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Results of Detailed Paleoseismic Studies of the Kindo Peninsula (Karelian Coast of the White Sea)

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Abstract—A standard complex of geomorphologic methods, including identification of aerial photos and space images, topographic and structural–geomorphologic area survey, trenching colluvial sediments and their mapping, and sampling of paleosoils and their dating by the radiocarbon method, was used for identification, parametrization, and dating of seismic dislocations of the Karelian coast of the White Sea. A set of kinematic indicators of paleoearthquakes (mass displacements and systematic rotations of fragments of rock ledges), which make it possible to interpret the directions of maximum seismic impact on detailed areas, is elaborated and tested. In the relief of the rock massifs of the Kindo Peninsula, these methods revealed a halo (10 × 6 km) of secondary seismic dislocations with a radiocarbon age of no more than 5.5 ka, which is a zone (4 × 2 km) of extension fractures and numerous displacements of stones surrounded by a belt of seismic gravitation faults. It is shown that some ledges and stepwise faults in the relief of these stones probably resulted from glacial denudation and further erosion of structural heterogeneities. At the same time, displacements of chipped stones versus inclination and their systematic rotation in rock ledges of different strike suggest intense seismic impacts after the formation of the stepwise surfaces and termination of their abrasion after glacial rebound of the territory. It is found that high-frequency seismic oscillations with high values of peak accelerations (0.4–0.8 g) and velocities (100–300 cm/s) are necessary for the formation of stone displacements. Kinematic indicators are used to reconstruct the directions of maximum seismic impact and determine the position of the epicenter of a paleoearthquake at several points. The zones of intensity of 7 and 8 are contoured to estimate the depth of the focus ($H = 1.9 \pm 0.2$ km) and magnitude ($M = 4.4 \pm 0.2$) of a seismic event using the macroseismic field equation. Typical WNW elongation of the first isoseist along the northern coast of the Kindo Peninsula is indicative of a seismogenic fault at the southern end of a micrograben of the Velikaya Salma Strait, which feathers the southeastern wall of the Kandalaksha Graben. The Holocene activity of this fault is confirmed by normal fault displacements of young sediments, which have been revealed in a series of transverse seismoacoustic profiles. These results quantitatively showed for the first time that the zone of the Kandalaksha Graben could provide conditions for low-magnitude "shallow-focused" earthquakes with high seismic intensity.

Keywords: displacements of stones, kinematic indicators, secondary paleoseismic dislocations, glacial denudation, neotectonic Kandalaksha Graben, White Sea

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INTRODUCTION

Accumulated paleoseismic data on peripheral areas of the East European Platform in the domestic and foreign literature over the last 15–20 years have stimulated active discussion of problems in the long-term assessment of seismic hazards in these regions. Estimates of the maximum seismic intensity (I_{max}) and, especially, maximum earthquake magnitude (M_{max}), however, are contradictory. This problem is especially urgent for the crystalline Fennoscandian (Baltic) Shield.

For example, some authors suggest the presence of seismic postglacial faults in the regional relief (Assinovksaya and Nikonov, 2004; Lukashov, 2004; Avenarius et al., 2005; Avenarius, 2008; Biske et al., 2009) and accept the presence of strong ($M = 6.5$–8.0) Late Pleistocene and Holocene earthquakes in some seismogenic dislocation zones (Lagerbäck, 1990; Mörner, 2003, 2004; Nikonov, 2003, 2004; Rodkin et al., 2012; Nikonov et al., 2014; Nikolaeva et al., 2016; Shvarev and Rodkin, 2018).

Researchers consider the presence of similar dislocations a serious argument for a significant increase in seismic hazard in northwest Russia. For example, maps C and D of a new suite of of general seismic zoning maps of Russia, GSZ-2016 (Explanatory note..., 2016), which have been compiled to replace the GSZ-97 maps, show a maximum seismic shaking intensity up to 7 and 8 on the coast of Kandalaksha Gulf and up to 7 in the northern part of the Karelian Isthmus.

As seen from a critical analysis of publications, most pay little attention not only to problems of parametrizing the newest dislocations, but of substantating their seismic origin according to commonly accepted criteria (*Paleoseismology*, 1996). Due to the low level of seismicity, a significant methodological problem is the absence of historical seismic dislocations or analogs in this region, which could be evidence of standard objects for comparison with ancient faults. It should be taken into account that, in the Late Quaternary, the Baltic Shield repeatedly underwent cover glaciation and cryogenic processes, which dislocated the subsurface part of the crust (Gruszka and van Loon, 2011). In addition, powerful water and mud flows from thawing glaciers could have intensely deformed sediments (Grigor'ev, 1986) including, as was shown by our research, the formation of horizons of intralayer plicative deformations well consistent along the strike, which are similar to seismic convolutions of lacustrine sediments (Gorbatov and Kolesnikov, 2016). These circumstances require careful interpretation of young dislocations in the region to avoid skip target and false alarm errors.

At the same time, the present-day relief of the Baltic Shield exhibits a clear fault stoney morphostructure, which may be a result of postglacial differentiated movements at the boundaries of segments of the crystal basements, as well as erosion of ancient fracture systems in the Late Quaternary. The faults are expressed as linear elements of the relief: e.g., straightened areas of river valleys, direct coast lines, ravines, and direct boundaries of rocky uplifts. These zones concentrate local rock dislocations in the form of ledges, cracks, open fissures, landslides, and separated stones, which are the most accessible to study in areas of truncated denudation–tectonic relief devoid of a solid glacial cover. In recent decades, these faults are unambiguously attributed to the results of strong seismic impacts; however, they can form without seismic shaking.

The White Sea Zone (the southwestern coast of the Kandalaksha Gulf) is one of the possible seismogenic structures of the region, is conjugated with the neotectonic Kandalaksha Graben, and is characterized by highly contrasting stone movements and a higher level of present-day seismicity relative to the adjacent regions (Lukashov, 2004). In our work, which studies a relatively small area (Fig. 1) of the southwestern coast of the Kandalaksha Gulf (the area of the Kindo Peninsula) with an expressive complex of dislocations of the glacial relief, we considered the genesis of these faults and assessed the role of seismic processes during their formation based on geomorphological, structural, and geological observations.

The finding and dating of a small group of likely seismic dislocations of the Kindo Peninsula and adjacent rock outcrops of Cape Zelenyi and Olenevskii Island are the results of previous studies of this area of the White Sea coast. The data on the disturbed relief include a combination of ditches and fractures with steep rock walls, ledges between displaced surface areas, reversed clasts, stony chaoses, and swallowtail ravines. The radiocarbon ($^{14}C_{cal}$) age of peat soils preliminarily indicates that the parental event occurred between 400 years BCE and 632 years CE (Marakhanov and Romanenko, 2014).

NEOTECTONIC STRUCTURE, ACTIVE FAULTS, AND SEISMICITY OF THE STUDIED REGION

The area of the Kindo Peninsula is characterized by a structural–denudation ridge–hilly pediment plain with absolute heights up to 100 m and formed on dislocated rocks of the White Sea Megastone. The Kindo Peninsula and adjacent regions of Velikii Island are composed of amphibolites and amphibole and garnet–amphibole schists with intrusions of gabbro and gabbronorites of the intermediate sequence of the Beloe More Group and Paleozoic porphyritic dikes. In the south of the peninsula, migmatized gneiss granites and biotite gneisses of the lower sequence of the Beloe More Group are dominant on Cape Zelenyi and Olenevskii Island. In the structural–tectonic aspect, the territory occurs on the eastern wing of the Ena–Loukh Synclinorium with a dominant north and northeast dip of rocks (Smirnova and Solodskaya, 1959; *Geologiya*..., 1960).

Analysis of a lineament network of the Karelian coast of the Kindo Peninsula (Baranskaya and Romanenko, 2013; Kosevich and Romanovskaya, 2014) showed the significant role of WNW-trending subsidiary faults relative to the normal fault system, which forms an axial graben of the Kandalaksha Gulf (Fig. 1).

