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Paleoenvironmental reconstructions and a sedimentological evidence of paleoseismic activity ca 9000 yr BP in Karelia, NW Russia, based on lake sediment studies on Mount Vottovaara

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Abstract. Karelia, like the entire Fennoscandian Shield, is a region with a low seismic activity. An example of the best-studied locality is a paleoseismic dislocation on Mount Vottovaara, which bears traces of disastrous Holocene geological events following the degradation of the last ice sheet. The evolution of the study area falls into three stages. At pre-Quaternary stage I, an uplifted block broken by numerous fractures and faults was formed. At glacial stage II, coarse clastic moraine was formed, the moving ice polished the crystalline basement surface and glacial scars were formed. At final deglaciation stages, the mountain top remained a nunatak. As Salpausselkä II marginal sediments retreated by about 70 km from the mountain, a postglacial stage in the region's evolution, at which an earthquake occurred, began. It could have been triggered mainly by the consequences of the degradation of the Late Weischelian glaciations such as the rapid removal of the glacial load that contributed to the rejuvenation of various old faults. Changes in paleoecological conditions for the Mount Vottovaara area were reconstructed based on the results of lithological, palynological, diatom and radiocarbon studies of bottom sediments from a small lake on the mountain top. Vegetation dynamics from the Younger Dryas to the Subboreal period is presented. Small lake evolution stages were distinguished based on analysis of diatom complexes and the pollen and spores of aquatic and aquatic-subaquatic plants and Pediastrum algae. The data obtained show that minerogenic sediments were abruptly succeeded by organic in the late Preboreal-early Boreal period. The thickness of Boreal sediments and changes in the composition of diatom complexes and spore-and-pollen spectra suggest a depositional hiatus triggered by a strong earthquake which changed the water level of the pond and its basin structure. The earthquake is also indicated by numerous dismembered, displaced, thrown-away and shifted rock blocks and seismogravity downfalls. Deflation and other types of weathering are responsible for the formation of seide-shaped piles of blocks and boulders on the mountain top.

Keywords: *paleoseismic dislocation; sediment record; pollen, diatoms; vegetation changes; Pleistocene; Holocene*

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INTRODUCTION

Traces of postglacial seismic activity in Fennoscandia have been actively studied in the past few decades (Morner 1985, 1989; Kuivamäki *et al.* 1998; Lagerback, Sundh 2008; Osmundsen *et al.* 2010; Morey *et al.* 2013; Nikolaeva *et al*. 2016, 2017, 2018; Shvarev *et al.* 2018; Shvarev, Rodkin 2017, 2018; Poleshchuk, Shvarev 2018). Karelia, like the entire Fennoscandian Shield, is a region which displays weak seismicity with a magnitude of 2–3 of earthquake intensity on MSK-64 scale (Lukashov 2004).

Paleoseismological studies were conducted earlier in Karelia by Lukashov (1976, 1987, 1993, 1994, 1995, 2002, 2004) and Lukashov and Belashev (2002) to reveal more vigorous seismic processes that those observed in the present history and to obtain more evidence on seismic events. Attempts were made to shed light on the seismic genesis of geological and geomorphological localities, such as paleoseismic dislocations by analyzing available geological, geophysical and geomorphological data, deciphering aerial photos, identifying structures and faults with signs of Holocene movement activation and conducting aerovisual and field studies of the target areas. As a result, Lukashov (2004) has revealed all types of local seismic deformations (seismotectonic, gravity-seismotectonic and seismic-gravity) in Karelia described earlier in the literature. In addition, he has identified the most essential features of their seismic genesis, indicating that they are confined to faults with signs of Holocene movement activation (fault, extension fault and shear disturbances of glacial exaration forms in the bedrock, deformations of the longitudinal profiles of rivers and bank levels, etc.). Seismotectonic and seismo-gravitational rocks concentrated in small areas were combined to form paragenetic groups.

Karelia has eight zonal paleoseismotectonic domains: 1– Ladoga, 2 – Onega, 3 – Nyukhcha, 4 – Segozero, 5 – Lehta, 6 – Kalevala 7 – Paanajärvi and 8 – Kandalaksha. The Ladoga, Lehta, Kalevala, Paanajärvi and Kandalaksha domains were found to host the epicenters of modern earthquakes (Fig. 1).

