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GEOLOGY

Seismogenic Deformations in Early Holocene Sediments of the Pechenga River Terrace (Kola Peninsula)

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The Kola Peninsula, an element of the northwestern Baltic Shield, is not a high-seismicity region at present. This has not always been the case, however, as is evident from seismic paleodeformations reflecting strong earthquakes. The latter were discovered in the course of geologic–geomorphologic works and the analysis of air photos of mainly crystalline rocks [1]. Morphologic patterns and genetic aspects of deformations in incoherent sediments of the Kola region have yet to be sufficiently studied despite the fact that many researchers have reported such structures. Their origin is usually attributed to glaciotectonic and cryoturbation processes. Indeed, distortions of such kind are widespread in Quaternary sediments, because the region under consideration was repeatedly subjected to glacial impact. At the same time, deformations in incoherent sediments were also caused by other phenomena—those related to the strong seismic impact. Deformations in incoherent sediments provoked by modern earthquakes are known not only in seismoactive regions, but also in territories of moderate seismicity, such as Canada, Fennoscandia, and Russia [2–5].

Recently, special studies were carried out to define different types of deformations in Quaternary sediments exposed in quarries and natural outcrops along river banks in the northwestern Kola region (Fig. 1) and to discriminate them from those related to the glacial impact.

One such section is located in the Pechenga River valley (Fig. 2). In this area, the 25-m-high terrace under a 20-cm-thick soil–vegetation layer on the right bank includes the following sediments (from top to bottom):

(1) Sandy–pebbly layer (0.0–0.5 m) occurring at the erosion surface.

(2) Uniform loams (0.5–3.2 m) with sandy–pebbly material at the base. The sediments contain shells of the marine mollusks *Pholas crispate* L. and *Mya truncata* L. The lower boundary of the layer is sharp and uneven because of the loamy material penetrating into sands.

(3) Fine-grained sands (3.2–8.4 m) characterized by cross-sinuous bedding (thickness ~0.3–0.75 m) and with intercalations of uniform massive sands (~0.02–0.8 m) and varved clays. The sand layer with cross-sinuous bedding in the upper part of the member is deformed. The lower boundary is eroded, wavy, and marked by pebbles.

(4) Inequigranular uniform largely fine-grained sands (8.4–13.5 m) with clay interbeds. Some sandy

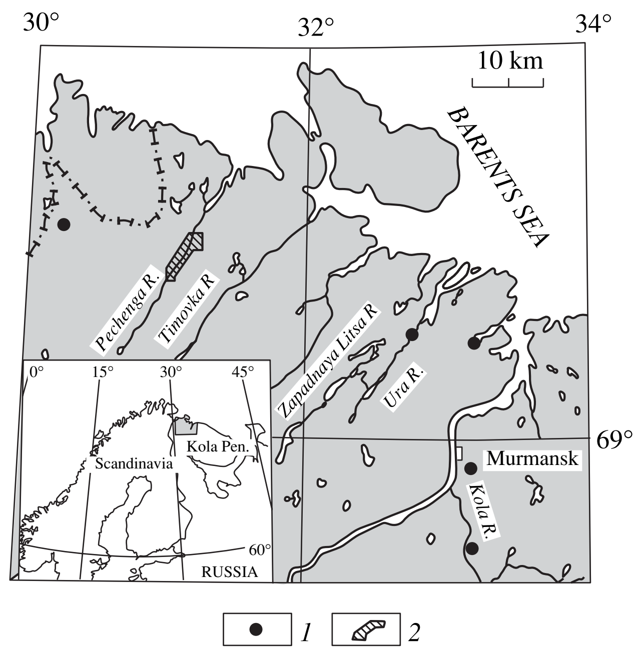

Fig. 1. Schematic location of examined sections in the northwestern Kola Peninsula. (*1*) Examined sections; (*2*) location of Fig. 2.