The present-day tectonic activity of the Kandalaksha Graben is indicated by extended narrow asymmetric depression zones (semigrabens), which are bounded from the southeast by normal faults, which were found in seismic acoustic bottom profiles of displacements (up to 10–12 m by amplitude) of anomalous thick sequences of Holocene lacustrine–glacial and marine sediments (Nevesskii et al., 1977; Maev et al., 2010; Rybalko et al., 2011). The postglaciation integral relative depression of the graben blocks versus the general glacial isostatic rebound of the territory is also well manifested in the typical curve of isobases to the northwest (Evzerov et al., 2014).

The newest structure of the Kandalaksha Graben demonstrates that its fanlike opening was characterized by a horizontal extension axis transverse to the longitudinal axis of the structure (Sim et al., 2011). The mechanisms of earthquake foci in the eastern part of the Baltic Shield, which exhibit dominant horizon-

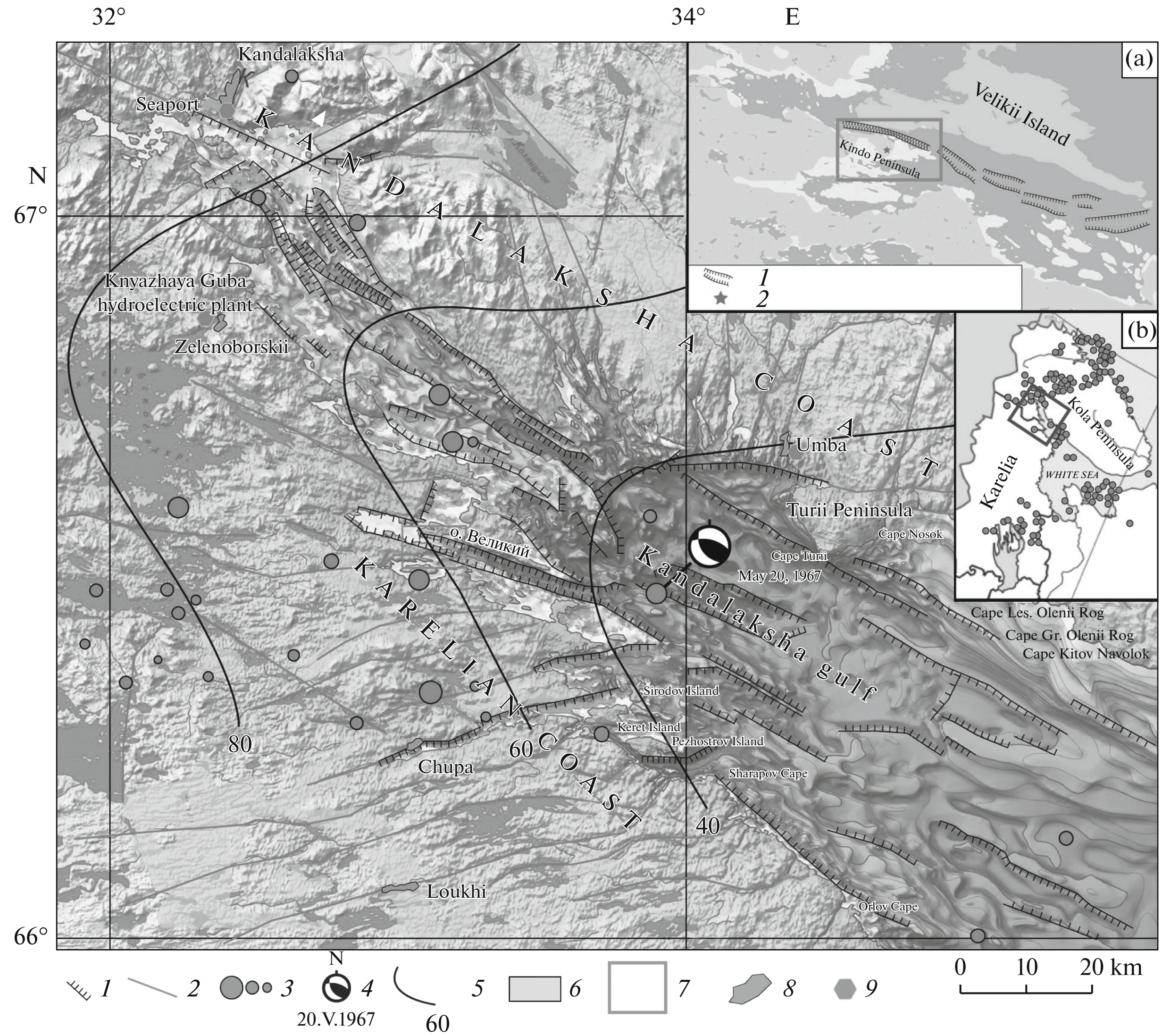

Fig. 1. Scheme of most recent tectonics of area of Kandalaksha Bay and location (insets) of area of paleoseimic studies. (*1*) Major tectonic ledges in graben system of water area according to analysis of digital relief model of territory (Nikiforov et al., 2012); (*2*) coastal faults distinguished by geomorphologic features; (*3*) epicenters of earthquakes with magnitudes of 0.9–4.5 for instrumental observation period (according to summary of seismic catalogs (Evzerov et al., 2014) (size of circle is correlated with *M*); (*4*) diagram of focal mechanism of 1967 Kandalaksha earthquake (areas of compression waves are shaded); (*5*) isobaths of isostatic rebound, m; (*6*) areas of accumulation of Quaternary sediments that overlap crystalline basement (based on geological maps of Soviet Union on scale of 1 : 200000); (*7*) studied area (for scheme, see Fig. 6); (*8*) populated area; (*9*) industrial and socially important objects. Inset: (*1*) micrograben of Velikaya Salma Strait; (*2*) Mt. Rugozero.

tal compression with a NW- and NNW-oriented axis, are consistent with the graben structure (Slunga, 1989; Avetisov, 1996). The NW to WSW change of the strike of the auxiliary faults relative to the axial normal faults of the Kandalaksha Graben (Fig. 1) indicate some rotation of the axes of tectonic stresses along its southeastern wall.

Under northeastern horizontal extension combined with northwestern compression, the tectonic stress in the zone of the Kandalaksha Graben may be discharged both at shear and normal fault–shear movements along the faults of longitudinal (northwestern) strike to the graben axis and reverse movements on orthogonal (northeastern) faults. Taking into account the dominant steep (vertical) faults of the crystal basement (Lukashov, 2004) and smaller strength of rocks to extension and shear rather than to compression, the most possible mechanisms of paleoearthquakes in the graben zone should be strike-slip and normal–strike-slip faults, whereas most seismogenic zones have faults longitudinal and diagonal to their axes. The results of studying the fractal properties of the lineament networks of this region are independent evidence of the significant role of shear deformations of the entire White Sea Basin (Moralev et al., 2000).

From the onset of earthquake detection in 1954, local seismic stations in the apex part of the Kandalaksha Gulf and coastal land have detected more than 40 seismic events with magnitudes from 1.2 to 4.8 and significantly higher density of foci relative to adjacent regions (inset (b) in Fig. 1). The strongest earthquake is the Kandalaksha earthquake of May 20, 1967 ($M_S = 4.8$; $H = 17$ km; $I_0 = \text{V}$), the epicenter of which (66.48° N, 33.9° E) was located in the axial part of the Kandalaksha Gulf almost at the intersection with the axis of the micrograben of the Velikaya Salma Strait. The isoseists of this earthquake generally occur along the axis of the graben, and the solutions of the foci mechanisms showed reverse–left lateral strike–slip movement along the steep plane of the NW-trending fault (Assinovskaya, 1986).

The distribution of earthquake epicenters indicates that tectonic activation of the Kandalaksha Graben affected both the water area and adjacent regions of the southeastern flank to a distance of 50–100 km. This distribution points to Holocene activity of latitudinal subsidiary faults, which have been distinguished on the map by Babak and Nikolaev (1984).