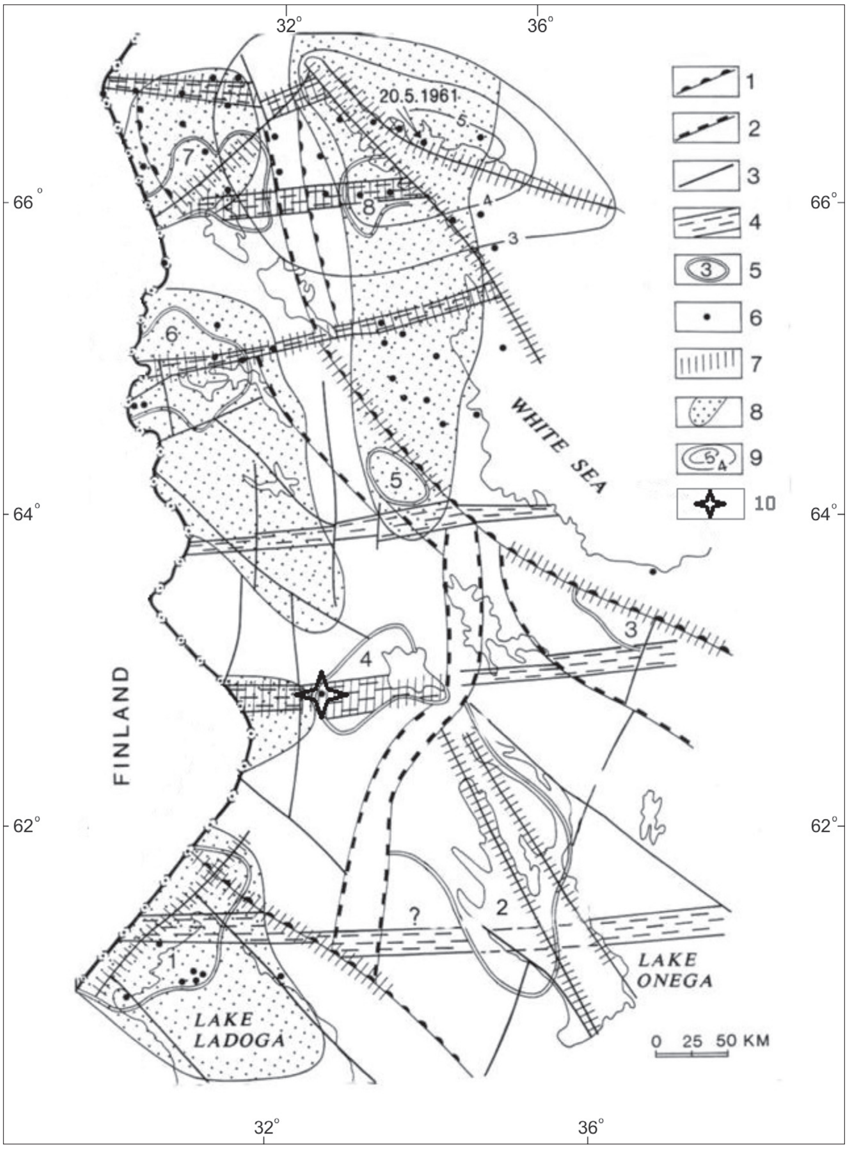

Fig. 1 Outline map of seismic zones in Karelia (Lukashov 1995) and location of the investigated territory. 1 – intrageoblock deep fault zones; 2 – intrablock deep fault zones; 3 – innerblock zones of deep faults; 4 – fault zones active before the Proterozoic; 5 – borders of local paleoseismic domains; 6 – epicentres of modern earthquakes (Panasenko 1980); 7 – zones of probable earthquakes (zones of 7 and over 7 points of intensity (MSK-64)); 8 – probable centres of low activity earthquakes deduced from analysis of geological and geophysical data (Ivanovskaya *et al*. 1988); 9 – isoseists of earthquakes in Kandalaksha Bay, White Sea 20.05.1967, intensity of 5 and more points (MSK-64) (Panasenko 1980; Ananjin 1980); 10 – location of the investigated territory. Numbers on the map refer to the names of paleoseismotectonic domains: 1 – Ladoga; 2 – Onega; 3 – Nyukhcha; 4 – Segozero; 5 – Lehta; 6 – Kalevala; 7 – Paanajärvi; 8 – Kandalaksha

Paleoearthquakes in Karelia had a magnitude of at least 7–8 (Lukashov 1995, 2004).

Zonal paleoseismic structures are associated with Precambrian mobile-permeable zones that display contrasting, differentiated neotectonic movements. They have inherited sags of synclinorium type that formed and evolved for a long geological time. Superimposed troughs, graben-synclines and grabens evolved in these sags at late stages (Lower Proterozoic – Riphean). Paleoseismic and modern seismic structures are similar in geodynamic and structural geological characteristics.

Mount Vottovaara attracts scientists who study local paleoseismic dislocations of postglacial age. It is a site of geological value, where glacial landscape formation processes are well defined on the big uplifted scarps of the crystalline basement with a thin morainic cover dominated by water and glacial erosion and frost weathering, creating a unique landscape with numerous huge chaotically scattered boulders and blocks molten out of basic moraine onto the basement surface. It is a model area with sites that look like "seides" (Fig. 2). Their formation mechanism should be studied to be able to distinguish them from archaeological structures.

Fig. 2 "Seides" – the boulders and blocks molten out of basic moraine onto the basement surface

The present paper is based on the results of integrated geological, geomorphological, neotectonic and paleogeographic studies conducted in various periods of time and available in the literature (Lukashov 1995; Lavrova, Demidov 1997; Shelekhova 1999; Lukashov 2002, 2004; Shelekhova, Lavrova 2009). The authors of the article presented updated palynological and diatom data. The results are an important addition to the available data. The study of sediments was carried out using lithological, radiocarbon and micropaleontological methods. They allowed us to more correctly reconstruct the paleogeographic conditions on Mount Vottovaara.

One of the most essential tasks in studies of the paleoseismic dislocations is to determine their age. Therefore, bottom sediments from the lake confined to seismic structure were studied and the age at which organic sediments associated with the time of opening of this structure began to accumulate in it was estimated.

STUDY AREA

The investigated lake is located near the top of Mount Vottovaara, which is the highest peak of the West Karelian Upland (417.2 m a.s.l.; N 63° 04′ 27′′; E 32° 37′ 32′′) where disastrous geological events at the Pleistocene-Holocene boundary during the degradation and melting of the last ice sheet occurred (Fig. 2).

Mount Vottovaara is a ridge which extends approximately N–S over about 7 km, consists of Jatulian quartzite and quartzite sandstone and is broken by numerous faults that seem to have been rejuvenated in postglacial time. The denudation surface relief is highly rugged, the top surfaces are subdued by erosion and their relative altitudes are up to 157 m (Lukashov 2004). In the Quaternary period, the crystalline rock surface was considerably transformed by multiple glaciations. It seems that traces of the last Valday (Ostashkovo) glaciation, such as *roche moutonee*, glacial grooves, ruts and scars, are most conspicuous there. It is a big shaking dislocation with a pit, 300 × 300 m in size and a depth of up to 6 m, on top.