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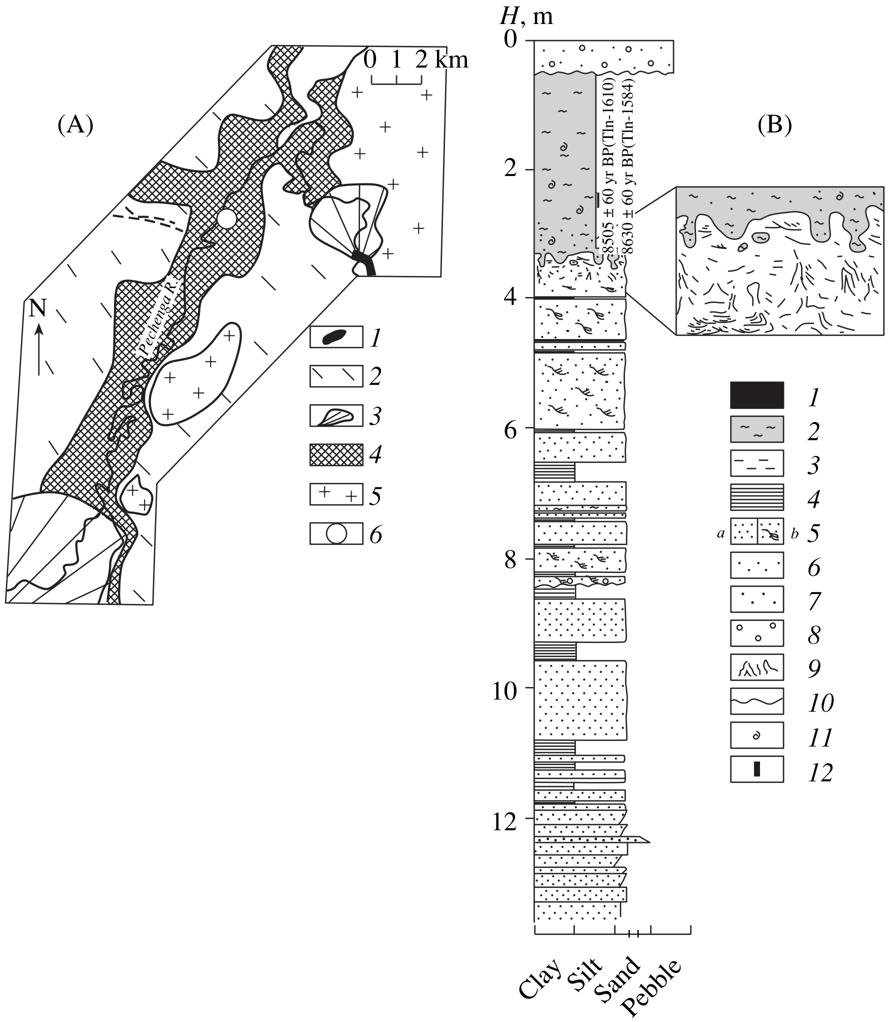

Fig. 2. (A) Different lithological types of Quaternary sediments in the Pechenga River valley and (B) section of late postglacial sediments. (A): (*1*) Marginal moraine pressure ridges; (*2*) main moraine; (*3*) fluvioglacial deltas; (*4*) glaciomarine and marine sediments; (*5*) crystalline rocks; (*6*) section location. (B): (*1*) Clay; (*2*) loam; (*3*) silt; (*4*) frequent clay–silt and clay–sand alternations; (*5*) fine-grained sand: (*a*) uniform, (*b*) cross-bedded; (*6*) medium-grained sand; (*7*) coarse-grained sand; (*8*) pebble; (*9*) deformed sand; (*10*) erosion boundary; (*11*) finds of marine moluscan shells; (*12*) sampling sites for radiocarbon age determinations.

layers bear elements of poorly expressed convolute bedding and ripple marks. All beds are bounded by subhorizontal surfaces.

The sandy–pebbly alluvial sediments overlie marine loams. Their genesis is indicated by abundant shells of marine mollusks. The radiocarbon age obtained for the *Pholas crispate* L. shells is 9200 ± 100 yr (LU-328). The spores–pollen assemblage from sediments of this section indicates, however, more mild climatic conditions characteristic of the Boreal time [6]. Subsequently, two *Pholas crispate* L. and *Mya truncata* L. shells provided radiocarbon ages of 8505 ± 60 (Tln-1610) and 8630 ± 560 (Tln-1584) yr [7]. Similar age is also defined for fragments of other shells. It can be assumed that the sea transgression in this area commenced approximately 8–8.5 ka ago. The plot of relative shift of the sealevel [8] shows that the accumulative cover of the terrane formed ~6 ka ago.

Judging from lithology, structures, and bedding patterns, marine loams are underlain by sediments constituting the distal part of a fluvioglacial delta. They were deposited by low-energy river and mud flows in the remote part of a near-glacier basin. Deformations observed at the boundary between loamy and sandy layers have lamp-shaped, oval-rounded, finger-shaped, or pocket-like patterns. Sometimes, they are isolated and are observed as rounded or irregular inclusions within the underlying sandy member. The largest inclusion, 5–10 cm across, is located at a depth of 20–23 cm within the sandy member. The sandy sequence beneath the loam unit is deformed down to a depth of 0.56 m. The deformations are observed as sandy protuberances, folds, overturned beds, and mushroom-shaped structures.