Thus, analysis of the present-day structural plan, lineament network, distribution of Holocene movements, and peculiarities of the regional stress field and seismicity of the Karelian coast admits the presence of point paleoseismic dislocations concentrated along activated faults. Directly in the area of the Kindo Peninsula, potential seismogenic structures can be wall faults of the micrograben of the Velikaya Salma Strait, which continues to Rugozero Bay, and their cross-cutting faults (Fig. 1, inset (a)). The presence of local paleoseismic dislocations along the tectonic zone of the Velikaya Salma Strait was suggested earlier (Avenarius, 2005, 2008; Romanenko and Shilova, 2012; Marakhanov and Romanenko, 2014). According to continuous seismic profiling, the micrograben is clearly evident in the relief of the primary bottom as a chain of asymmetric depressions 100–300 m deep, which are divided by barriers (Maev et al., 2010). The south wall of the micrograben, which is adjacent to the Rugozero–Kuzokotskii tectonic block, is steeper and more dissected, emphasizing the greater velocity of Holocene vertical movements along this fault.

FACTUAL MATERIAL

The most representative rock massif (the area of Mt. Rugozero in the center of the Kindo Peninsula) is characterized by the most intense dislocations of the postglaciation relief. The mountain (the height of the top is 99.7 m above sea level) is located in the western and central parts of the peninsula. This rock massif is a rounded–elongated range similar to a whale back, 3 × 1.5 km in size with stepwise southern and eastern slopes and weakly dissected top surface smoothed by a glacier. The stone is composed of Archean schistose amphibolites with dip angles of layers of 10°–40°. The highland in the rocky piedmont is composed of Holocene marine terraces with sandy–pebbly sediments and boulders. The territory is covered by a dense pine forest, which hampers photography of operational areas.

The stepwise faults of the relief of the eastern and northeastern slopes of Mt. Rugozero have been mapped in detail at a point with coordinates of 66°32.7′ N, 33°8′ E. The steepest slopes are complicated by a series of steep rock ledges 1–2 to 5–7 m high, which are intersected by a branched network of erosion gullies, the bottom and slopes of which are overlapped by a thin colluvial cover (Fig. 2). Locally, often in the lower parts of the slope, the gullies narrow, ending in fissures up to 3 m deep.

The rock ledges are formed along vertical fissures, and the step surfaces mostly coincide with planes of rock foliation (measured in the ledge walls), which dip below the slopes of the highland. In plan view, the terracelike steps smoothly contour the core of the stone, changing strike from east to north. The height of the ledges and the degree of fracturing of the stone increase in the same direction. For example, the E-trending ledges are characterized by smoothed edges and the absence of clastic inrush at the base. The steep walls of longitudinal ledges on the eastern and northeastern slopes of the mountain are complicated by fresh tension surfaces of massive stones, horizontal movements of some individualized stones (Fig. 3) along the surfaces of foliation, and more rarely, separation of small stony columns (Fig. 4g) along the vertical lateral-pressure fractures. Below the steep walls, there are massive and linear inrushes of angular stones (Fig. 4d), the tail widths of which reach 1.5 times the height of the ledges.

The eastern slopes demonstrate the presence of two fresh (without features of glacial and fluvial weathering) tension cracks of NW and NNW strike, which intersect parallel ledges at 45°–90°.

Steeply dipping NW-trending fault A, 5–10 cm wide, is traced for 30 m and intersects six ledges 0.5–3.0 m in height (Fig. 5). In the intersection zones, there are eight protrusions of rocky plates as opposed to inclination of the step surfaces, including three counterclockwise-rotated stones on the southeastern flank of the fault (Fig. 5).

Parallel to fault A from the west, there is a 5-m steep ledge at a distance of 5–10 m, the upper part of which exhibits very large (up to 30 t) detached rhombic stones along the step line in plan view. The stones are displaced by foliation planes 10–40 cm toward the fault (to north) with formation of tension cracks in their rear parts (Fig. 5, point 4).

NNW-trending fault B, 150 m long, is located in the upper part of the eastern slope. In the relief it is

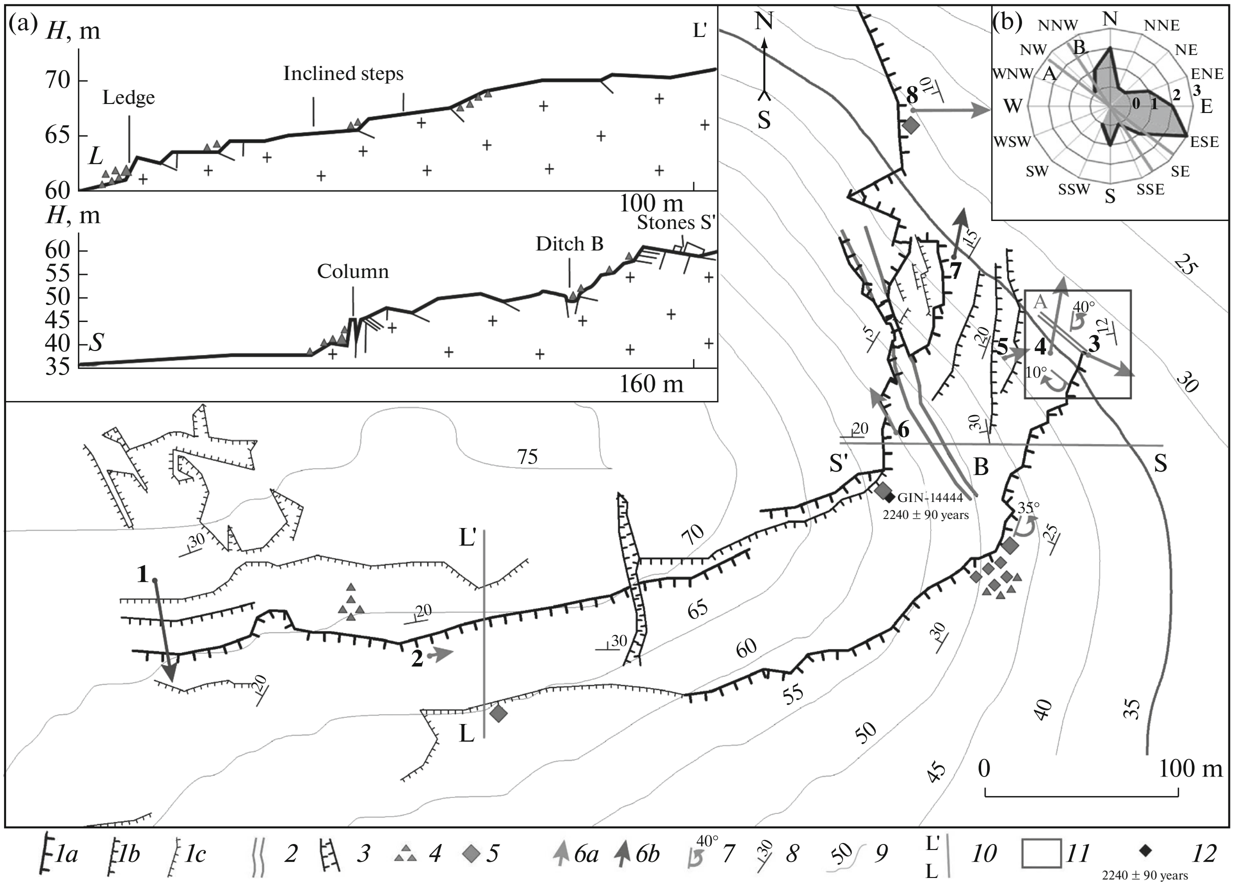

Fig. 2. Structure of zone of postglacial dislocations of primary rocks on eastern slopes of Mt. Rugozero. (*1*) Ledges 7–5 (*a*), 5–2 (*b*), and 2–1 (*c*) m high; (*2*) faults A and B; (*3*) gullies; (*4*) stone collapses; (*5*) inrushes of large stones; (*6*) displacements of inrushed stones along inclined surfaces: against (a) and along (b) inclination (arrow length is correlated with displacement values; numbers of vector correspond to number of points in Table 1); (*7*) rotations of stones and strike of tension walls; (*8*) bedding elements of schistose rocks; (*9*) isohyphses of relief, m above sea level; (*10*) line of profile; (*11*) area shown in detail in Fig. 5; (*12*) sampling places of buried soil and its radiocarbon age. Insets: (a) structure of geological–geomorphological profiles; (b) compass diagram of direction of displacement of stones and strike of extension cracks.

expressed as a chain of ditches 0.5–3.0 m wide, which transit to the short fissures at intersections with edges of inclined steps. The pull-apart fault occurs in a rear part of the stone 50 × 30 × 7 m in size separating it from the rocky step by an open fracture (Fig. 4a), which was formed due to sliding stone along the NW-dipping plane.