The geological evolution of the area falls into three stages: 1) pre-Quaternary, when an uplifted block, broken into numerous fractures and faults, was formed, 2) glacial and 3) postglacial. The glacial stage is divided into subglacial and periglacial stages (from 24,000 to 11,000 ^{14}C yr BP, when coarse clastic moraines were formed and ice movement was accompanied by glacial polishing of the crystalline basement surface and the formation of glacial scars (Demidov 1997; Demidov *et al.* 1998). During the last glaciation the Vottovaara Ridge was part of an ice-divide zone between Lake Onega and Lake Ladoga ice flows. The fact that it is considerably uplifted suggests that it impeded ice movement at the final stages of deglaciation. Its top remained a nunatak, a rocky island along which a glacier, tens of meters in thickness, was moving. About 11,000 ^{14}C yr BP, the continental ice retreated from the mountain. Approximately 10,800 ^{14}C yr BP, the ice margin was about 40 km NW of the mountain, near Salpausselkä I marginal moraines. A periglacial stage in the environmental evolution of this area began. About 10,200 ^{14}C yr BP, marginal Salpausselkä II moraines were already 70 km NW of it (Shelekhova, Lavrova 2009). These events were followed by a postglacial stage in the evolution of the area. Mount Vottovaara is now located at the boundary between northern and middle taiga subzones and is part of the West Karelian District dominated by pine forests. The top of the mountain is covered with forest-tundra vegetation.

The average annual precipitation is less than 500–700 mm on the study area. Average temperature is –12–13ºC in January and +14–15ºC in July. At the top of the mountain, loose sediments are almost completely absent. At the foot of the slopes dominated podzol soil (Gromtsev 2009).

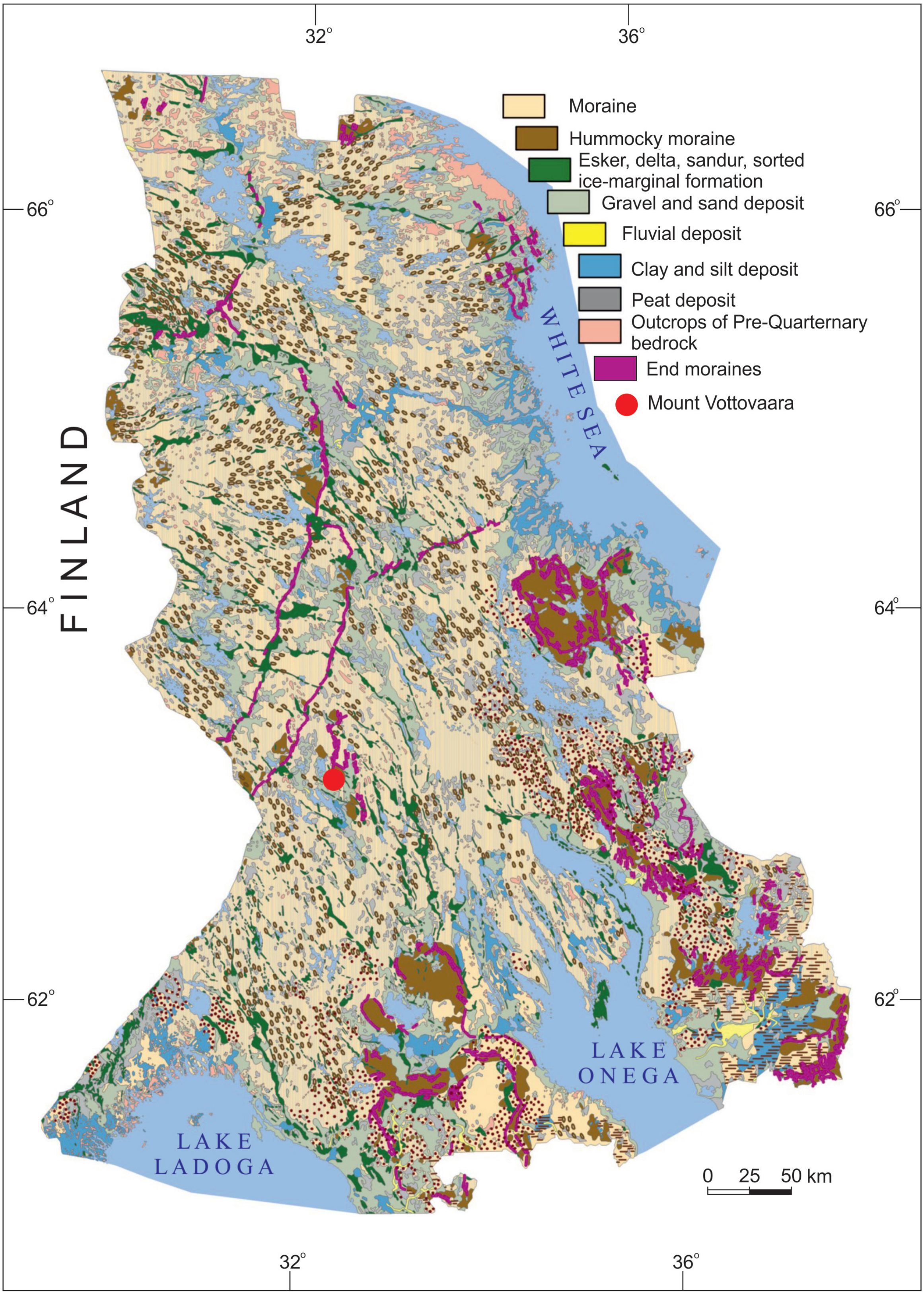

Fig. 3 Location of Mount Vottovaara on the map of Quaternary deposits (Niemela *et al*. 1993; simplified version)