The location of protuberances and pockets at the contact between inequigranular sequences suggests that, in the case that the underlying bed is composed of fluid material, the graded bedding of imprints is related to differences in the load and material density. Deformations appeared at a time when overlying sediments had already been deposited. The coarse material sank more rapidly and pressed down the underlying layer, resulting in the formation of sags and pockets. The deformation of the lower layer began to terminate only when the fine-grained material began to accumulate in upper parts of pockets and higher.

The analysis of deformations shows that the upper part of the sequence includes pockets filled with material from the overlying layers, whereas the lower part contains squeezing folds. These deformations can be regarded as indicators of the initial tension (formation of pockets and deeps) and subsequent stronger compression of the sequence (formation of narrow folds). Such distortions of incoherent sediments could be related to liquefaction (sharp decrease in solidity) caused by the destruction of the structure due to concussion (or deformation) and a sudden temporal growth in the amount of interstitial liquid. The essence of the energy of the liquefaction or dynamic instability of bottom sediments consists in the partial transfer of external kinetic energy to particles and its consumption for their relative movement, i.e., for the change in the porosity of sediments, their compression, and expansion [9]. In this case, the replacement of compression by extension can be caused by a succession of seismic pulses. Processes of liquefaction frequently accompany strong earthquakes [2, 10].

In terms of morphology, the deformations are similar to seismic structures observed in postglacial sediments on the southern coast of the Finnish Bay [5].

The deformations under consideration probably reflect a single event, because we did not detect any even and extended units that would mark different-aged deformation phases between the layers. Evidence of the gradual filling of deeps (pockets and sags) is also lacking.

The absence of any inclined surface and the pattern of deformations exclude their formation by underwater slumping processes.

The deformations in postglacial sediments of the Pechenga River terrace formed either during or after the deposition of the loamy layer with molluscan shells. Therefore, they most likely appeared 8.0–6.0 ka BC. This period corresponds to the Boreal warm climatic phase, which excludes any influence of glaciers or cryogenic processes on the deformation of sediments. Thus, analysis of the deformation structures discussed above makes it possible to suggest that they resulted from a strong seismic pulse.

Previously, we established that strong earthquakes occurred in the Murmansk district about 8950 ± 150 (TA-2293) yr BC [11]. This age value characterizes the initial stage of organic matter accumulation in the lake whose formation was related to the damming of a small creek valley by landslides after the earthquake. Thus, the available data indicate, at least, two seismic events in the Holocene.

Deformation structures in Quaternary sediments unrelated to glaciotectonic processes are also known in other areas of the northwestern Kola region (Fig. 1). They are developed in fluvioglacial (mainly in distal parts of deltas), glaciomarine, lacustrine-glacial, and lacustrine sediments. These deformations are represented by upthrust, overthrust, and subordinate dip-slip faults distorted by complex underwater slumping deformations, folds, and local convolute structures. The deformations are observed in sediments of different lithological types, ranging from varved clays and fine-grained silts to inequigranular sands. In the examined sections, the deformed sequence is frequently sandwiched between sediments with undisturbed initial bedding. The incoherent state and subparallel bedding of sediments underlying and overlying the deformed members suggest that the horizontal or slightly inclined layers were the first to be subjected to deformation. The features mentioned above preclude a glaciotectonic or cryoturbation origin of the observed structures. Their formation can be explained by an underwater slumping of sediments. An abundance of such deformations in a certain area (e.g., in the Kola, Ura, and Saida-Guba river valleys) may also be related to high seismicity during the period of their simultaneous formation, when the sediments were unconsolidated and water-saturated. However, the absence of reliable age estimates for these deformations does not allow us to interpret reliably their genesis.

It should be noted that the northwestern Kola region, with seismogenic deformations in incoherent sequences, was repeatedly subjected to historical and recent earthquakes. The most significant seismic events occurred near the Kola Settlement in 1772 and 1819. Their magnitude was as high as 4.6 and 4.1, respectively [12]. Traces of older earthquakes have also been found in crystalline rocks of this region in the course of special geologic–geomorphologic works [1]. Their magnitude is estimated at ~7.1 or more; i.e., the seismicity of the study region was substantially higher as compared to the present-day one.

The discovery of seismogenic deformations in Early Holocene incoherent sediments of the Pechenga River terrace and presumably similar deformations in other areas of the Kola Peninsula implies that the study region was subjected to earthquakes during or immediately after deglaciation. The strongest earthquakes most likely occurred during the Late Pleistocene–Early Holocene boundary period.

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