GEODYNAMICS & TECTONOPHYSICS
Published by the Institute of the Earth's Crust, Siberian Branch, Russian Academy of Sciences

RECENT GEODYNAMICS

2022 VOLUME 13 ISSUE 5 ARTICLE 0676

ISSN 2078-502X

DOI: 10.5800/GT-2022-13-5-0676

TRACES OF SEISMIC ACTIVITY IN THE LAKE BOTTOM SEDIMENTS OF EASTERN FENNOSCANDIA

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ABSTRACT. This paper presents the results of a study on traces of ancient earthquakes in the lake bottom sediments of eastern Fennoscandia (Kola region and Karelia). Based on the sediment cores from six lake basins located within large active structures of the region, consideration is being given to the most typical features of sedimentation affected by neotectonic movements of the Earth's crust. The data presented here provide lithological-stratigraphical, paleobotanical and chronometrical evidence for lakes. The paper causes and mechanisms of formation of seismic structures in bottom sediments and their distinction from deformations of another origin.

Generalized earthquake history in provided an opportunity to organize the existing information on the time of paleoearthquake manifestations and distinguish three active periods in paleoseismicity. These are Late Glaciation-Early Holocene marked by the most rapid uplift after the retreat of the last ice sheet (13500–8100 cal yr BP), Middle Holocene (6800–6600 cal yr BP), and Late Holocene (3100–200 cal yr BP). The results of this study showed that the number and intensity of seismic events changed at different stages of sedimentation. Since the Younger Dryas, fault zones (or their segments) have been repeatedly activated. Combined with the data on paleoseismicity in adjacent parts of Fennoscandia, our studies indicate an irregular pattern of the Late Pleistocene-Holocene seismic activity in stable areas formerly covered by glaciers. The obtained data make further adjustments to the neogeodynamic and seismic estimates of intraplate areas.

KEYWORDS: earthquake-induced deformation; earthquake; bottom sediment; lake; fault; Fennoscandian Shield; Kola region; Karelia; Holocene

FUNDING: The research was carried out under research topics of the Geological Institute of the Kola Science Centre of the Russian Academy of Sciences (project AAAA-A19-119100290145-3).

RESEARCH ARTICLE

Received: December 10, 2021
Revised: February 8, 2022
Accepted: February 14, 2022

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FOR CITATION: Nikolaeva S.B., 2022. Traces of Seismic Activity in the Lake Bottom Sediments of Eastern Fennoscandia. Geodynamics & Tectonophysics 13 (5), 0676. doi:10.5800/GT-2022-13-5-0676

1. INTRODUCTION

The Fennoscandian (Baltic) crystalline shield is now considered as a part of the large Scandinavian seismotectonic province with regular, postglacial isostasy-related, attenuated seismicity referring to weak earthquakes and microearthquakes as well as to rare large earthquakes [Stepanov, 2001; Yudakhin et al., 2003]. Instrumentally recorded low-level earthquakes have long been recognized as a basis for plotting the Russian part of Fennoscandia (Murmansk Region and Karelia) on seismic zoning maps as almost aseismic. The situation began to change in early 1990s, when the evidence for great Holocene earthquakes started to appear over the entire Fennoscandia [Lagerbäck, 1992; Lukashov, 1995; Nikolaeva, 2001; Mörner, 2004; Lagerbäck, Sundh, 2008; Olesen et al., 2013; Sutinen et al., 2018; Smith et al., 2014; Shvarev, Rodkin, 2018; Nikolaeva et al., 2021b, 2021c]. The results of these and other current research studies were published in 2020 as part of "International database of Glacially Induced Faults" containing data on all the late glacial and post-glacial faults and their related paleoearthquake sources reported to date [Munier et al., 2020].

In the light of incoming information about the Holocene seismicity of Fennoscandia, the determination of earthquake age and, therefore, of fault activation time is still poorly explored subject. Solving this problem is of scientific and practical importance, especially for the Kola region, in which critical infrastructure (Nuclear Power Plants, Hydroelectric power plants and others), closed administrative-territorial formations and mining enterprises are located.

One of the most important sources of information on the timing of Holocene seismic events is the study of lake bottom sediments. The sediments yield climate records and records of dynamic natural environments, in particular of different types of catastrophic events. Among the latter are tsunamis, seiches, underwater landslides, and turbidity currents caused by earthquakes. Traces of earthquakes in sediments or "soft sediment deformation structures" (SSDS) [Seilacher, 1969; Owen, Moretti, 2011; Moretti et al., 2014] are the evidence for seismic activity of the areas in the past.

At the beginning of paleoseismological studies in Fennoscandia in the late XX century [Lukashov, 1995; Demidov et al., 1998], evidence began to accumulate, showing the traces of seismic events in the lacustrine sediments of Karelia. To date, these investigations have been expanded along with the study of seismic deformations in rocks; there is also data illustrating seismically induced structures in sedimentary cover, including those in the lake bottom sediments of the Kola region [Nikolaeva et al., 2017, 2019; Tolstoborov et al., 2018, 2019]. A relatively thin sediment cover, comprising primarily an organic-poor glacial deposit, shifts the focus of attention to the lake bottom sediments whose high organic content, unlike low organic matter contents in bedrock, provides good opportunities for dating of seismic events.

The paper reports recently obtained data on traces of the Holocene earthquakes in lakes. Based on the sediment cores from six lake basins located within large active structures of the region – Karpinsky lineament, Kandalaksha graben in the water area of the White Sea, post-tectonic Lake Imandra basin and West Onega seismic lineament, – consideration is being given to the most typical features of sedimentation affected by neotectonic movements of the Earth's crust. The lithological-stratigraphic analysis emphasizes the scrutiny of SSDS formation mechanisms and identification of seismogenic features in sediments. Based on the published age data of paleoearthquakes in western Fennoscandia – Sweden, Finland and Norway, – the present paper discusses an irregular pattern of Late Pleistocene-Holocene seismic activity in stable areas, formerly covered by glaciers.

2. ACTIVE TECTONIC STRUCTURES OF EASTERN FENNOSCANDIA AND SEISMICITY

The Fennoscandian (Baltic) Shield is a large protrusion of the Archean-Proterozoic basement at the northwest of the East European Platform. This area is characterized by heterogeneity involving a well-defined block structure, variation of crustal thickness and nature of magnetic and gravity fields, which largely determines neo- and present-day lithospheric regime in the region [Yudakhin et al., 2003]. One of the regional-specific features is the attenuation of glacial isostatic uplift of the continent whose rate and amplitude were different in various parts of the region [Stroeven et al., 2016]. This lasted from the end of the Late Pleistocene through the Holocene. During glacial and deglacial periods in the region, there occurred crustal stresses which could cause earthquakes.

Fig. 1, a shows major seismic lineaments and active faults of the Kola-Karelia [Nikonov, Shvarev, 2015; Nikolaeva et al., 2021b]. The most extensive and largest fault zones border the Kola block on two sides and are located in water areas of the White and the Barents seas. These are oblique slip known as the Karpinsky lineament on the north and normal faults and oblique slips of the Kandalaksha graben in the White Sea Basin on the south [Trifonov, 1999; Baluev et al., 2012]. These faults were initiated in the Precambrian and rejuvenated repeatedly in later epochs of tectonic activation, including in the Holocene. The West Onega (Vottovaara–Girvas) seismic lineament stands out for its extension on the territory of Karelia [Shvarev, Rodkin, 2018]. Lower-rank structures coincide with the neotectonic Lake Imandra basin and the Paleozoic Khibiny Massif in the inner part of the Kola region. Lower-order feathering faults are conjugated with all of the above-mentioned zones.

The Kandalaksha graben zone is one of major seismic lineaments of the northwestern Fennoscandian Shield. The White Sea is a place where was located the epicenter of the largest 1627 historical earthquake with intensity (I_0)=VIII and magnitude M_w=6.5 [Sharov et al., 2007]. The Karpinsky lineament which belongs to the Murmansk seismogenic zone is marked by the epicenters of recent, historical and paleoearthquakes [Sharov et al., 2007; Nikonov, Shvarev, 2015]. Small seismic events with M=2–4 are still recorded nowadays, thus providing evidence of tectonic activity of these zones.

Large (≥VIII) Late glacial and postglacial earthquake effects have thus far been recognized both within and beyond linear zones. Fig. 1, b shows the areas of concentration of residual crustal deformations: densification is clearly defined in the western part characterized by the most critical intensive variable for total amount of late glacial and postglacial uplift as compared to the eastern part [Nikolaeva, Evzerov, 2018]. Amplitudes and rates of uplift in the area show an eastward decreasing trend.