In the studied area, several dozen displacements along inclined foliation planes of plates and stones of massive rocks have been chipped from indigenous ledges including from the lower parts of walls with the formation of niches. The stones mostly jut transverse to the ledges into the free space and, in two cases (points 2 and 7), are displaced along the ledges.

Point 8 shows a 4-m ledge of a plate 2 × 2 × 0.8 m in size chipped from the base with the formation of a niche, which is partly covered by a vertical stony column detached from the ledge (Fig. 3, point 8; Fig. 4f).

We documented only those cases when concordance between the tension wall and the rim of a chipped fragment could reliably be established by a similarity of form. Table 1 shows the parameters of natural observations, namely: the mass of the stones (calculated by their volume and average density of rocks), the azimuth of the displacement vector, the values of general and vertical displacements, the bedding elements of the slip plane, and the strike of the tension wall.

Natural observations showed that the stones in the form of rhombic, triangle, and irregular plates 0.2–2.0 m thick and 0.5–5.0 m wide with typical displacements of 5–60 cm and a vertical component of –20 to +7 cm are dominant. The displacement of the stones of the eastern (80°–130°) and northern (330°–10°) courses dominate, along with single movement of the stone along the slope to the south (Fig. 2, inset (b)), and the maximum displacement values of are typical of azimuths of 90° and 110°.

In addition to translatory stone displacements in the area of Mt. Rugozero, five rotations of fragments

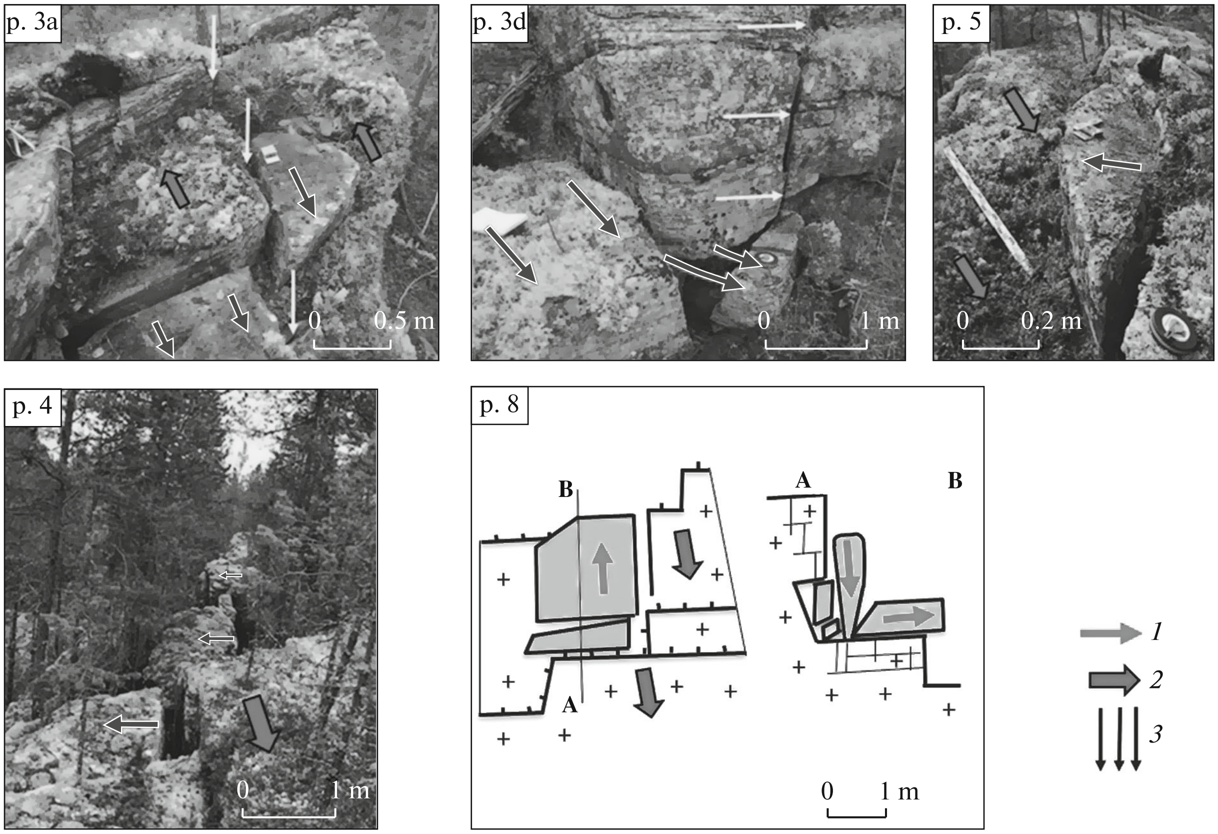

Fig. 3. Displacements and rotations of fragments of rock ledges of Mt. Rugozero. (*1*) Direction of displacement; (*2*) direction of maximum inclination of ledge surfaces; (*3*) fault A. Location of points 3a, 3d, and 4 is shown in Fig. 5 and that of points 5 and 8 is shown in Fig. 2.

Table 1. Characteristics of displacements of stones of rock ledges of Mt. Rugozero

Point*	Mass of stone, kg	Azimuth of transportation, deg	Displacement (general and vertical) L/H, cm	Azimuth and inclination of dip line of sliding plane, deg	Strike of the tension wall, deg	Calculated peak velocity *PGV*, cm/s
1	500	170	55/–20	170/–	80	220
2	400	80	10/–	–	90	125
3a	600	110	40/6.9	260/12	0–10	280
3b	1500	110	14/2.4	260/12		160
3c	1000	130	5/0.7	260/12		95
3d	500	120	30/4.7	260/12		240
4	30000	10	30/0.0	280/20	130	220
5	500	70	14/3.6	290/20	0	170
6	20000	330	–	300/15	150	–
7	1000	10	20/–1.7	300/15	140	170
8	13000	90	40/6.3	250/10	170	275

* For location of points, see Fig. 2.

Fig. 4. Major types of postglacial violations of relief of rock massifs of tudied area: (a) vertical fracture B with opening up to 50 cm, Mt. Rugozero, wall of ledge near point (6) north view; (b) fracturing of horizontal rocky plate with unidirectional opening fragments up to 30 cm, area of settlement of Chupa, top view; (c) fracturing of migmatites in exposed ancient fault zone, southern coast of Velikii Island, north view; (d) coarse-stone inrush below 6-m ledge, Mt. Rugozero, top view; (e) inrush of large stone from coastal ledge, Cape Zelenyi, north view; (f) separation of rock column below protruded stone, Mt. Rugozero, point 8 (for sketch, see Fig. 3).

of ledges of different strike have been revealed, including two cases established by comparison of the foliation planes of rocks in the suggested tension walls and rotated stone.

In the rear part of one step of the slope of Mt. Rugozero, a trench 50 cm deep was dug close to a stone 1 × 3 m in size, probably thrown from the overlying ledge (see Fig. 2 for location of trench). Paleosoil sample no. GIN-14444 was taken from the lower edge of the stone for radiocarbon dating, which was determined at the laboratory of the Geological Institute, Russian Academy of Sciences. The black paleosoil is overlapped by a layer of rubble colluvium with gruss, which is replaced by the present-day brown peat soil. Because the paleosoil formed in the closed depression before the collapse of the stone and formation of colluvium, 2240 ± 90 yr is the lower age limit for collapse of the stone.

