 have caused silting and resuspension of sediments in Canadian lakes. Lake Bourget (France) has homogenites that correlate with the A.D. 1822 earthquake (local intensity VII–VIII), the strong historical earthquake of the French outer Alps (Chapron *et al.* 1999). Doughty *et al.* (2010) present evidence of lake-wall fail-

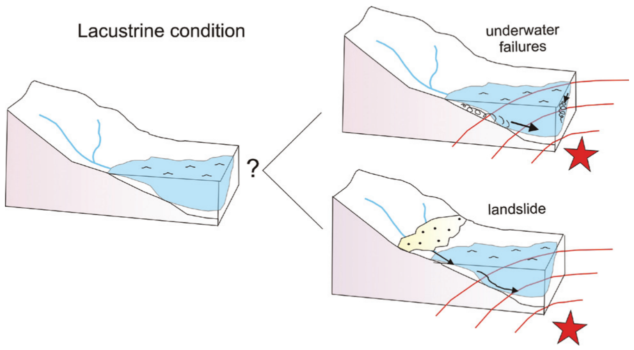

Fig. 8 Comparison between two possible scenarios explaining origin of seismogenic terrigenous layers in lake sediments. Shaking from the fault zone (subduction zone earthquake) either dislodging internal material to the lake (above), or bringing external material to the lake (below) (after Morey *et al.* (2013))

ures using chirp seismic profiles of the lakebed that show that sediments were removed from the slopes of the lake and redeposited into the deepest part of the lake. The paleo-earthquake formed the breccia textures (rip-up clast of gyttja, peat, and silt, wood) and sand layers inside the gyttja in a small basin in the inner part of the Kola Peninsula (Nikolaeva *et al.* 2017). The age of sand from layer 3 (10,400–7200 cal yr BP) coincides with the age of paleo-earthquakes reported for different parts of the Murmansk coast. Previously, we determined that a strong earthquake occurred around Murmansk 9959 ± 211 cal yr BP (Mitrofanov *et al*. 1995; Nikolaeva 2008). Verzilin *et al.* (2013) described seismic ditches and cracks in the Teriberka area, formed by strong earthquake yielded ages from 7210 ± 104 cal yr BP. We assume that landslide processes due to seismic shaking could form a sandy layer in the lake R1.

Lake T1. The erosional unconformity bed and the formation of sand in the bottom part of the layer 3 in Lake T1 occurred during the penetration of high-energy sea water, possibly tsunami or strong storm. During formation of these deposits, the sea coastline was slightly higher than the runoff threshold from the lake; the modern absolute elevation is ca. 18 m a. s. l. However, the protected location of the lake basin from the open sea excludes the formation of these sediments as a result of the storm. The most likely scenario is tsunami process. Similar sedimentation which generated by a tsunami has been noted in a number of lakes around the Northern Atlantic (Bondevik *et al.* 1997; Romundset, Bondevik 2011; Kempf *et al.* 2017). Tsunami deposits of layer 3 were formed ca. 10,400–8200 cal yr BP. Around the same time, the Storegga tsunami triggered by a giant Storegga slide in offshore western Norway propagated into the Barents Sea (Romundset, Bondevik 2011).

Comparison between a tsunami facies of the Storegga slide (western Norway) (Bondevik *et al.* 1997) and the tsunami facies of Lake T1 (the Murman coast of Barents Sea, locality Teriberka) did not reveal a certain similarity. In the tsunami facies of Lake T1 we do not see the facies of the Storegga slide: a graded (facies 4) or massive (facies 5) sand bed with marine diatom fossils overlies the erosive surface, organic conglomerate with rip-up clasts of peat, gyttja and marine silt (facies 6) and organic detritus (facies 7) (Bondevik *et al.* 1997). We explain this by a large distance from the Storegga slide and Lake T1 or other unknown local tsunami in the Barents Sea. At present it is difficult to determine whether deposits of Lake T1 are Storrega's tsunami deposits or other tsunami deposits. This is quite likely, since Krapivner (2018) reported that the landslide caused the formation of an accumulative ridge from seismogenic gravity of about 9000 cal yr BP near the "Kola trough" of the Barents Sea.

Special attention is attracted by the layers 4 (laminated gyttja) and 5 (sand) (Fig. 5), lying higher in the section than layer 3. These deposits may be as tsunami facies too or be formed by other processes (slumping, seiche, etc.). The layers were formed after 8400–7900 cal yr BP, after the lake had been isolated from the sea. The sea coastline was lower that the runoff threshold from the lake, on a height of 16 m a. s. l. The sand contains freshwater diatoms (Fig. 6). The event happened at that time when this basin was filled by fresh water and there was no influence of the sea. We do not exclude the formation of layers 4 and 5 due to the tsunami, but we are considering another scenario – the seismic shaking. According to the results of radiocarbon dating, layer 3 from Lake R1 and layers 5–6 from Lake T1 were formed at the same time (not earlier than 8220 ± 120 cal yr BP, but not later than 7270 ± 170 cal yr BP, i.e. in the time span of 8200–7200 cal yr BP). However, we believe that more sediment cores are required for a final conclusion on the genesis of the deposits.

A revision of disturbances in successions of coastal basins near Kola Bay (lake 5 and others, reported by Corner *et al.* (1999, 2001)) indicated no clear facies of tsunami Storrega. Sedimentation deformations can also be generated by other sources. Seismic shaking, submarine landslide, cliff collapse into the water could have caused a tsunami wave, especially in fjords (Hansen *et al.* 2013). According to seismo-acoustic and geological data, there are data on strike-slip shifts and seismo-gravitational block sliding in the Kola Bay (Shipilov *et al.* 2017). Disturbances in lake sediments may be associated with the activation of the Karpinsky fault (Nikonov, Shvarev 2015).

CONCLUSIONS

A detailed study of deposits in small coastal lake basins along the Russian coast of the Barents Sea showed that the Murmansk coast in the early Holocene was subject to different catastrophic events.

1. Distinctive sedimentation, which is very different from the overlaying and underlaying deposits, has been detected in sedimentary successions of the two lakes – near Teriberka (Lake T1) and near the Kola Bay (Lake R1). These deposits are represented by mixed gyttja, sand, plant macrofossils, and characterized by changes in diatom flora and sand in organic matrix. The two different events most likely happened on the Murmansk coast. Sediments of Lake T1 reveal tsunami deposit, and sediments of Lake R1 reveal seismigenic deposits.

2. According to radiocarbon analysis data, a tsunami occurred between 10,400–8200 cal yr BP, and a paleo-earthquake occurred between 8200–7200 cal yr BP.

3. Sedimentological analysis of cores and revision of disturbances in other lakes of the Murmansk coast showed that there are no clear diagnostic signs of similar to the Storrega tsunami facies in their sections. These differences are due to a large distance from the source or other local paleo-tsunami in the Barents Sea.

Our study reflects the initial stage of studying disturbances the primary stratigraphy in the bottom sediments of coastal lakes. Future studies will allow a more detailed identification of the mechanisms of the catastrophic phenomena of the Late Pleistocene and Holocene.

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