The lake basins studied are located within four segments shown in Fig. 1, a. Segment I is located near the Kola Fjord coast of the Barents Sea and tends to the first-order tectonic boundary between the Barents plate and Baltic crystalline shield. Segment II belongs to the Imandra neotectonic depression coinciding with the long-lived tectonic fault. The origin of the depression can be traced to conjugation of submeridional and sublatitudinal faults. Segment III is adjacent to the northern side of the Kandalaksha graben. Segment IV belongs to the central Mount Vottovaara (h=417.2 m) – one of the highest uplands in Karelia – and is located in the West Onega (Vottovaara–Girvas) seismic lineament zone [Shvarev, Rodkin, 2018].

All the lakes studied are located in the area with well-exposed outcrops of the Precambrian metamorphic rocks covered partially by a thin layer of sediment. These are primarily moraine, fluvioglacial, glacial marine and limnoglacial sediments and less frequently marine, lacustrine,

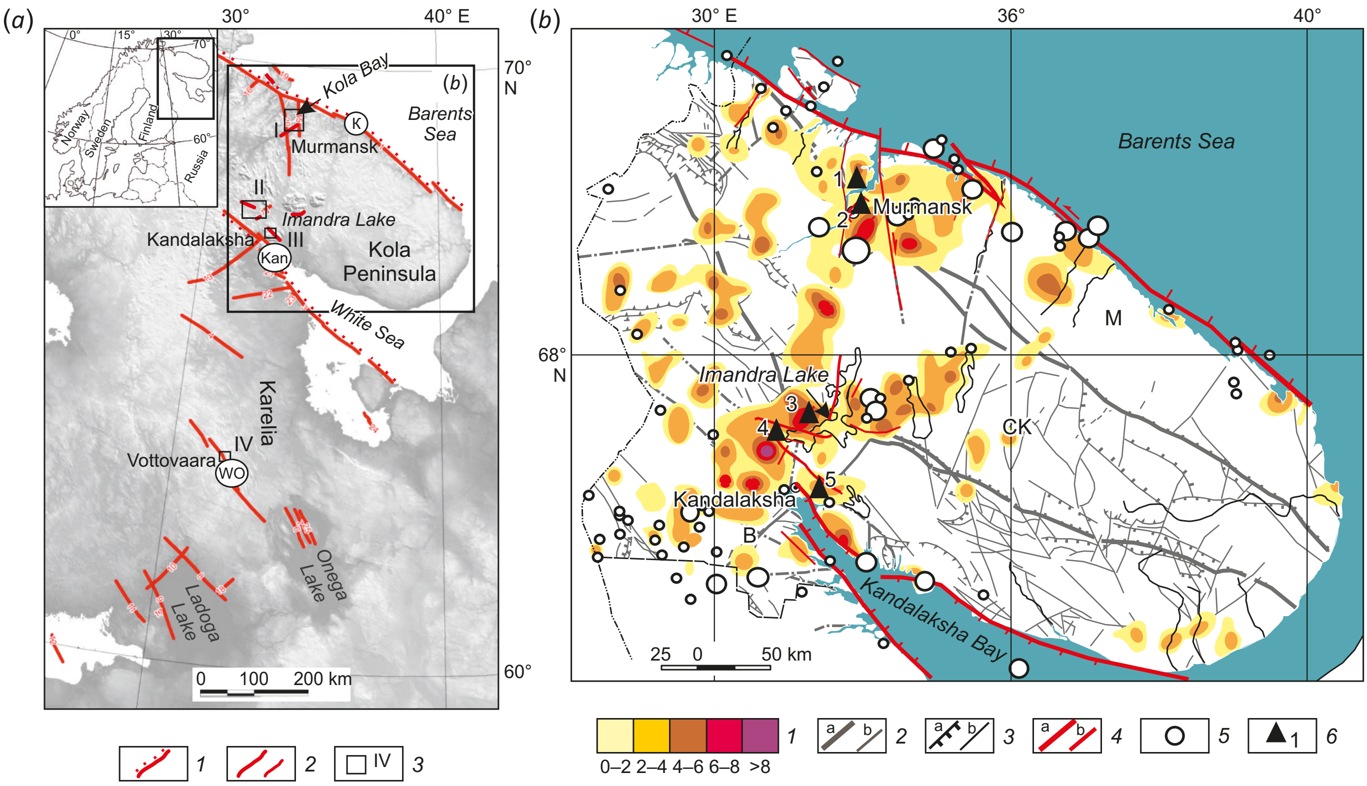


Fig. 1. Active faults of eastern Fennoscandia [Nikonov, Shvarev, 2015; Nikolaeva et al., 2021b] with additions and locations of lake basins referred to in the present study (*a*). An amended diagram showing the relationship between residual deformation densities neotectonic structures and movements (*b*) after [Nikolaeva, 2001]. Digital elevation model based on GTOPO-30 data.
(*a*): *1* – major seismogenic zones; *2* – seismic lineaments and local faults with late- and post-glacial activation; *3* – study areas and their numbers. K – Karpinsky lineament, Kan – Kandalaksha graben, WO – West Onega seismolineament.
(*b*): *1* – residual deformation densities per unit area (15×15 km); *2–4* – faults: *2* – major (a), minor (b) after [Mitrofanov, 2001], *3* – normal faults and reverse faults (a), strike-slip faults (b), *4* – late glacial and postglacial faults exhibiting evidence of activation major (a), minor (b); *5* – earthquake epicenters according to the Kola Department GS RAS, after [Asming et al., 2010]; *6* – lakes referred to in the present study: 1 – Retinskoe, 2 – Skalistoe, 3 – Chuna, 4 – Upoloksha, 5 – Riga-Lambina. Geoblocks (composite terranes): M – Murmansk, CK – Central Kola, B – Belomorsk, after [Balagansky et al., 2016].

alluvial, and biogenic sediments [Niemelä et al., 1993]. A combination of different landforms – preglacial, denudational-tectonic, structural-tectonic, glacial, erosional and accumulative – determines the present-day relief of the areas.

During the glacial isostatic uplift of the region, small and medium-sized lake basins were isolated from the seas (Barents and White) and from large inner paleolakes in the central part of the territory (Imandra, Ladoga and Onega). The formation of most of the lakes in Kola-Karelia and the start of organic matter accumulation there in are assigned to the time of deglaciation termination ~13000–10000 years ago [Evzerov et al., 2010; Stroeven et al., 2016].

3. METHODS AND MATERIALS

The research methodology was aimed at identifying seismically induced structures in the lake bottom sediments. The research was carried out in two stages involving field and laboratory studies.

Fieldwork. The field studies included drilling and sampling using catamaran in summer and a portable piston drill of domestic production for drilling in ice in winter. The cores were drilled down into bedrock or moraine. Each core was 1 m long and 54 mm in diameter, sampled with an overlap of 5–10 cm. Visual features (color, texture, inclusions, and mechanical composition) provided the basis for making lithological description. High-altitude position of the lake was determined from 1:25000 scale topographic maps.

The lithological study involved an examination of all types of sediment deformations, a critical analysis and consideration of their formation mechanisms, and an identification of seismogenic features [McCalpin, Nelson, 1996]. Special emphasis has been placed on the deformations based on sediment lithology and abrupt changes in diatom communities and spore-pollen spectra. The inferred seismogenic layers were sampled. The samples were taken both from the distinguished horizon and its overlying and underlying sediments which allowed determining the age of the event or its lower and upper age limits. The dimensions of the samples for diatomic and spore-pollen analysis were 1.0–2.0 cm, for radiocarbon dating – 7.0–10.0 cm.

Laboratory studies. Laboratory studies included radiocarbon dating of organic matter (gyttja, turf peat, wood) and a study of microfossils. Radiocarbon dating of organogenic sediment samples was carried out in the Radiocarbon Laboratory of St. Petersburg State University according to [Arslanov, 1987]. The radiocarbon dates were calibrated to calendar years using OxCal 4.4 software and IntCal20 calibration curve [Reimer et al., 2020]. The results of diatomic and spore-pollen analyses were also taken into consideration. A detailed description of this research method was published in [Pokrovskaya, 1966; Kosova et al., 2020].

4. RESULTS AND DICUSSION

The objects of research are six lake basins whose general characteristic is presented in Table 1. Lakes 3, 4 and 6 are nameless and have no names on topographic maps, so that, for reasons of presentation, we have named them Upoloksha, Chuna and Vottovaara. Stratigraphic correlation of cross-sections is based on radiocarbon ages and spore-pollen and diatomic analyses.

The following section will give a closer examination of the material obtained from drilling in bottom sediments of the lakes in the Kola region, which was an opportunity to take a new look at the deformations observed in lake sediment cores.