The rock massif near Biofilter Bay and the northern coast of Cape Kindo (2.5–3.0 km ESE of Mt. Rugozero) ranges up to 30 m, which steeply terminates toward the sea. It is characterized by longitudinal fractures and deep fissures that extend to the sea. The flat top of the range exhibits numerous fracturing of rock outcrops, which have been smoothed by a glacier, locally, with significant displacements of fragments in W–N and S–E quadrants, with squeezing of some stones to the top. In addition, clockwise rotations of stones by 30°–45° were observed in the latitudinal ledges.

A series of latitudinal ledges that descend to the coast in an echelon manner, with relatively weakly developed stone landslides and the absence of stone displacements, were found in a 20-m rock massif on the southern coast of Velikii Island located opposite Mt. Rugozero (1 km northeast). The ledges are cut by ditches and linear fracture zones along the exposed ancient faults (Fig. 4c), which extend into small bays overwhelmed by stony chaoses. The bays are bounded by strongly fractured rock outcrops of migmatized granite gneisses and amphibolites.

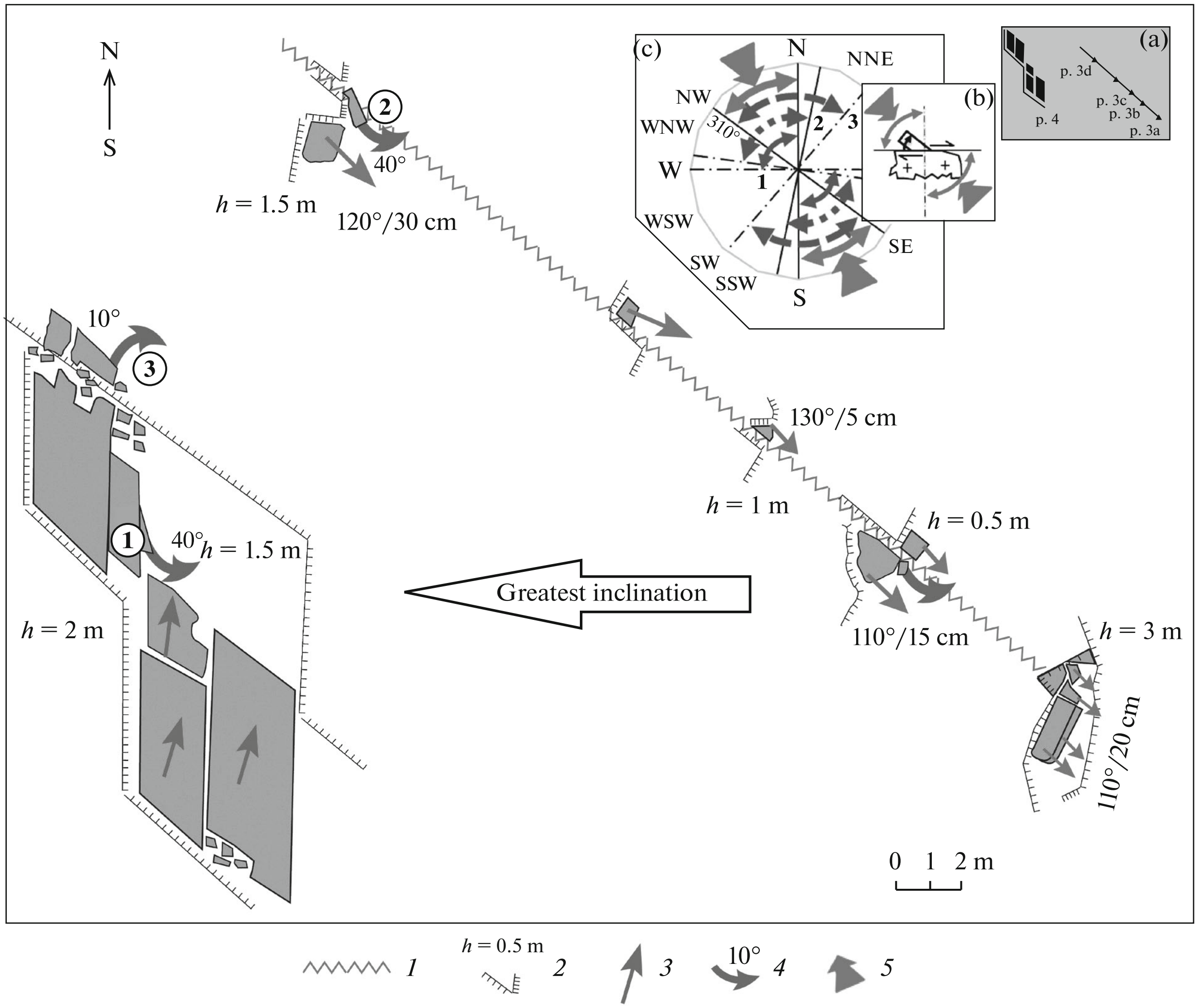

Fig. 5. Mass displacements and rotations of stones in fault zone A on slope of Mt. Rugozero. (*1*) Fault A; (*2*) ledges and their height; (*3*) vectors of displacement of stones along inclined surfaces of ledges; (*4*) directions of rotation of stones; (*5*) possible directions of maximum seismic impact (for insets, see Figs. 5b, 5c). Insets: (a) mutual location of areas and points of study (see characteristic of point in Table 1); (b) principal scheme of determination of quadrants of seismic impact (arch) along strike of tension wall and direction of rotation of stone; (c) determination of azimuth sectors of maximum seismic impact (bounded by arches) by superposition of quadrants for three rotated stones (1–3) (numbers in circles in plan).

The relief of the low (up to 15 m) rocky range on Cape Zelenyi (2.5 km south of Mt. Rugozero) is complicated by a series of asymmetric smoothed crests with single landslides in the coastal part (Fig. 4e). The range is cut by a transparent cutting up to 15 m thick with a steep south wall up to 5 m high and a flat bottom with peat. We should emphasize the absence of boulder landslides below the steep southern wall of the cutting and a buried colluvial wedge in the peat layer, which could indicate seismic influence in this place. For example, a peat layer 60 cm thick with rare inclusions of angular clasts no larger than rubble size was found in the trench, which was dug in the near-wall part of the bottom up to marine pebbles. Thus, the latitudinal cutting of Zelenyi Island is probably an ancient relief form, which did not undergo significant renovation after exposure from the sea.

Small traces of fracturing of primary rock outcrops and individual stones, which are visible in the storm flood zone devoid of land plants were found on Olenevskii Island and adjacent uninhabitated small islands (3.5 km south of Mt. Rugozero), as well as on the southern coast of Velikii Island east of Lobanikha Bay (5–6 km east of Mt. Rugozero).

DISCUSSION

Detailed study of the ledges, fissures, ditches, and other linear faults in the rocks of the Kindo Peninsula revealed no evident features of pulsatory tectonic movements during their formation: displacement of reference surfaces marked, e.g., by glacial striation; slickenlines on the ledge walls; and continuation of faults or plicative deformations in the overlapping loose sediments. Thus, it is incorrect to consider zthese linear faults have a seismic tectonic origin based on morphological features alone.

Most likely, the stepwise difference of the surfaces of rock ledges, locally interpreted as seismic tectonic ledges, are caused by structural heterogeneity of the rock massifs, which is manifested during selective activity of glacial exaration and postglacial erosion, gravitation, and cryogenic processes with possible seismic vibration impacts. For example, the rock ledges mapped on the eastern slopes of Mt. Rugozero are curved in plan view, which is atypical of tectonic dislocations (Fig. 2), and their convex parts are directed toward the top, which is also atypical of the tension walls of rock landslides. The conjugation of rock ledges with rotation of the strike line of amphibolite foliation around the core of the massif (Fig. 2) indicates that the stepwise slopes resulted from exposure of a geological structure rather than manifestation of the most recent tectonic dislocations or gravitation sprawling over the marginal part of the rock massifs. For example, traces of smoothing typical of glacial weathering remained on the ledges of the southern slopes of Mt. Rugozero and on the slopes of other rock massifs.