MATERIALS AND METHODS

Coring and sampling

Field work, coring and sediment description were carried out during summer field campaigns in 2004–2006. A borehole drilled in the mire that surrounds the lake is situated 300 m south-westwards from the top of the mountain in the lowering of the crystalline basement which has the form of the amphitheatre. The walls and bottom of the latter are damaged by a number of seismodis locations of the postglacial age (seismoslides, collapse holes, crushed and dislocated blocks, etc.) (Demidov *et al.* 1998). A borehole was drilled with the use of the 'Russian' corer (a 100 cm long chamber with a diameter of 5 cm). The coring in the peat-bog gives the following stratigraphy: 0–230 cm – liquefied, gyttja-like peat suspended in water; 230–275 cm – peat; 275–302 cm – gyttja with plant remains; 302–308 cm – brownish-grey silt with plant remains; 308–360 cm – grey clayey silt. Samples collected at a depth of 230–350 cm and spaced 250–200 cm apart (250–350 cm apart for diatom analysis; lit-par-lit, 5–10 cm apart) were subjected to spore-and-pollen analysis. Unfortunately, gyttja-like peat at a depth of 0–230 cm was too liquefied to take samples. Therefore, the paleoenvironment of sediment formation for the entire sedimentary sequence has not been reconstructed. A total of 38 samples were taken for micropaleontological studies.

Pollen analysis

Samples for pollen analysis were prepared using the method of Grichuk (1940) based on separation by heavy liquid (CdI_2 + KI). Calculation of relative pollen frequency was based on the total pollen sum, spores were excluded. A minimum of 500 pollen grains per sample were counted and pollen diagrams were constructed using the programs Tilia and Tilia Graph (Grimm 1990). Pollen identification was based on Moore *et al*. (1991). The diagram (Fig. 4) was subdivided in accordance with models for Late Pleistocene and Holocene time (Khotinsky 1977, 1987).

Diatom analysis

The fossil diatom flora was studied in a 120 cm long sediment core (depth 230–350cm), from which samples were taken layer by layer at 2.5, 5, 10 cm intervals. Diatom analysis was performed on 19 samples. Sample processing included treatment with Na_{2}-P_3O_{10} and solution of heavy liquid CdI_2+KI (specific gravity – 2.6) followed by washing with distilled water. The slides were mounted with aniline-formaldehyde tar with refraction index of 1.68. Diatoms were indentified with a light microscope "Jenaval" (Carl Zeiss Jena) at 1000 × magnification under oil immersion. The diatom taxonomy was based on Krammer and Lange-Bertalot (1986–1991) and Loseva (2000).

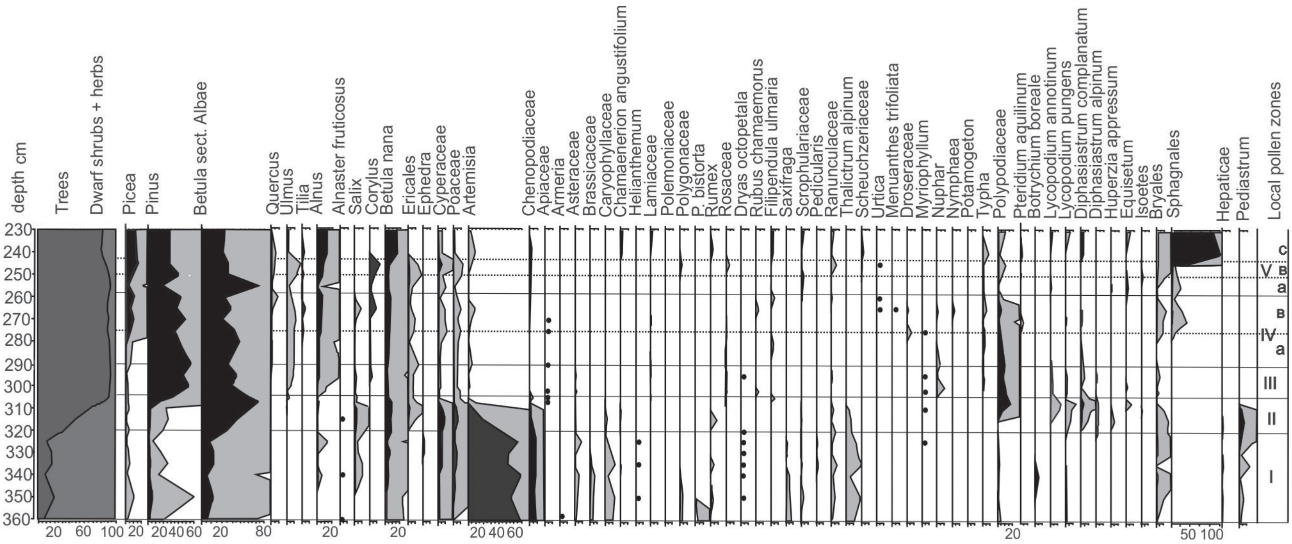

Fig. 4 Spore-pollen diagram of bottom sediments of the lake on Mount Vottovaara. Compiled by N. Lavrova, 2019

Table 1 Results of the radiocarbon (^{14}C) dating

Location	Lab. code	Type of sample	Depth, cm	^{14}C age (yr BP)	68% probability (cal yr BP)	Mean calendar age ± 1σ (cal yr BP)
Vottovaara	SU-2824	gyttja	295–302	8920 ± 60	9940–10158	10049 ± 109
Pizanets	TA-1742	gyttja	458–462	8500 ± 150	9318–9675	9497 ± 178

Radiocarbon (^{14}C) dating

The absolute age of sediments from Mount Vottovaara was determined by radioactive carbon method (^{14}C) at the Radiocarbon Laboratory of the Geological Survey of Finland (laboratory index SU-) (Table 1). A sample from the Pizanets District was dated in the laboratory of the University of Tartu (laboratory index TA-). For the calibration of dates http://www.calpal-online.de was used.