4.1. Deformations in bottom sediments of lakes in the Kola region

Lake Retinskoe (Table 1) has an isometric shape and is 3 km from the Kola coast and 15 km south of the Barents coastline (Fig. 1, b). Fig. 2, a shows the cross-section whose basal part is composed of marine silt and clays with pebble and rock debris (layer 1) overlain by freshwater gyttja (layers 2, 4–5). After ice sheet retreat, the lake basin was occupied by the sea. The number of marine diatom species, which is dominant in the silt of layer 1, decreases significantly in the younger stratigraphic levels. The gyttja

Table 1. Study sites and lake characteristics

Area	Lake/cross-section	Coordinates N	Coordinates E	Altitude a.s.l., m	Lake area, m^2	Depth, m	Core length, cm
I	Retinskoe/R	69°07'37.7"	33°18'55.4"	51.5	3.5	4.5	100
	Skalistoe/SK	68°56'07.79"	33°09'19.78"	180.0	0.04	6.5	170
II	Upoloksha/Up1	67°31'58.9"	31°45'10.8"	133.4	0.385	3.2	213
	Chuna/Ch1	69°34'94"	32°29'60"	204.9	0.11	3.5	200
III	Riga-Lambina/RL	67°12'506"	32°51'929"	136.0	0.21	4.5	330
IV	Vottovaara/V	63°04'27"	32°37'32"	400.0	0.09	6.0	350

unit was formed in the already existing freshwater environment.

An abrupt change in hydrodynamic regime is evidenced by the deposition of layer 3 – coarse sand grains in the organogenic sediments overlying layer 2 with erosive unconformity (Fig. 2, a). Erosion and formation of the interlayer of sand, obviously removed, could be related to the Tapes transgression of the region, tsunami or storm over wash, or to shallowing or drying-up of the water body. By this time, however, there was no longer any flow of sea water into the lake. This is evidenced by A.N. Tolstobrova's analysis of the composition of diatoms from the sand sediments deposited in layer 3 where freshwater diatoms can only be found [Nikolaeva et al., 2019]. Around 7000–8500 years ago, there already occurred a dramatic fall in the sea level of ~27 m near the Kola Bay [Corner et al., 2001], which does not imply any sea water flow into the lake basin. Diatom communities and spore-pollen spectra did not show any changes related to drying up of rather deep (deeper than 10–12 m) lake basin [Kremenetski et al., 1997; Evzerov et al., 2017] at that time either.

If the sand grains in the organogenic sediments were derived from the costal sedimentary environment, then this anomaly in sedimentation may have been caused by a sudden displacement of mineral sediments from the shores during an earthquake. Another reason may have been the

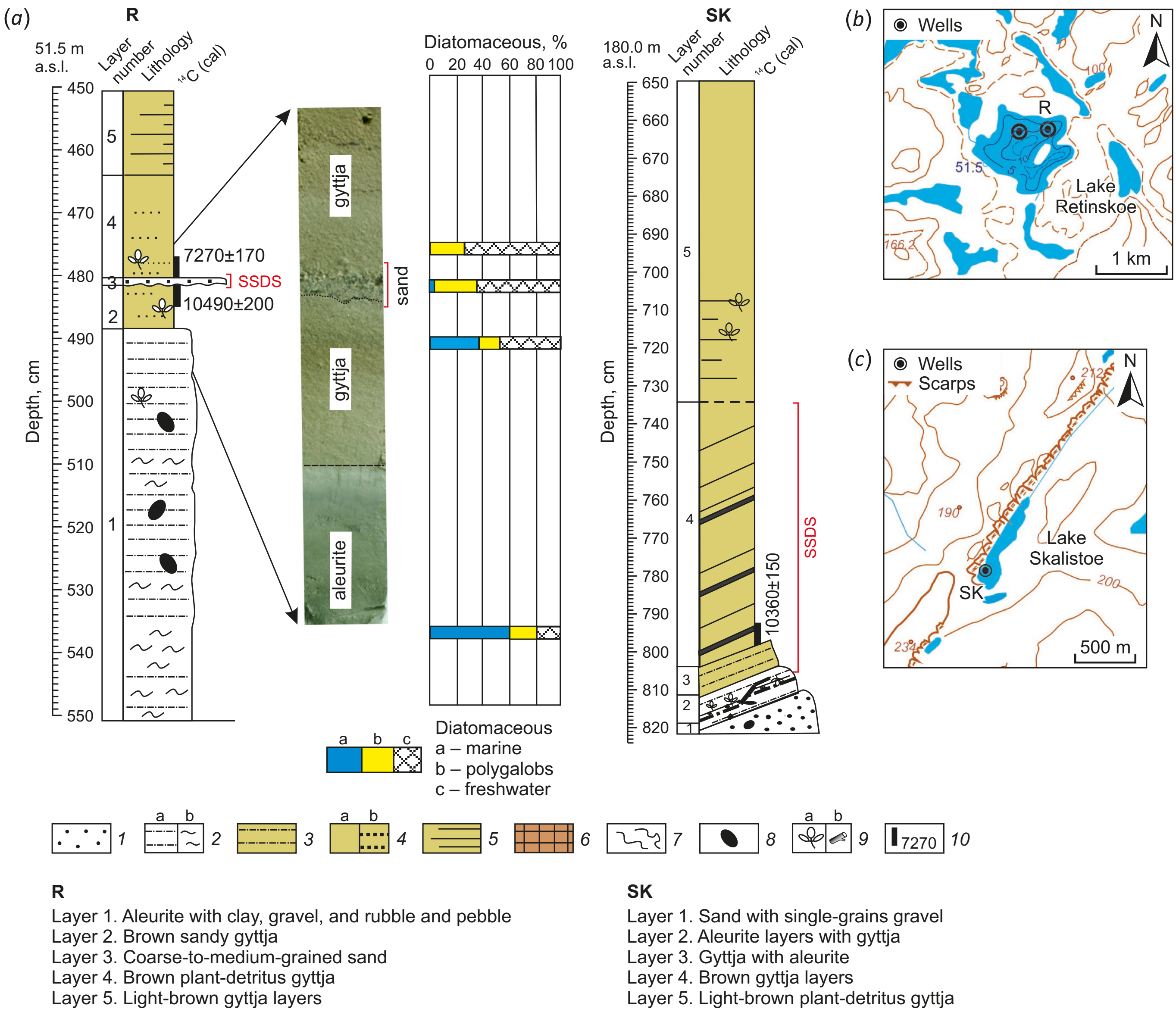


Fig. 2. Soft sediment deformation strictures (SSDS) in the bottom sediment cores from Lakes Retinskoe after [Nikolaeva et al., 2019] and Skalistoye (*a*) and borehole location (*b, c*).
Elevation (100 m contour interval) on fragments (*b, c*). *1* – sand; *2* – silt (a), clay (b); *3* – silt with gyttja; *4* – homogeneous gyttja (a), sandy gyttja (b); *5* – layered gyttja; *6* – mixture of gyttja, sand, silt and peat; *7* – deformations; *8* – gravel, pebbles; *9* – plant detritus (a), wood (b); *10* – radiocarbon dates in calendar years.

earthquake-induced deposition of particles brought into suspensions from the shallow water, which were redeposited later on.

The thin sand layer in the gyttja unit was formed between 10400±200 (LU–7907) and 7200±170 (LU–7908) cal yr BP, so that the average age of the event may me assigned ~8800–8900 cal yr BP.

Lake Skalistoe (see Fig. 1, b), with a narrow near-fault basin, is located 0.5 km from the southeastern Kola coast. It is located at the basement of a 2.8 km long NE-trending (35–40°) scarp (h=20 m) (Fig. 2, a, c). The SK sedimentary cross-section consists of mineral (layers 1–3) and organogenic (layers 4 and 5) units. At the initial stages of sedimentation, there occurred the deposition of late glacial sands and silt derived from transportation of large amounts of fragmentary material from the remained dead-ice massifs and intensive erosion processes in deposits on the exposed land surface.

A distinguishing feature of the SK cross-section is that the lower sedimentary rock layers are strongly dislocated. Silt and gyttja in layers 2–4 are obviously tilted ESE at an angle of 25° to the horizontal. An almost 1 m thick inclined unit is clearly of secondary post-sedimentary origin. According to radiocarbon dating, the gyttja at the contact with silt dates back to ~ 10360±150 (TA-2293) cal yr BP [Nikolaeva, 2008]. Considering the lake-basin location in the source area of large paleoearthquakes and gravity-induced rockfalls at the basement of the scarp facing the interior of the lake basin, this date can be interpreted as the age of seismic suture opening and rockfall occurrence.