It can be suggested with a high degree of probability that the stepwise surfaces of the southern and eastern slopes of Mt. Rugozero resulted from glacial plucking of stones of rocks and their separation from the rock massif along foliation planes. In this respect, it is logical that stepwise dislocations form on the slopes located in the shadow and along the direction of glacier movement (ESE), and analogous dislocations are absent on the flatter (smoothed) western slopes, where the force of glacial impact was directed toward the massif. At the same time, the fresh habit, sharp angular forms, and no traces of exaration or further abrasive smoothing on the ledges of the eastern slopes show that, after disappearance of the glacier and rebound of the territory above sea level, they continued to be renewed as a result of gravitation and cryogenic or seismic processes. Probably, the postglacial age is characterized by a set of stone displacements, extension fractures, and a halo of gravity dislocations in the area of Mt. Rugozero and adjacent rock massifs.

The inrushes of stones, separation of stony columns, landslides, and other dislocations with a leading role played by gravity could not be an argument in favor of strong seismic impacts in the studied area, although they should be ascribed to the seismic gravity group when proving their genetic relationships to seismic impacts.

More definite conclusions on a possible relationship between dislocation of the relief of rock massifs and seismic impacts can be drawn based on the genesis of tension cracks and displacements of chipped stones along weakly inclined rock surfaces, which were found on the slope of Mt. Rugozero and the top surface of the rock massif of Biofilter Bay.

The lack of mechanical weathering features in strongly rear fractures of stones indicate that they formed from separation of stones along horizontal sliding surfaces (often accessible to observations as open fractures with platy cleavage peeling off the walls) rather than erosion expansion or weathering. The displacement of large stones versus inclination of the sliding surface excludes gravitational mobilization of stones. Thus, the source of impact necessary for opening stony stones should be related to the horizontal force applied by the rock massif.

Wide opening of fractures in rocks, as a rule, is atypical of cryogenic processes related to frost wedging in fractures, because these fractures can expand only until water occurs in the form of films. The only possible explanation for the formation of wide vertical fractures according to cryogenic theory could be related to cyclic filling of frost cracks by water-saturated finely disperse material able to undergo temperature deformation during freezing. No traces of this filling, however, have been found. In addition, the vertical tension cracks are linked to sliding surfaces and have a side output that prevents atmospheric water from remaining in cracks and inundating the loose host material. Separation of small stones may be related to plant roots growing along fractures; however, they cannot explain the movement of large stones weighing tens of tons.

Thus, no features of exogenic transportation of stones have been revealed at this stage of study, which, however, does not exclude their possibility. In addition, for the above-mentioned hypothetical scenarios, some facts are still unclear about fracturing of rock outcrops along systems of fractures with opening fragments in strongly certain direction (Fig. 4b), movement of stones along tension cracks, and the absence of a systematic decrease in the value of displacement with increasing stone size. An alternative explanation for the separation of stones from ledges along the existing fracture system and the formation or opening of small extension cracks in the rock massif is a horizontal seismic pulse directed either from the massif (an impact) or from the crack (a burst). For example, possible evidence of seismic stone dislocations in the area of Mt. Rugozero is the opposite rotation of some stones in ledges with a strike of 0°–20° (counterclockwise, four cases) and 130° (clockwise, one case) for greater rotations (up to 40°) in the ledges of the first group. The same direction of rotation of three stones in the ledges with longitudinal strike can be related to tangential stresses that formed during horizontal surface oscillations directed at an acute angle to the tension crack.

Let us consider the parameters of seismic movements necessary for the formation of stone dislocations judging from the assumption of a weak link between the stones and the rock massif.

For horizontal displacement of stones for an oscillated surfacing with peak acceleration *PGA* (a), the maximum inertia force (ma) should exceed the frictional force of sliding (kmg), which is not related to the stone, i.e., $PGA \geq kg$, where k of 0.4–0.8 is the coefficient of dry friction of rocks and g is gravitational acceleration (980 cm/s^2). Thus, the necessary $PGA \geq$ 0.4–0.8$g \approx$ 390–780 cm/s^2, which corresponds to a seismic impact of intensity VIIII–IX according to the current instrumental macroseismic scale (Explanatory note..., 2016).

The values of stone displacements make it possible to calculate the peak velocity PGV (v) of horizontal displacement of the surface during a paleoearthquake using the equation of kinetic energy balance (Rodkin et al., 2012). Equating the kinetic energy ($1/2mv^2$) of the horizontal impact of the stone and the total work of its movement against the friction force ($kmgL$) at distance L and incrementation (decrease or increase) of its potential energy ($\pm mgH$) with a change in height H, the formula for calculations is

$$PGV = \sqrt{2(kgL \pm gH)},$$

where $k = 0.8$ is the maximum coefficient of dry friction of the rocks.

The calculated peak velocities necessary for stone displacements vary from 95 to 280 cm/s (195 cm/s, on average, Table 1), corresponding to seismic impact with an intensity of IX. The maxima of peak velocities are confined to fault zones A and B (points 3, 8), indicating their genetic relationship with stone displacements.

Thus, the calculated parameters of coseismic movements indicate that, probably, an impact (likely short-term) of the high-frequency component of seismic oscillations with high values of peak accelerations is necessary for the formation of stone displacements with typical movement values of tens of centimeters. The evident discrepancy between calculated the high seismic intensity and general character of the relief of rock massifs is interesting, in particular, the absence of any large seismotectonic fault dislocations (seismic cuttings, seismic ledges) synchronous stone faults in local zones (rock ledges). This phenomenon should further be explained from the physical viewpoint, which assumes a sharp decrease in seismic effects with increasing scales of rock massifs.

Interpretation of stone displacements should take into account the two dominant systems of directions: ESE (seven cases) and N (three cases); the calculated PGV values for both groups of dislocations are almost equal (192 and 195 cm/s, respectively). The presence of main maxima on the compass diagram of displacements does not indicate their seismic nature, because the chipping directions are caused by the primary orientation of vertical fractures of the rock ledges. However, despite the nearly smooth change of the foliation strike by more than 90° and possible rotation of background fracturing along the system of ledges, the displacements have only two directions without NNE, NE, and SSE azimuths. This corresponds to seismic scenarios, but should seriously be substantiated by comparison of strike azimuths of the displacement directions and density distribution of background fractures. It should be noted that more reliable conclusions on the presence of seismic shaking can be drawn when analyzing the spatial distribution of the displacements vectors for free lying stones; however, it is difficult to reveal the position of these stones before transport under conditions of a solid moss–lichen cover.

In the case of seismic origin of stones separated by two fracture systems, it is possible to reconstruct the possible directions of dominant surface oscillations. It is clear that, for two mutually perpendicular directions of stones displacement (ESE and N) with equal peak velocities, the seismic impact should have equal and maximum possible components along these directions, i.e., directed either along their bisector (NE–SW) or perpendicular to it (NW–SE). The first scenario partly contradicts the pattern of displacements shown in Fig. 5 indicating NW–SE direction.

Successful experience in using data on the systematic rotation of elements of structures with different strikes for kinematic interpretation of strong earthquakes (Korzhenkov and Mazor, 2001), including data to reveal the epicenter, makes it possible to apply approaches similar to our measurements of stone rotations. The horizontal rotation of a stone is caused by a shear coupling of forces from seismic waves at an angle to the linear element (in this case, the edge of the ledge). It is easy see that two possible rotational directions correspond to two opposite quadrants of maximum seismic impact (the dominant direction of oscillations), which are constructed at the intersection of the strike line of the tension wall and the normal to it (Fig. 5b).

These observations make it possible to find the search quadrants of seismic impact for each stone. The area of intersection of quadrants of all stones makes it possible to localize the most probable directions of maximum seismic impact in the zone of eastern slopes of Mt. Rugozero. The azimuth diagram with our measurements (Fig. 5c) shows that these directions were located between the north and northwest or south and southeast. It is important that the azimuths of maximum seismic impact, which were interpreted by the directions of rotation, agree with the interpreted translational displacements of stones. Probably, the maximum seismic impact in the area of the eastern slopes of Mt. Rugozero was directed from the NW to SE.