RESULTS AND DISCUSSION

Results

A model showing the evolution of geological processes and vegetation during the retreat of the continental ice from the area and climatic changes in the Late Pleistocene-Holocene is based on the study of lacustrine-mire sediments surrounding a small lake located in a seismogenic basin near the mountain top.

Pollen analysis

The evolution of the plant cover and lake, shown on a spore-and-pollen diagram (Fig. 3) and based on the results of the palynological study of bottom sediments, was traced. The data obtained were used to estimate the relative age of the sediments.

Local pollen assemblage zone I (LPAZ I) corresponds to the time of grey clayey silt accumulation at a depth of 360–320 cm. The palynological spectra display a well-defined periglacial pattern. LPAZ I is dominated by herbaceous plant (mainly *Artemisia*) pollen (60–70%). Tree plant pollen dominated by *Betula* sect. Albae makes up only 13–24%. Poaceae and Cyperaceae pollen occur in small quantities. Spore-bearing plants are dominated by Bryales. The presence of the pollen of heliophytes (*Ephedra* and *Helianthemum*) and cryophilic species, growing now in areas with colder and continental climates (*Thalictrum alpinum* and *Alnaster fruticosus*), is noteworthy. The composition and ratio of the main constituents of the spectra suggest that the spore-and-pollen spectra for this zone were formed in the Younger Dryas 11,000–10,300 ^{14}C yr BP (12,900–11,700 cal yr BP).

LPAZ II in the sediments was identified at a depth of 320–304 cm. It consists of grey clayey silt and a thin brownish-grey silt layer with plant remains. The LPAZ I-LPAZ II boundary (Fig. 3) is drawn at a level above which the amount of woody plant (dominated by *Betula* sect. Albae) pollen begins to grow rapidly, the Poaceae (including *Phragmites*) and Cyperaceae pollen and Lycopodiaceae, Polypodiaceae spore curves go up and the amount of *Artemisia* pollen decreases. *Pediastrum* colonies are abundant. Brownish-grey silt spectra display scarce *Myriophyllum* and *Potamogeton* pollen grains.

LPAZ III was identified in sediments consisting of gyttja with plant remains (304–290 cm). The contact between the gyttja and underlying silt is well-defined. The boundary between the pollen zones is drawn at a level above which woody species pollen predominate totally. The spore-and-pollen spectra typically display an increase in the abundance of *Pinus* pollen due to a reduction in *Betula* sect. Albae. The solid curve on the diagram (Fig. 3) is formed by *Alnus* pollen; *Ulmus* pollen grains were encountered. Herbaceous plant spectra display an increase in Poaceae (including *Phragmites*), Ericales and motley grass pollen, while *Artemisia* disappears practically. The amounts of hygro- and hydrophyte (*Nuphar, Typha latifolia, T.angustifolia, Sparganium* and *Myriophyllum*) pollen and Polypodiaceae spores increase rapidly. The spore-and-pollen spectra show substantial changes in the plant cover in the Boreal period 9300–8000 ^{14}C yr BP (9900–9200 cal yr BP).

LPAZ IV a (depth 290–275 cm) and IV b (depth 275–258 cm) were identified in overlying gyttja and peat. They are similar in the increased contribution of thermophilic species (*Ulmus*, etc.) pollen, indicating that the spore-and-pollen spectrum was formed in the Atlantic period 8000–4600 ^{14}C yr BP (8800–5300 cal yr BP). The BO/AT boundary was drawn above the *Pinus* pollen maximum; a rise in the *Alnus* (including *Almus glutinosa*) pollen curve, the occurrence frequency of broad-leaved species and *Corylus* pollen coincide with it. The pollen subzone is distinguished by a high pollen content of Ericales, Poaceae and some other herbaceous plants.

The spore-bearing species group is dominated by Polypodiaceae. The contribution of *Betula* sect. Albae pollen to the spore-and-pollen spectra of LPAZ IV increases, while that of *Pinus* pollen in LPAZ IV b increases again (57%). In addition, the contribution of Sphagnales at the gyttja-peat contact increases. Curiously, mire species, such as Droseraceae, *Rubus chamaemorus* and *Menyanthes trifoliate*, grow there.

LPAZ Va, identified in the peat (depth 258–250 cm), displays a decline in broad-leaved species and *Alnus, Corylus* and *Picea* pollen indicative of an abrupt cooling event in the early Subboreal period (SB-1). Woody plant spectra are dominated by *Betula* sect. *Albae* pollen and herbaceous spectra by *Cyperaceae* pollen; the contribution of sucspore-bearing species as Sphagnales has increased. The increased contribution of thermophilic plant pollen in the next LPAZ Vb is consistent with a Subboreal warming event (SB-II).

LPAZ Vc displays a marked increase in Sphagnales spores, which seems to be due to mire transition to the oligotrophic stage of evolution. The spore-and-pollen spectra of this pollen zone could have been formed in the late Subboreal period (SB-3). It has been noted above that we have failed to take samples from the liquefied gyttja-like peat layer (depth 0–230 cm) which seems to have been deposited in the Subatlantic period (SA).

Diatom analysis

In total, 115 diatom species from 15 genera were identified in all investigated samples. Five local diatom assemblage zones (LDAZ) corresponding to the paleoclimatic periods of the late glacial and Holocene were identified according to changes in the composition of diatom species in the sediment section of a small lake (Fig. 5).