Lake Upoloksha with sandy-stony, partly flooded shores, is 4 km west of the Upoloksha Bay of Lake Babinskaya Imanrda. Five boreholes were drilled into the bottom sediments [Nikolaeva et al., 2017]. Borehole Up1 (Fig. 3) tapped inequigranular sands (layer 1), silt (layer 2), weak laminated

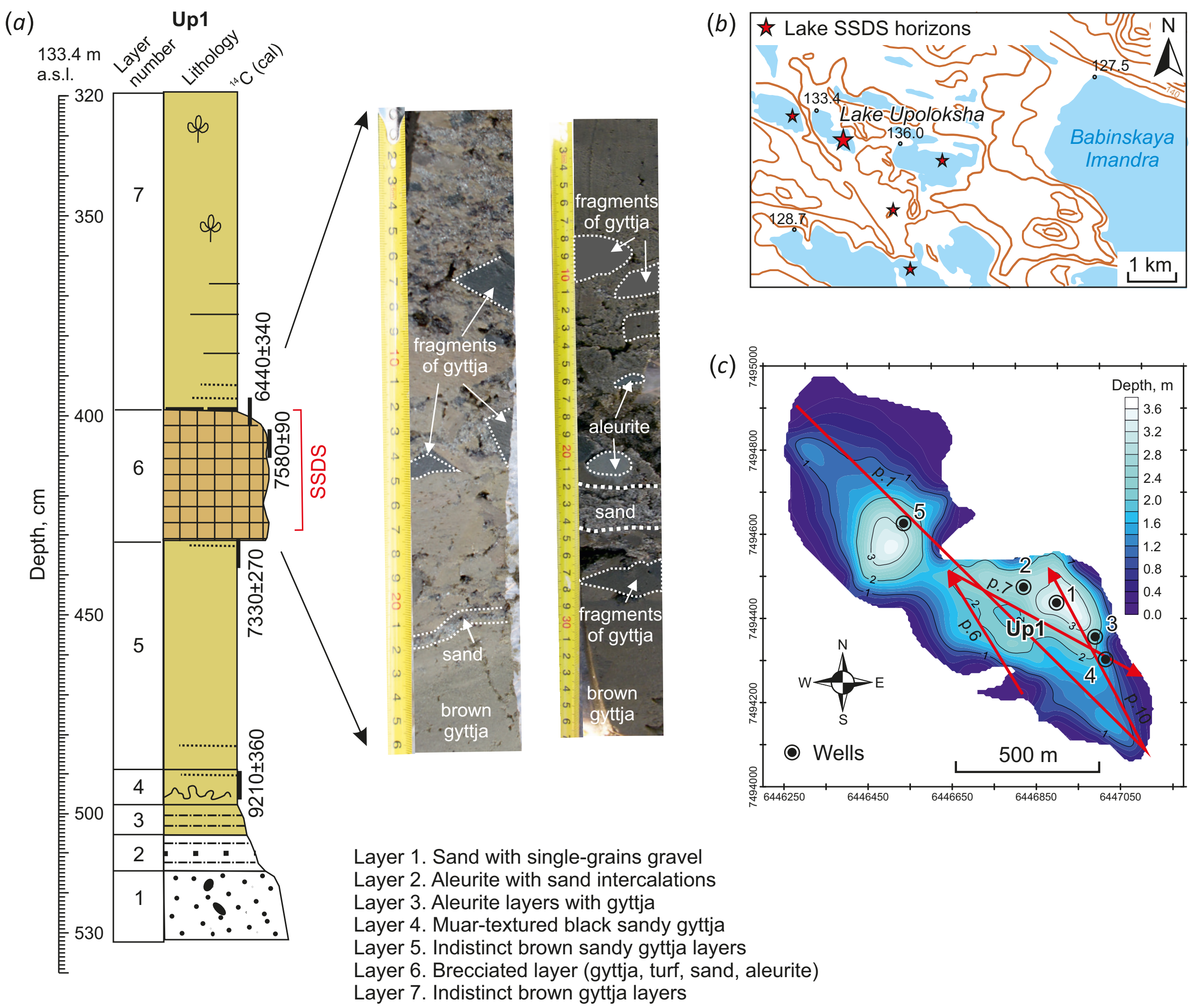


Fig. 3. Position of the breccia horizon in the sedimentary sequence of Up1 (*a*), location of lakes with seismogenic horizons on the western coast of Lake Babinskaya Imandra (*b*), bathymetry of Lake Upoloksha after [Rodionov et al., 2018] (*c*) and location of boreholes. Legend for (*a*) see Fig. 2. Red arrows on (*b*) show GPR profiles for Fig. 4.

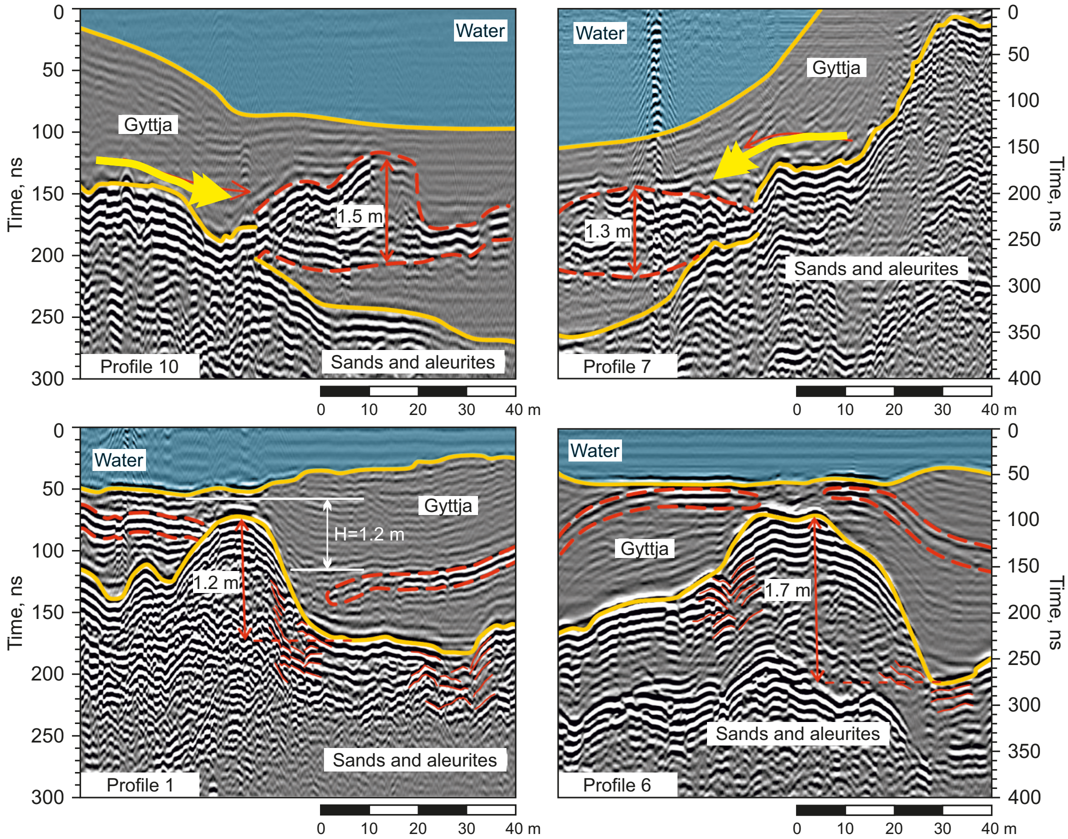


Fig. 4. Fragments of GPR profiles reflecting disturbances in bottom sediments of Lake Upoloksha after [Rodionov et al., 2018]. The yellow arrows indicate the direction in which the material is displaced. For the location of the profiles, see Fig. 3, c.

to laminated gyttja (layers 3–7). The gyttja varies in color from black at the bottom section, near the contact with silt, to brown and light-brown at the top section.

A typical feature of the sediments is the occurrence of brecciated horizon in the gyttja unit (Fig. 3, a). It consists of a mixture of different-shape and different-size pieces and fragments of black and brown ("variously colored") gyttja, silt, peat, sand, plant remains and wood fragments (4–5 cm) enclosed in sapropel matrix. The occurrence of brecciated horizon in the sections implies catastrophic changes in sediment deposition at an early period of quiescent sedimentation.

There has also been a noticeable change in the structure of diatom complexes [Kosova et al., 2020]. This change involves the abrupt decline in the abundance of diatoms attributed to a huge supply of terrigenous material from the catchment area. According to data of N.B. Lavrova, this layer is distinguished in spore-pollen spectra as a local pollen zone [Nikolaeva et al., 2017].

Georadar sensing of the lake bottom also showed sediment disturbance and dislocation. The 1.3–1.7 m vertical displacements of layers along the top of the sand and silt unit, as well as and sediment-slide areas, are clearly defined on the obtained radarograms whose fragments are shown in Fig. 4 (see the details in [Rodionov et al., 2018]).

The most probable formation mechanism for the anomalous horizon is erosion and an abrupt (instantaneous) displacement (sliding) of sediments from the basin flanks into a deeper part of the water body. This process involved breaking down of the sediments, resulting in their suspension and subsequent redeposition on the previously deposited non-deformed layers. This also explains the occurrence of black gyttja pieces in the brecciated horizon at a depth of 410–430 cm, lying in much younger stratigraphic level that the black gyttja lying at the bottom of the section at a depth of 490–500 cm (see Fig. 3, a).