Further discussion of localizing the epicenter of a possible paleoearthquake is based on the assumption

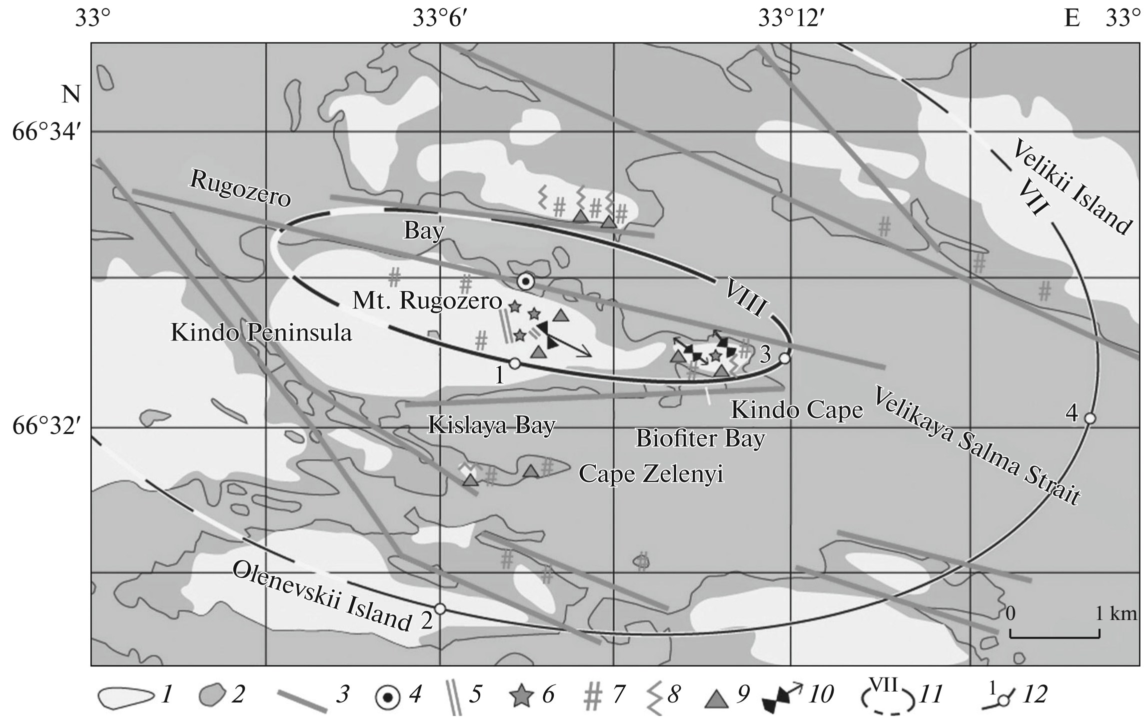

Fig. 6. Distribution of possible paleoseismic dislocations in area o Kindo Peninsula, structural position of focus, and isoseists of paleoearthquake. (*1*) Stones; (*2*) Quaternary sediments; (*3*) lineaments based on morphostructural analysis; (*4*) epicenter of paleoearthquake; (*5*) extension cracks; (*6*) stone displacements and rotations; (*7*) areas of areal fracturing; (*8*) linear faults (cuttings, fissures) with features of seismic renovation; (*9*) inrushes; (*10*) directions of maximum seismic impact along displacements of stones (arrows) and quadrants of seismic impact from interpretation of systematic rotation of stones; (*11*) isoseismals and intensity of earthquakes; (*12*) points for calculating focal depth and magnitude (for explanations, see text).

that the maximum seismic impacts in operation areas were directed along the epicenter–observation point line. This is based on observations of strong earthquakes in epicentral zones that showed that direction of collapse or tilting of buildings are mostly directed toward the epicenter or from it; i.e., these directions, which were measured at many points, are intersected in the epicentral area (Korzhenkov and Mazor, 2001). The orientation of directions of destruction along seismic rays can be explained mostly by the impact of the Rayleigh surface waves close to the epicenters of strong earthquakes. However, in the case of dominant impact of transverse waves, the directions of displacement should be oriented perpendicular (rather than parallel) to directions to the epicenter.

The epicenter was most likely located northwest (rather than southeast) of Mt. Rugozero, corresponding to an increased concentration of displaced stones on the eastern slopes from south to north. The displacements and rotations of stones in the area of Biofilter Bay in the eastern part of the Kindo Peninsula correspond to possible directions of seismic impact in this area, which are focused in the WN and SE quadrants (Fig. 6). Thus, our data indicate the location of the earthquake epicenter in the area of the northern coast of the Kindo Peninsula, close to Mt. Rugozero.

It should be taken into account during interpretations of possible Holocene paleoearthquakes in the studied area and areas of the White Sea coast that, during isostatic rebound, the rock massifs underwent abrasive treatment, which decreases preservation of traces of possible seismic events including systematic stone displacements. For example, the features of abrasive smoothing were found in the relief of the lowland rocky ranges of the Velikii Island and Cape Zelenyi. Determination of the age of possible earthquake should take into account that the stone faults of the eastern slopes of Mt. Rugozero could be formed only after exposure of the rock massif from the sea level and termination of abrasive processes. The age of this event, according to the curve of isostatic rebound of the Kindo Peninsula (Romanenko and Shilova, 2012), is 5.5 ka for the lower (most expressed) areas of rock dislocations, which occur 30 m above sea level.

The radiocarbon age of a single sample of buried soil could not be accepted as the lower age limit of the suggested seismic event, because an individual stone could be chipped from the ledge without seismic shaking. More reliable conclusions can be drawn only after dating of several collapses and in the case of their synchronous formation with stone displacements.

STRUCTURAL POSITION, MACROSEISMIC FIELD, AND MAGNITUDE OF A POSSIBLE PALEOEARTHQUAKE

If displacements of stones and extension cracks have a seismic origin (with some assumptions), and areal stone collapses and inrushes are seismogravitation dislocations, we can interpret the major parameters of the macroseismic field of a possible seismic event. To reveal the structural position of the paleoearthquake focus, the location of the epicenter near the northern coast of Mt. Rugozero is compared with the pattern of the lineament network in the area of the Kindo Peninsula and adjacent water area. The lineaments were distinguished from space images and analysis of a digital relief model (Fig. 6).

The results of lineament analysis show that WNW-trending faults, which border the micrograben of Rugozero Bay and isolated by the direct lines of the coast, play a leading role in this area. These faults are especially well expressed in the northern coast of the Kindo Peninsula. The subordinate lineaments of the lower ranks are mostly characterized by a NW and NE strike. The present-day activity of faults of this area is indirectly supported by the highly contrasting velocities of vertical movements at the boundaries of microblocks during the Holocene (up to 1.5 mm/yr), which were calculated by the dating of bottom lacustrine sediments found at different heights and which were separated from the sea during unequal rebound of the Kindo Peninsula (Baranskaya and Romanenko, 2013).

In comparison with the Kindo Peninsula, weaker seismic dislocations of the rock massifs of Velikii Island adjacent from the north to the micrograben of Rugozero Bay allows us to accept that the coastal fault, which is closest to the peninsula (southern), is seismogenic, which corresponds both to the results of epicenter localization and activity of the southern wall of the micrograben in the Velikaya Salma Strait.

Taking into account the MSK-64 macroseismic scale, our data on the distribution of possible secondary paleoseismic dislocations allow us to attribute Mt. Rugozero and Kindo Cape to a shaking zone with an intensity of VIII, which is indicated by a system of extension fractures and mass stone displacements, whereas massifs with traces of probable vibration fracturing and seismogravitation faults (Velikii Island, Cape Zelenyi, Olenevskii Island) belong to the zone with an intensity of VII. In a first approximation, these two areas can be contoured by elliptical isoseismals typical of epicentral zones of shallow-deep earthquakes, which extend along a possible seismogenic fault in the water area of Rugozero Bay. The most notably shallow depth and extension of the seismic focus are manifested in the typically elongated isoseist closest to the epicenter.