Local diatom assemblage zone (LDAZ) I (350–315 cm) corresponds to the Younger Dryas (Fig. 5). At this time, it is accumulated of grey clayey silt. A cold climate at that time is also indicated by the composition of diatom complexes in the sediments (Shelekhova 1999). The complexes consist of very small arctoboreal (arcto-alpine and boreal) forms that invade water bodies after ice retreat (species of the genus Fragilaria *sensu lato*, *Gomphonema* sp.*, Caloneis bacillum, Achnanthes* sp., *Diploneis* sp., *Navicula pseudoscutiformis and Nitzschia* sp.).

LDAZ II (depth 315–307 cm): The composition of the diatom complex at that time (Fig. 5) indicates that the species of the genus Fragilaria *sensu lato* predominate (90%), while formerly prevalent species become either scarce or disappear completely. This evidence suggests that the climate became warmer and the lake was heated to great depths under warmer conditions in the Preboreal period.

LDAZ III (depth 307–295 cm): The above plant distribution pattern is also evidenced by the rapid succession of the predominant diatom complex indicative of a rapid decline in the water level of the lake the composition of which is typical of a shallow water body fed by atmospheric precipitation. Arctoboreal species, adaptable to an acid environment (*Frustulia saxonica, Caloneis bacillum, Neidium* sp., *Anomoeoneis brachysira, Pinnularia interrupta, P. microstauron, Gomphonema* sp., *Eunotia* sp., *Stenopterobia intermedia*), evolved in a poorly mineralized water environment, suggesting that narrow near-shore and the lowest sites were gradually paludified. Diatom flora evolved gradually and plant groups succeeded each other without rapid changes as far as the Preboreal-Boreal boundary, and sedimentation was slow but continuous (the water level of all Karelia's water bodies in the Boreal period declined).

LDAZ IV (depth 295–260 cm): Diatom analy-

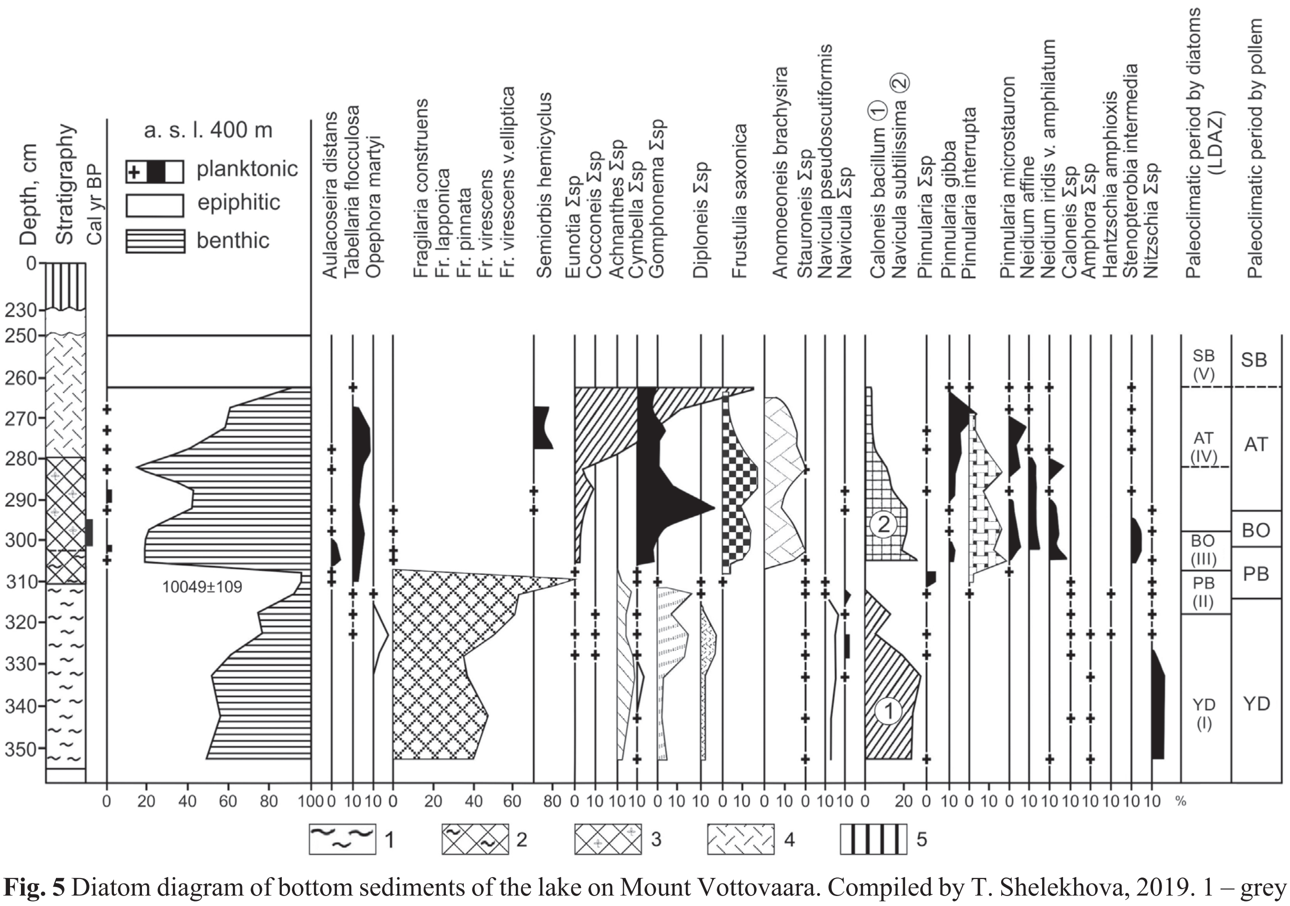

Fig. 5 Diatom diagram of bottom sediments of the lake on Mount Vottovaara. Compiled by T. Shelekhova, 2019. 1 – grey clayey silt; 2 – brownish-grey silt with plant remains; 3 – gyttja with plant remains; 4 – peat; 5 – gyttja-like peat

sis has shown that the species diversity of the diatom complex, consisting of the species of the genera *Cymbella* sp., *Frustulia saxonica, Anomoeoneis* sp., *Caloneis bacillum, Pinnularia gibba, P. microstauron, Neidium affine and N. iridis var.amphilatum*, increased considerably in the Atlantic period. Paludification processes had become more vigorous by the end of this stage, as indicated by the predominance of typically mire species of the genus Eunotia (over 90%). This evidence is consistent with the results of spore-and-pollen analysis.