The age of the anomalous horizon was determined by radiocarbon dating of organic matter above, beneath and inside layer 6. The dates obtained correspond to the Atlantic Period of the Holocene – 7330±270 (LU-7364) – 6440 ±340 (LU-7365 cal yr BP). At about the same time, there have been formed similar horizons in some other lakes (see Fig. 3, b). Taking into account neotectonic and seismic activities of the Imandra basin, the relationship between sediment disturbances and seismic processes is to be expected.

Lake Chuna occupies a crystalline basement trough located 6 km from the western edge of the basin of Lake Ekostrovskaya Imandra, in the seismogenic fault zone [Nikolaeva et al., 2018]. The bottom sediments were studied in 2014. In order to specify the lithology of deposits and identify seismogenic horizons, a few additional boreholes were drilled in August 2020 in the deepest part of the lake nearest to the SW underwater gorge (Fig. 5, a, b).

Cross-section Ch1 exhibits neither disturbance of stratification nor gap in sediments. However, three intervals in sediment cores are worthy of note (Fig. 5, a). Two of them are in the basal part of the section: layer 2 with rectangular- and irregular-shaped inclusions of clays in a thin bed of silt inclined at an angle of 15° and layer 4 with terrigenic material seen as thin beds of organogenic sediments (sapropels). Higher in the succession there is an interlayer of detritus gyttja with abundant 2×3 cm fragments of birch bark (*Betula sp.*) (Fig. 5, c), some fragments of wood, and gravel grains.

Dislocation of sediments in the basal part of the section may be due to sliding of rock material down the slopes and its intermixing. This phenomenon is reasonably related to the secondary effect of a large earthquake that occurred as a result of the nearby Chuna fault activation [Nikolaeva et al., 2018]. The event occurred before the accumulation of organic matter in the lake, earlier than 9800±230 (LU–7572) cal yr BP. Considering this fact together with OSL dating (optically stimulated luminescence dating) and

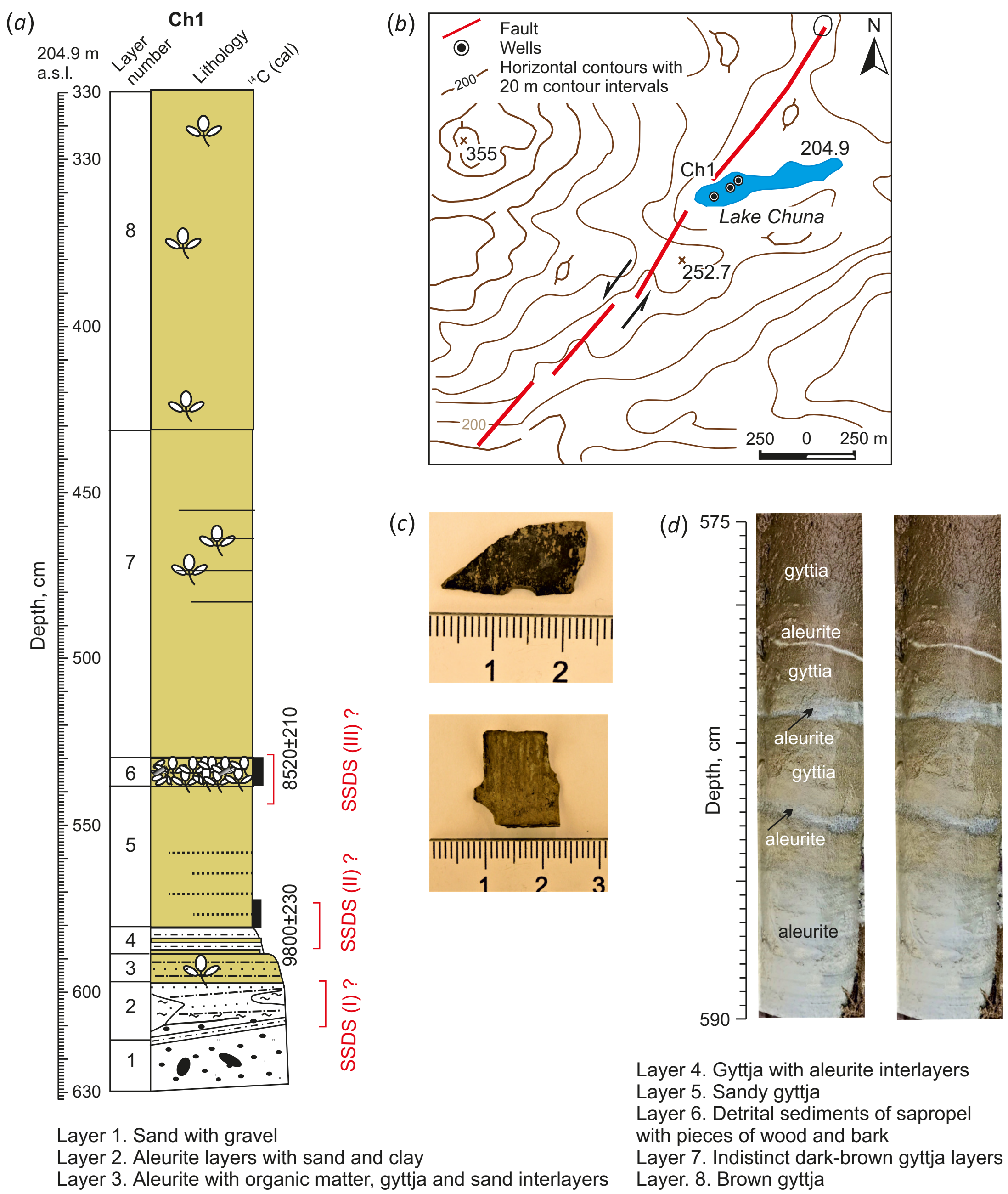


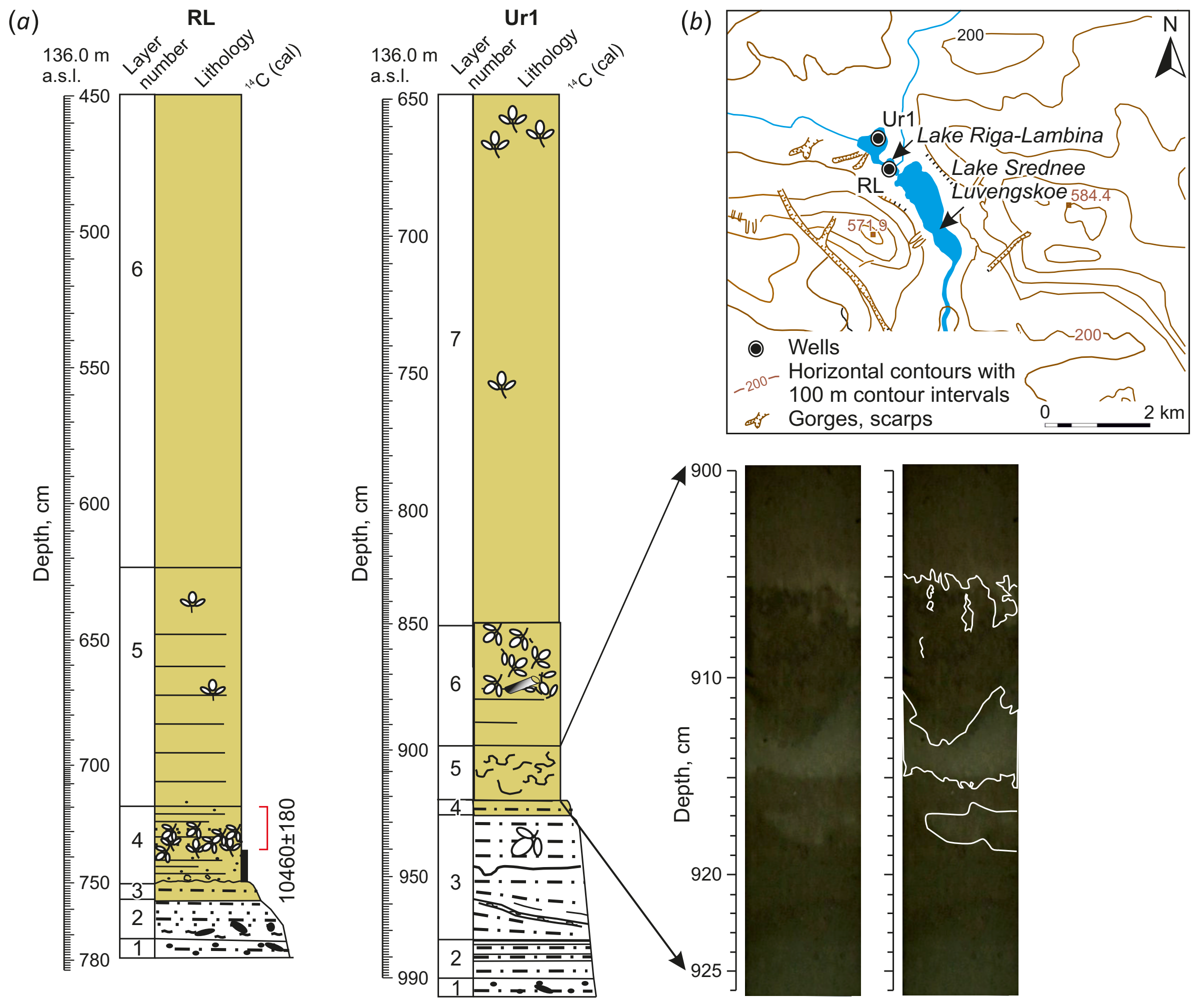
Fig. 5. Lithostratigraphy of bottom sediments of Lake Chuna (*a*), location of the lake basin and boreholes (*b*), birch bark *Betula sp.* from layer 6 (*c*), cores from interval 575–590 cm (*d*). Legend for (*a*) see Fig. 2.

paleogeographic environment of the region, the age of an earlier seismic event was assigned to the Late Glacial period ~13500 cal yr BP.