The focal depth and magnitude of the paleoearthquake were determined by standard analysis of the macroseismic field. We used the macroseismic field equation (Drumya and Shebalin, 1985) with an averaged attenuation coefficient, which describes the correlation between the shaking intensity (I_i) at some observation point and magnitude (M), the epicentral distance from this point (R_i), and the focal depth (H):

$$I_i = 1.5M - 3.5\log\sqrt{R_i^2 + H^2} + 3.$$

It follows from this equation that the formula for the difference in intensity at two observation points is

$$I_1 - I_2 = 3.5\log\sqrt{\frac{R_2^2 + H^2}{R_1^2 + H^2}}.$$

The decrease in intensity with distance in this equation does not correlate with the magnitude, which makes it possible to determine the focal depth according to our data. Let us express H from the formula for the difference in seismic intensities:

$$H = 3.5\log\sqrt{\frac{R_2^2 + aR_1^2}{a - 1}},$$

where $a = 10^{(I_1 - I_2)/1.75}$. Taking into account the anisotropy of the seismic intensity gradient, for further calculation, we choose two pairs of points which occur at the intersections of isoseismals with their minor and major axes (Fig. 6). Substitution of the parameters of pairs of points 1–2 ($I_1 = 8$; $R_1 = 0.9$ km; $I_2 = 7$; $R_2 = 3.8$ km) and 3–4 ($I_3 = 8$; $R_3 = 3$ km; $I_4 = 7$; $R_4 = 6.4$ km) results in $H_{1-2} \approx 2.1$ and $H_{3-4} \approx 1.7$ km, i.e., $H = 1.9 \pm 0.2$ km. Note that the formation of systematic displacements of stones at a distance of ~1.5–2.5 km from the epicenter indicates that the resulting seismic impact in this sector was directed to the horizon at ≤45°; thus, the focal depth could not have been significantly higher than this distance, comparable with the calculation result.

To calculate the paleoearthquake magnitude, let us rewrite the macroseismic equation as

$$M = \frac{2}{3}I_i - 2 + \frac{7}{6}\log(R_i^2 + H^2).$$

Substitution of the characteristics of one of the two observation points from each point into this formula yields the lower and upper magnitude values: $M_{\min} = 4.2$ and $M_{\max} = 4.6$ or $M = 4.4 \pm 0.2$.

We can indirectly determine the length of the seismogenic fault (L, km) and the maximum value of displacement along it (D, m) using the regression correlations of these parameters with the magnitude for instrumentally detected earthquakes. Taking into account the low focal depth of the paleoearthquake and shear scenario of earthquakes typical of the region, it makes sense to use the regression equation for seismic shear surface dislocations to estimate these parameters for the seismogenic fault (Lunina, 2001):

$$\log L = -1.95 + 0.49M \quad (r = 0.75,\ n = 112),$$

$$\log D = -4.86 + 0.71M \quad (r = 0.85, n = 97).$$

Substitution of the calculated magnitude yields the following quantitative characteristics of the focus: $L = 1.7 \pm 0.3$ km and $D = 2 \pm 0.5$ cm. It follows from this L value that extension of the seismogenic fault did not exceed the depth of the hypocenter ($L < H$, on average), thus the seismic focus was apparently buried.

These magnitude values of possible earthquake are somewhat lower than the magnitude of the Kandalaksha earthquake of 1967 ($M_S = 4.8$) and is significantly lower of indirect estimations according to the chronicles of the magnitude of the earthquake on May 31, 1627 ($M = 6.5 \pm 0.5$; $H = 25$ km; I_0 = VIII), which occurred at the center of the White Sea coast (Nikonov, 2004). The shaking intensity of this earthquake was no more than VI, which does not suggest the formation of seismic dislocations expressed in the relief of the rock massif.

The paleoearthquake magnitude can also be estimated from the average mass velocities (PGV) determined in the area of Mt. Rugozero ($R \approx 0.5$ km). This estimate used a nomogram (Rodkin et al., 2012) elaborated from statistically significant empirical correlations of $PGV = f(M, R, H)$ from a large statistical data set on explosions and strong earthquakes. The value of the search magnitude, according to the graphs, is 6; however, due to the small area of development of secondary seismic effects (60–80 km^2), this value is considered overestimated.

CONCLUSIONS

The following conclusions can be drawn based on our comprehensive paleoseismic studies of the southwestern coast of Kandalaksha Bay of the White Sea.

(1) An area (10 × 6 km) of postglacial dislocations with a radiocarbon age of no more than 5.5 ka has been identified on the slopes and top surface of rock massifs of the Kindo Peninsula. This zone (4 × 2 km) is characterized by the presence of tension cracks and numerous displacements (up to 50 cm) and is surrounded by a belt of gravitation dislocations.

(2) It is found that the complex of dislocations can bear traces of seismic shaking in the form of directed horizontal protruded stones from rock ledges and their systematic rotations in the walls of the same strike and localization of the epicenter of a possible paleoearthquake, which was interpreted based on these kinematic indicators, coincides with the zone of maximum intensity of dislocation of the relief.

(3) The earlier suggested seismotectonic or gravitation–seismotectonic origin of ditches, fissures, some ledges, stepwise surfaces, and other linear dislocations of rock massifs has been proven false. Probably, they are a result of glacial denudation and further erosion of structural heterogeneities of the rock massifs.

(4) The quantitative estimates of possible seismic shaking show that impacts of the high-frequency component of oscillations with high (0.4–0.8 g) values of peak accelerations are necessary for the formation of stone displacements.

(5) The formation of a group of paleoseismic dislocations could be related to local shallow-focus ($H \approx 1.9 \pm 0.2$ km), low-magnitude ($M \approx 4.4 \pm 0.2$) earthquakes with an intensity up to VIII, which is evident from the results of qualitative analysis of the macroseismic field.

(6) Peculiarities in the orientation of the major axes of isoseismals and localization of the epicenter show that the paleoearthquake focus was probably located in the zone of a longitudinal (WNW–trending) fault in the water area of Rugozero Bay, which is a continuation of the southern end of the micrograben of the Velikaya Salma Strait, which surrounds the Kandalaksha Graben.

(7) The most recent structural plan of the Kandalaksha Graben, which formed under regional NW and NNW horizontal compression, shows that normal–strike-slip and strike-slip faults were most likely responsible for the paleoearthquake, whereas longitudinal (magistral) and diagonal (auxiliary) (to the graben axis) faults in the zone of its southeastern wall were potential seismogenic zones.

We also proposed a new methodological approach to identify and analyze secondary seismic dislocations, which is able to solve seismogeological problems on the crystalline shield when no seismotectonic faults are found or they are inaccessible to study of the seismic zoning and estimation of seismic hazard in the areas with especially important and technically complex structures.

Our data assume the possible origin of a Holocene low-magnitude earthquake in the area of the southeastern wall of the Kandalaksha Graben without seismic fault features on the surface with a typical low focal depth, which caused high seismic intensity and numerous traces of seismic shaking (secondary seismic dislocations) of the relief. A possible, similar seismic event in the future should be taken into account in the exploitation and planning of especially important and technically complex structures in the area of the Karelian coast of the White Sea (the chain of Niva hydroelectric plants, hydroengineering structures, infrastructural objects of the Kandalaksha Seaport and Oktyabr'skaya Railroad, and high-voltage power lines).

It should be emphasized that our results have yields no ultimate conclusions on the genesis of the entire complex of dislocation of the relief, although some of them undoubtedly bear traces of seismic shaking. Further studies of this region should be directed, first, at ultimately solving the problem of the origin of stone displacements, their dating, identification of a genetic relationship with numerous gravitational dislocations, and the search for traces of seismic events in profiles with loose sediments. For example, deformation structures, some of which are similar to seismogenic convolutions and injection dikes, have been found relatively near (10–30 km) the studied area in three profiles of Upper Pleistocene and Holocene sediments (area of the Polyarnyi Krug railway station, the settlements of Chupa and Malinovaya Varakka). The later age and rapid attenuation with distance of the seismic intensity of a possible paleoearthquake in the area of the Kindo Peninsula, however, prevent their correlation with this event.

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