LDAZ V (depth 260–250): The absence of diatom flora in peat samples from a depth of 258–250 cm is indicative of the m ire evolution in the Subboreal period and supports the results of spore-and-pollen analysis.

DISCUSSION

The results of palynological studies, diatom analysis and radiocarbon dating allowed us to trace the history of the development of a small lake, vegetation and the territory surrounded by Mount Vottovaara.

According to the data obtained, a low concentration of pollen and spores, the abundance of pollen of herbaceous plants, especially xerophytes, suggests that spore-and-pollen spectra for LPAZ I were formed in the Younger Dryas (11,000–10,300 ^{14}C yr BP/12,900–11,700 cal yr BP). At that time, the study area was dominated by periglacial wormwood-goosefoot xerophilous communities, while the proportion of tundra dwarf arctic birch-green moss species in the plant cover was much smaller. Low pollen concentrations suggest that the plant cover was not dense, alternating with bare ground patches. As there was no dense plant cover, silt and clay were washed down into the lake, but its position on the mountain top was responsible for slow sedimentation.

The data obtained show that the spectra LPAZ II were formed in the Preboreal period (10,300–9300 ^{14}C yr BP / 11,700–10,500 cal yr BP), suggesting the considerable restructuring of the plant cover. As the climate grew markedly warmer, periglacial communities became less abundant and were replaced by forest communities. At that time, the study area was dominated by thin birch forests followed by thinned birch forests of north-taiga appearance. Communities with the ground fern cover were confined to the foot of the ridge, while club-moss formed the ground cover in forests growing on slopes.

The abundance of *Pediastrum* algae and possibly some moss species in the lake suggests the existence of a small deep lake, the shoreline of which began to overgrow with reed and sedge. As sedimentation continued and the lake became shallower, plants submerged into the water (pondweed and water milfoil) invaded the lake. Mineral sediments are enriched in organic matter composed mainly of phytoplankton and partly of poorly decomposed macrophyte remains. The low layer of the sediments seems to be due to extremely slow sedimentation. Addition of terrigenous material was retarded by a dense plant cover, and the accumulation of organic sediments was impeded by a cold climate. The abundance of macrophyte pollen indicates a significant decrease in the lake level. Thus, the periglacial pattern of the palynological spectra and the arctoboreal diatom flora complex are indicative of a very cold climate, which was due to the proximity of the retreating ice margin. About 10,200 ^{14}C yr BP, Mount Vottovaara was completely ice-free, because at that time Salpausselkä II marginal sediments were 70 km NW of it (Lukashov 2004). A postglacial stage in the evolution of the area, reflected higher in the sequence, commenced.

Boreal vegetation typically displays a dense forest canopy. Birch, green-moss and tall-grass pine forests spread on hill slopes. It seems that on reaching a certain altitude above sea level, the forests became thinner and looked like elfin woodland at the forest margin. The abundance of macrophyte pollen indicates a considerable decline in the lake water level. Plants with floating leaves (yellow water lily), commonly growing at a depth of 2–3 m, were major contributors to overgrowing. The vigorous growth of macrophytes was conducive for the formation of coarsely detritic gyttja typical of runoff-free shallow water bodies.

The above plant distribution pattern is also evidenced by the rapid succession of the predominant diatom complex indicative of a rapid decline in the water level of the lake the composition of which is typical of a shallow water body fed by atmospheric precipitation. Arctoboreal species adaptable to an acid environment (*Frustulia saxonica*, *Navicula subtilissima*, *Neidium* sp., *Anomoeoneis brachysira, Pinnularia interrupta, P. microstauron, Gomphonema* sp., *Eunotia* sp., *Stenopterobia intermedia*) evolved in a poorly mineralized water environment, suggesting that narrow near-shore and the lowest sites were gradually paludified. Diatom flora evolved gradually and plant groups succeeded each other without rapid changes as far as the Preboreal-Boreal boundary, and sedimentation was slow but continuous. This phenomenon is due to a decrease in the level of the lake, characteristic of the lakes in the Boreal. The results of the diatom analysis (epiphitic taxa, which dominated earlier, were replaced by benthic forms) and a sharp change in the genetic type of sediments (from grey clayey silt to gyttja with plant remains) suggest that the fall of the lake level occurred due to a catastrophic event. Attention should be paid to changes in the species composition of diatom flora. It is represented by species that had not previously developed in the lake, such as *Navicula subtilissima, Neidium iridis var. amphilatum,* etc. (Fig. 5).

On the basis of data from many studied sections of Karelia (Shelekhova 2000; Vasari *et al.* 2007), it is known that with a decrease in the level of lakes in the Boreal, the species composition never changes drastically and significantly. There was a sharp increase in the amount of pollen *Betula* sect. *Albae*, an increase in the curves of pollen of Phragmites, Cyperaceae, Typha, Nuphar, Potamogeton, etc. Thin sediments together with abrupt changes in lithology, spore-and-pollen spectra and diatom complexes suggest a depositional hiatus in the late Preboreal-early Boreal as a result of an earthquake.