The occurrence of another seismic event can be evidenced by the formation of layer 6 which contains abundant plant remains, birch bark and wood. This layer may have formed as a result of different events – climate fluctuations or erosion processes. However, according to data of N.B. Lavrova, the palynological analysis did not show any significant climate change [Nikolaeva et al., 2021a]. Simultaneous occurrence of an earthquake epicentered in the Chuna fault zone and disturbance of the nearby lake water surface imply that there could occur a horizon containing abundant remnants of trees and shrubs falling from the nearby fault scarp into the lake depression during an earthquake.

The gyttja sample from layer 6 yielded the age of 8520 ±210 cal yr BP or 7720±170 ^{14}C (LU–10115), and a wood fragment from the same horizon yielded the age of 8078–8168 cal yr BP (7235±25 ^{14}C) (IGAN$_{AMS}$–8221) [Nikolaeva et al., 2021a]. The dates obtained are close to each other and provide an opportunity to refine significantly the age of the seismic event falling within the range of 10300 to 7100 years ago (^{14}C) and to assign it to the period ~8000–8100 cal yr BP.

Lake Riga-Lambina is located near low-mountain tundra areas of Luvengsky archipelago complicated by numerous seismic dislocations [Shvarev et al., 2021]. Nowadays,



RL
Layer 1. Sand with aleurite and single-grains gravel
Layer 2. Aleurite with sand and clay intercalations
Layer 3. Gyttja with aleurite
Layer 4. Sandy plant-detritus gyttja
Layer 5. Brown gyttja layers
Layer 6. Homogeneous brown gyttja

Ur1
Layer 1. Sand with aleurite and single-grains gravel
Layer 2. Aleurite layers
Layer 3. Aleurite layers with organic matter
Layer 4. Aleurite with gyttja
Layer 5. Gyttja deformations
Layer 6. Plant-detritus gyttja
Layer 7. Light-brown gyttja

Fig. 6. Lithostratigraphy of bottom sediments (*a*) and location of the lake basins Riga-Lambina and Srednee Luvengskoe (*b*). Legend for (*a*) see Fig. 2.

this lake is connected to the near-fault basin of Lake Srednee Luvengskoe by a swamped arm (Fig. 6).

Cross-sections RL and Ur1, penetrated by two wells, fall similarly into two parts. The basal part is represented by intercalation of sands, silt and clays overlain by gyttja as seen in Fig. 6, a. Sand and silt deposits were formed in a periglacial environment, from the end of the Younger Dryas to the beginning of the Preboreal, under eastward-trending glacial degradation conditions. The basins of Riga-Lambina and Srednee Luvengskoe lakes were at that time a single body of deep water formed in the preglacial depression. Further sedimentation occurred during the Holocene.

In the cores studied, worthy of note are a bend and thin inclined beds of silt in layer 3, and liquefaction in the form eroded and festoon bedding in gyttja of layer 5 of cross-section Ur1 (Fig. 6). РЛ well core showed an interlayer of concentrated detritic sapropel (layer 4 of RL cross-section, Fig. 6).

In RL and Ur1 cross-sections, as well as in sediment cores from Lake Chuna, there is no obvious stratigraphic disturbance that could be related to seismic events. Bending deformations and thin inclined beds of silt in cross-section Ur1 may have resulted from gravity (seimogravity) sliding down a slope. Detritus gyttja interlayers in RL cross-section may have formed as a result of the decrease in water level of the lake due to climate xerophytization processes [Nikolaeva, Lavrova, 2021]. However, SSDS visible in the lower part of layer 5 in cross-section Ur1 can be interpreted as the traces of liquefaction and fluidization induced an earthquake environmental effect because they exhibit typical seismogenic characteristics [Seilacher, 1969; Sims, 1973].

Nevertheless, the conjugation of lake basins with the near-fault intermountain depression and the paleoseismological and paleogeographical data available imply the opportunity to consider these lake basins as former tectonic troughs. In this case, it is precisely the beginning of organic matter accumulation in the lakes that has to be related either to opening or shaping of the edges of the Srednyaya Luvenga depression and to its rejuvenation. Based on the estimated time of commencement of sedimentation in Lake Riga-Lambina, the fault activation occurred about 10460 ±180 cal yr BP (LU–7573) [Nikolaeva, Lavrova, 2021]. Perhaps, the formation of large rockslides and numerous rockfalls on both sides of the Srednyaya Luvenga basin can be confined to the same age-related boundary [Shvarev et al., 2021].

4.2. Deformations in bottom sediments of lakes in the Karelia

Different traces of ancient earthquakes can be observed in the cross-sections of lakes of Karelia (Fig. 7, a). Among those are tilted beds, folds, and fault ruptures in varved clays, as well as in Late Holocene clays and silt. The results for seismoacoustic profiling at the bottom of **Lake Putkozero** (cross-section s6 in Fig. 7) revealed seismogravitational rockfalls along the coastal zone [Lukashov, 2004]. It is worthy of note that they are a continuation of rockfalls in the area of the lake (Fig. 7, b).

Another lake, **Vottovaara** (Table 1) (section s7 in Fig. 7) is located in the western Karelia, 300 m southwest of the top of the Mount Vottovaara [Demidov et al., 1998; Lukashov, 2004]. The lake basin contains wetlands and is confined to the descent of bowl-shaped landscape composed of crystalline rocks. According to data of Lukashov (2004), at the bottom and on the sides the bowl there are observed seismic dislocations in the form of crushed and displaced rocks, troughs or fractures, with the Mount Vottovaara area itself related to the Segozersky paleoseismogenic structure.

The lithological-stratigraphic, spore-pollen and diatomic analyses of the cross-section show that a relatively deep lake began to form in the Younger Dryas [Demidov et al., 1998; Shelekhova, Lavrova, 2019]. Since that time, there began the accumulation of aleurites (Fig. 8, section s7). In the Boreal and early Atlantic Period, the lake water level declined dramatically, the climate became warmer, and there began the lake sapropel deposition. In the late Atlantic Period, there occurred shallowing and eutrophication of the lake. It started to turn into swamp with turf accumulation.

An occurrence of a large seismic event is attributed to the sedimentation gap and an abrupt change of dominant species of diatomic complex [Shelekhova, Lavrova, 2019]. This implies a catastrophic and rapid decline in the water level of the lake. The radiocarbon date from the lower part of the gyttja related the event to the Preboreal-Boreal boundary, 10049±109 cal yr BP (SU–2824). The water body almost ceased to exist at the moment of seismic deformation occurrence.

4.3. Genesis of deformations in the lake bottom sediments

One of the major points of discussion is genesis of deformations in lake sediments of Kola-Karelia. There has now been developed a number of criteria that allow differentiation between seismogenic and non-seismogenic soft-sediment deformation features [Sims, 1973; Allen, 1986; Owen, Moretti, 2011; Moretti et al., 2014]. Common characteristics are long lateral extension; similarity between experimentally formed and earthquake-induced structures; deformation occurrence irrespective of the sediment structure and bedding type; spontaneous occurrence. The authors of [Moretti et al., 2014] completed this number of characteristics with the location of sediment basins in the areas of paleoseismic and/or recent seismic activity and the fact that intensity and number of SSDS have

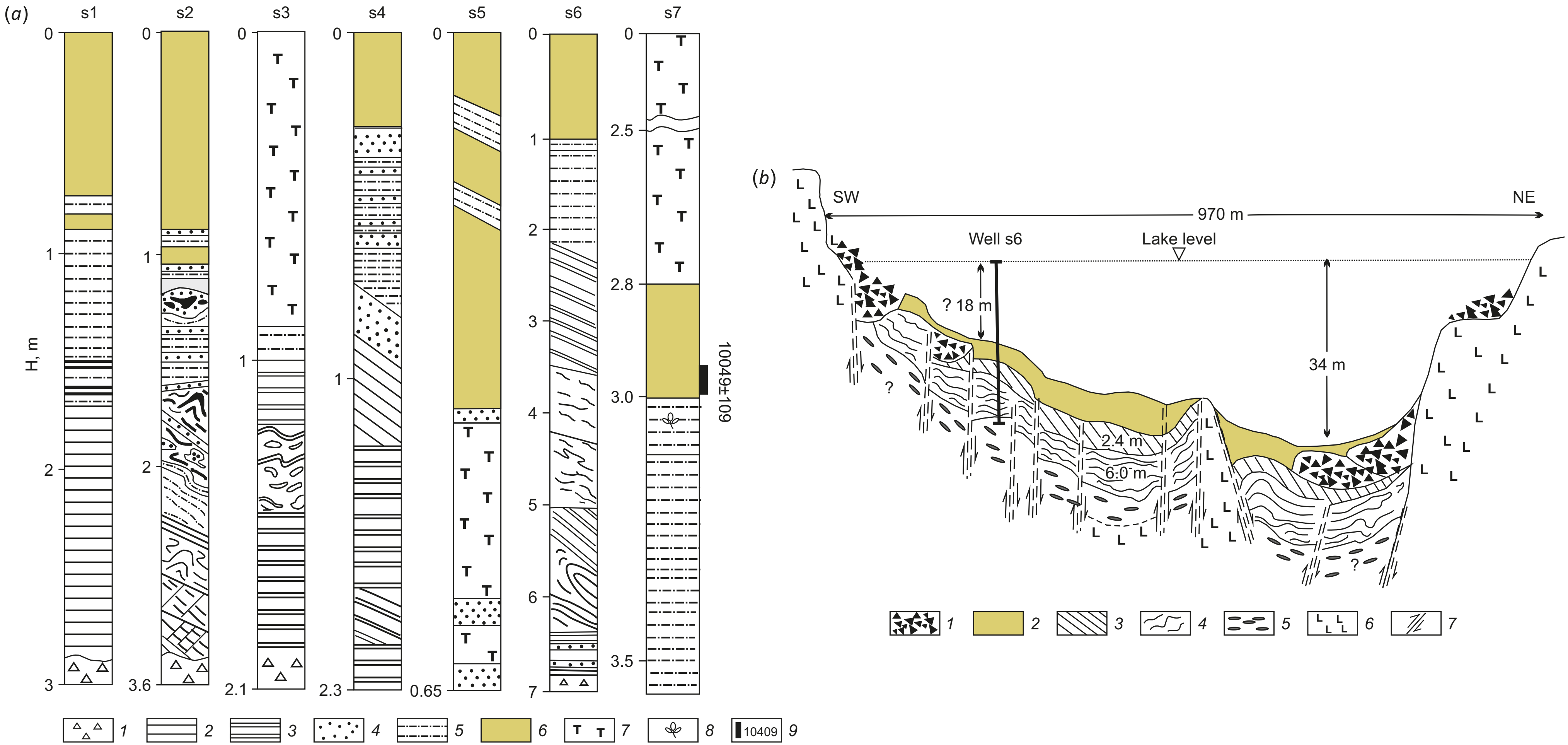


Fig. 7. Disturbances in the sections of bottom sediments in Karelia (*a*) and seismoacoustic profile (Lake Putkozero) (*b*) after [Lukashov, 2004].
(*a*): *1* – till; *2* – varved clay; *3* – homogeneous clays; *4* – sand; *5* – silt; *6* – gyttja; *7* – peat; *8* – plant detritus; *9* – radiocarbon dates in calendar years. The location of the lakes: s1 – cross-section through bottom sediments outside the area of local seismodislocations, s2 – Tserkovnaya Bay (Lake Onega), s3–s4 – Puutsaari Island (Ladoga Lake), s5 – Lake Pizanets (Zaonezhsky Peninsula), s6 – Lake Putkozero (Zaonezhsky Peninsula), s7 – Vottovaara lake after [Shelekhova, Lavrova, 2019]. (*b*): *1* – seismogravitational rockfall; *2* – gyttja; *3* – homogeneous clays and silts; *4* – deformed varved clay; *5* – till; *6* – gabbro-dolerites; *7* – fractures.

to vary in a lateral direction depending on the distance to the earthquake epicenter. Numerous examples show that microfaults, landslides, turbidites, homogeneities and convolute structures found in the lake sediment cores are often directly related to recent or historic earthquakes [Chapron et al., 1999; Monecke et al., 2006; Guyard et al., 2007; Lajeunesse et al., 2017; Vologina et al., 2021].

The studied lakes in which SSDS were found are located directly within the sources of large paleoearthquakes confined to active fault zones [Lukashov, 2004; Nikolaeva, 2008; Nikolaeva et al., 2018]. Therefore, it is to be expected that their bottom sediments may provide confirmation of major earthquake events. However, only four lakes – Retinskoe, Skalistoe, Upoloksha and Vottovaara – provided evidence for seismogenic origin of their sediment disturbances. As mentioned above, these disturbances are in contrast with deformations caused by climatic, biogenic or erosional processes. The presence of terrigenous interlayer in the gyttja of Lake Retinskoe could not be linked to the Tapes transgression or drying-up of the lake. This is contradicted by the paleogeographic and climatic conditions at that time and by the distribution of diatom communities. According to sediment disturbance patterns of Lake Upoloksha (randomly arranged fragments of different rocks, turf and fragments of wood incorporated into the sediments), the displacement was rapid and instantaneous and can be due to seismic impulse strong enough to disturb the silt, sand and gyttja layers. Inclined bedding is often found in fault-trough lake sediments [Lukashov, 2004]. It is beyond question that there is a relationship between a gap in lake sediments, followed by discharge of water from the lake near the Mount Vottovaara in Karelia, and a large seismic event [Demidov et al., 1998]. Besides, similar deformations, such as microfault displacements, underwater landslides and different-colored gyttja in lake sediments of Finland are interpreted as the traces of Holocene earthquakes dating back to ~6700 years ago and ~10000 years ago [Ojala et al., 2019].

Lack of well-pronounced lithological disturbances in Lake Chuna and Lake Riga-Lambina may be due to the occurrence of earthquakes prior to organic matter accumulation in lakes, as well as to some other factors (for example, complex lithological cross-sections, and a small number of drilled wells and supporting geophysical studies. Some researchers believe that the traces of seismic events can only be recognized as liquefaction-induced deformation structures in sediments depending on intensity and duration of an earthquake [Moretti et al., 2014]. It should be acknowledged that the geological archive containing soft-sediment deformations in lakes is still incomplete and understudied.

However, despite differences in geological and tectonic conditions of their occurrence, the earthquakes and the soft-sediment deformation structures in cores from lacustrine deposits share common features involving a clearly disturbed hydrodynamic environment, spontaneous nature and aquatic environmental disturbances in several areas before and after the seismic event. Subsequent deposition of suspended material gave rise to the formation of terrigenous or other extraneous interlayers, with other spectra of diatoms.

4.4. Spatial distribution, magnitudes and age of paleoearthquakes

Most of the researchers concluded that soft-sediment liquefaction can be induced by an earthquake of M_w≥5 [Ambraseys, 1988; Galli, 2000; Obermeier et al., 2005]. According to [Moretti et al., 1995], a M_w>8 earthquake can potentially cause SSDS at the maximum distance of 100 km. [Galli, 2000] presents data showing that 90 % of all liquefaction effects occur within the distance of 40 km from the epicenter. However, the occurrence of SSDS at lower-intensity and lower-magnitude earthquakes is almost neglected, though in some cases liquefaction effects took place during earthquakes of intensities VI–VII [Keefer, 1984; McCalpin, Nelson, 1996].

The lakes studied are located near extensive and active tectonic structures: Murmansk, stretched for 100–110 km along the Barents Sea coast, Kandalaksha graben with a length of ~90 km, sub-basin of the Babinskaya-Ekostrovskaya Imandra neotectonic basin with a length of 50–55 km and E-W strike, and West Onega lineament exceeding 30 km in length (see Fig. 1, a). Such faulting parameters correspond to M_w=6.5–7.5 earthquakes typical for Late glacial and postglacial seismicity of Fennoscandia [Olesen et al., 2013; Sutinen et al., 2018; Shvarev, Rodkin, 2018].

A generalization of scattered radiocarbon age data for paleoearthquakes of Kola-Karelia and a study of SSDS in lacustrine deposits (Fig. 8, a) made it possible to update the information and to distinguish three active age periods. These are Late Glacial – Early Holocene period marked by the most rapid uplift after the retreat of the last ice sheet when seismic events occurred more often and were the strongest ones (13500–8100 cal yr BP), and Middle Holocene (6800–6600 years ago) and Late Holocene (3100–200 years ago) periods. Fig. 8, b shows that seismic events occurred also in the deglaciation period. It is significant that the Middle Holocene is characterized by more quiescent seismic motion level. Generally, the age periods distinguished are in a good agreement with the data on the western Fennoscandia. The Finnish researchers, who generalized the data on the age of seismic activity of Fennoscandia, confined these periods approximately to 12000–10000, 5000–7000 and 1500–3000 years ago [Ojala et al., 2019].