Radiocarbon analysis of the gyttja which deposited in the lake after the hiatus (depth 310–300 cm) has shown that it began to accumulate in the Boreal period (8920 ± 60 ^{14}C yr BP; Table 1). This gap in sedimentation and numerous traces of seismic dislocations suggest that gyttja formation was triggered by a strong earthquake which struck the area in the late Preboreal-early Boreal period (the sediment sequence is shown in Fig. 5). The earthquake could have been brought about by the degradation of the Late Valday Glaciation and the rapid removal of the ice load which contributed to the rejuvenation of various old faults. The paleoseismic dislocation was undoubtedly formed in postglacial time, as indicated by extensive evidence. For example, dislocations, occurring as steep walls with fresh rugged surfaces, traces of rock crushing and the detachment of massive rock blocks, are encountered on the surface of the different slopes of the mountain. Rapid pulse-like landscape evolution processes are indicated by numerous dismembered blocks shifted relative to each other; thrown-away and displaced rock blocks; seismic-gravity downfalls indicated by blocks similar in the degree of weathering or overgrowing with lichens; blocks detached from the scarp wall so that a niche was formed, cracks; gaping extension joints in the basement; crushed ice-processed *roche moutonee* surfaces with fresh fractures; “fresh” fault scarps; fractures extending along the mire bottom; and a seismogenic pit with a lake in the centre.

Outside the pit, Jatulian quartzites are massive, while within the pit they are broken into numerous blocks displaced in height and laterally relative to each other. Outside the paleoseismic dislocations the glacial scars are oriented in one direction, SE – 120°, typical of this part of the region, but glacial scar orientation in the pit is different from the normal one by 30–40 degrees, indicating damage to the surface polished by the glacier. The lower magnitude limit, at which shaking deformations occur, is at least 6–7 (on MSK-64 scale) (Nikonov 1995). Seismic deformations in the Vottovaara Ridge could have occurred at the Preboreal-Boreal boundary, as indicated by the occurrence of similar forms in the same seismogenic structure 26 km NE of Mount Vottovaara in Lake Pizanets (Lukashov 2004). There, in the near-fault lake basin, seismic-gravity downfalls, up to 150 m in width, rest on fluvioglacial delta and esker sediments, clearly indicating the postglacial; time of their formation. Furthermore, the radiocarbon date obtained in this area for the formation of overlying gyttja (8500 ± 150 ^{14}C yr BP; Table 1) is also similar to that obtained for MountVottovaara. Thus, the similar age of Mount Vottovaara and Lake Pizanets deformations confined to the same seismogenic structure could show that they were formed simultaneously (Lukashov 2004).

Our data show that the residual lake continued to be overgrown by pondweed, cattail and yellow pond-lily. The sediments became thicker, and further shallowing was accompanied by the spreading of horsetail, sedge and reed. The water-free shores were invaded by wormwood, goosefoot and heather. Increased atmospheric precipitation in the Early Atlantic time contributed to the washing-down of organic-humus matter and plant remains into the lake. This, together with the deposition of autochthonously derived gyttja resulted in the filling-up of the lake basin and the beginning of peat deposition in the late Atlantic period. Mire vegetation consisted of peat-forming species such as Sphagnum mosses, reed, sedge and horsetail; gooseberries, bogbean and sundew were encountered.

In the early Atlantic period, the study area was covered by mid-taiga pine and pine-birch forests with alder and a minor contribution of thermophilic species. Spruce appeared in the forests in the late Atlantic period. Spruce stands are confined to the foot of the mountain ridge. Green-moss and less commonly tall-grass pine and birch-pine forests, where elm, lime, hazel-nut and alder were occasionally encountered, grew on drier slopes.

In the early Subboreal period, forests were dominated by birch, while the contribution of lime, elm, hazel-nut and alder decreased markedly. A more recent warming event triggered the spreading of mainly green-moss mid-taiga pine and spruce-pine forests. Sphagnum pine and birch stands grew on the mire margin, while its centre was invaded by sedge, Scheuchzeria and Sphagnum moss communities. The absence of diatom flora in peat samples from a depth of 258–250 cm is indicative of the mire evolution in the Subboreal period.

CONCLUSIONS

Thus, the studied lake began to form in the Younger Dryas (ca 10,800 ^{14}C yr BP) after the retreat of the ice margin from Mount Vottovaara. Its further evolution displayed variations in water level, eutrophication and filling with organic-mineral sediments. Their composition and thickness depend not only on the native characteristics of the watershed but also on neotectonic movements. Mineral sediments were deposited during the Younger Dryas and the Preboreal. In the Boreal time and in the early Atlantic period, the water level declined considerably, the climate became warmer and gyttja was formed in the lake. The vigorous overgrowing and shallowing of the lake in the late Atlantic period are responsible for its degradation and transition to a mire stage of evolution, the onset of peat deposition.

It should be noted in particular that an earthquake could have occurred at the Preboreal-Boreal boundary (8920 ± 60 ^{14}C yr BP / 9940–10158 cal yr BP), when a local paleoseismic deformation occurred (Demidov *et al*. 1998; Shelekhova, Lavrova 2009), which is confirmed by micropaleontological data. Recently, paleoseismic dislocations on the top and slopes of the mountain have been studied in detail (Shvarev, Rodkin 2017, 2018). However, no new data have been obtained on the dating of paleoseismological events and the paleogeographic conditions of their formation. Besides, we think that numerous huge boulders on the mountain top, resting on "stone feet" (smaller boulders), were created by natural processes as a result of exaration that occurred mainly during the last glaciation, as well as erosion, frost weathering and paleoseismic tectonics. Boulders and blocks were molten out of basic moraine and found themselves "resting on feet" as a result of the removal of the unconsolidated material beneath them by water and wind. However, many merely rest on the basement surface. Most of the so-called "seides" are not real seides. Therefore, due to the special interest in such unique objects, there is a need for their detailed study and preservation for future generations.

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