The results of the study of Late Glacial and Holocene seismicity of the Kola region and Karelia show that the same

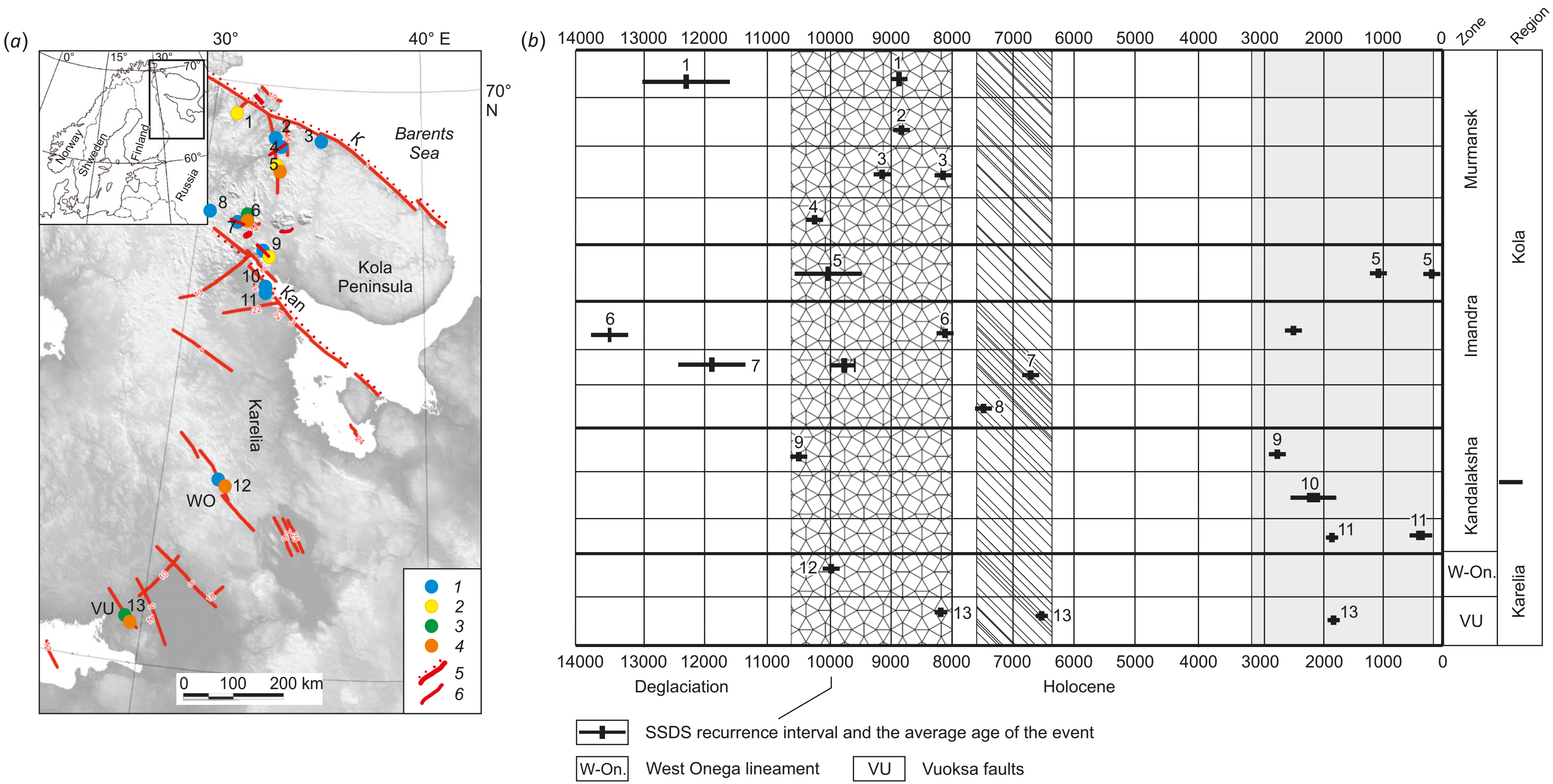


Fig. 8. Spatial distribution of paleoearthquake traces (*a*) and calibrated radiocarbon age of events in the eastern part of the Fennoscandian Shield (*b*).
1–4 – sites of age determination of paleoearthquakes: *1* – from bottom sediments of lakes, *2* – buried organic matter under rock falls and in gorges, *3* – SSDS in fluvioglacial, limnoglacial, deltaic and marine sediments, *4* – paleogeographic reconstructions and correlations; *5* – major seismogenic zones; *6* – seismic lineaments and local faults with late- and post-glacial activation. The numbers of the sites on the map a correspond to those in Fragment (*b*). Sites: 1 – Pechenga, after [Nikolaeva, 2009], 2 – Kola fiord, after [Nikolaeva et al., 2019], 3 – Teriberka, after [Tolstobrov et al., 2018], 4 – Murmansk, after [Nikolaeva, 2008], 5 – Shongui, after [Nikolaeva et al., 2021c], 6 – Chuna, after [Nikolaeva et al., 2018], 7 – Upoloksha, after [Nikolaeva et al., 2017], 8 – Kovdor, after [Nikonov, 2007], 9 – Luvenga, after [Nikolaeva, Lavrova, 2021], 10 – Keret, after [Tolstobrov et al., 2019], 11 – Velikaya Salma, after [Marakhanov, Romanenko, 2014], 12 – Vottovaara, after [Shelekhova, Lavrova, 2019], 13 – Vuoksa, after [Shvarev et al., 2018].

fault or zone might have experienced several events occurred at different times [Shvarev et al., 2018]. Thus, for instance, the Vuoksi fault zone in Karelia was multiply reactivated. Tectonic activation of the fault and its related 7–9 intensity earthquakes occurred not only in Late Glacial and Holocene (11600–8300, 5700–5100 and 1900–1800 years ago), but also in the end of the Mikulian interglacial – Early Valdai interstadial. Multiple reactivation of the strike-slip and normal-fault system along the Kandalaksha faults can be traced back 12000 years ago [Nikonov, Shvarev, 2015]. Three impulses of strong seismic events (13500, 8100–8300, ~2500 years ago) with M_w≈6.0 are confined to the Chuna fault zone on the western flank of the Imandra basin of the Kola region [Nikolaeva et al., 2018]. According to the radiocarbon and paleogeographic data, in the fault zone striking NNW along the Kola River valley [Nikolaeva et al., 2021c] there were three episodes of high seismic activity: 9500–10 500, 892–1182, and 200–300 years ago.

A generalization of the palaeoseismic data obtained shows that high-magnitude peak and frequency of earthquakes took place in Late Glacial and Early Holocene, after the retreat of the ice sheet. Most of the researches attribute this phenomenon to the glacioisostatic effect playing an important role in the formation of post-glacial seismicity [Mörner, 2004; Olesen et al., 2013; Lagerbäck, Sundh, 2008; Kukkonen et al., 2010; Ojala et al., 2019]. However, the Mid- and Late Holocene seismic events which occurred thousands of years after deglaciation need other explanations and imply other tectonic factors and mechanisms.

5. CONCLUSIONS

Therefore, the data on the time of occurrence of coseismic deformations in lake bottom sediments and palaeoseismic data for Kola-Karelia make it possible to distinguish major periods of past seismic activity of the shield and refine considerably the occurrence intervals of single events. The occurrence time of palaeoseismic events corresponds to three major periods: 13500–8100 years ago, 6800–6600 years ago, and 3100–200 years ago. The age estimates obtained show an uneven temporal distribution of earthquakes in the area, with the highest seismic activity typical of the Early Holocene. The Middle Holocene is characterized by a more quiescent seismic environment as compared to the Late Holocene. It has been found that the same fault or zone exhibit features of multiple reactivation and seismic events occurred during the Late Glacial and in the Holocene. A spatial distribution of soft-sediment deformation structures from the lakes studied there with is uneven: they correlate with linear neotectonic and post-glacial faults as well as with single blocks beyond them.

It is worthy of note that further study of disturbances and deformations in lake bottom sediments will favor the paleoseismogeological investigations in regions and areas considered aseismic for a long time. The data obtained make further adjustments to geodynamic and seismic estimates of the intraplate areas.

6. ACKNOWLEDGEMENTS

The author expresses her gratitude to Prof. A.A. Nikonov, Dr. Sci. (Geol.-Min.), IPE RAS, for providing competent and valuable consultations, to D.S. Tolstobrov, D.A. Maksimov and A.I. Rodionov, FRC KSC RAS, for providing assistance to carry out fieldwork studies, and to reviewers for careful reading of the manuscript and making some critical remarks.

7. CONFLICT OF INTERESTS

The author has no conflicts of interest to declare. The author has read and agreed to the published version of the manuscript.

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