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Structural and Lithological Comparison of Convolutions in Lacustrine Complexes ($Q_{3\text{-}4}$) of the Baltic Shield, Northern Yakutia, Tien Shan

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Abstract—In order to clarify the genesis of liquefaction folds (convolutions) developed at lithological boundaries in lacustrine sediments, such structures in three regions were compared. Folds in each region differ in morphology, composition of sediments, and the vertical gradient of their density and viscosity upon deformation. It is proposed to use the ratio of the widths of syn- and anticlinal folds in the convolution horizon (K_S) to analyze the latter, in which $K_S > 1$ corresponds to the normal viscosity gradient, and $K_S < 1$, to its inversion. Convolutions of the Baltic Shield and Yakutia from $K_S \geq 1$ are noted in the most liquefied sediments with unstable density stratification (sands-on-silts), which indicates the possibility of their spontaneous formation during lithogenesis. Folds with $K_S \approx 1$ are widespread in Yakutia, which indicates their cryogenic genesis. Convolutions in the Tien Shan were formed with stable sediment stratification in terms of density (silts-on-sands); low-fluidized coarse-grained sediments with viscosity inversion were also involved in deformation. These features indicate the seismic initiation of liquefaction processes. The results substantiate the lithogenic genesis of convolutions in lacustrine complexes of the Baltic Shield, cryogenic and lithogenic in Yakutia, and seismogenic in the Tien Shan. It is proposed to determine the scatter of the K_S value in the diagrams for diagnosing the genesis of convolutions. For lithogenic structures, this parameter is shifted to the region with $K_S > 1$, and for seismites, it is relatively symmetric with respect to $K_S = 1$.

Keywords: lacustrine sediments, convolutions, soft-sediment deformation structures, seismites, cryoturbations, convective instability, vertical gradients of density and viscosity of sediments, genetic diagrams, Baltic Shield, Northern Yakutia, Tien Shan

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INTRODUCTION

Intraformational deformational structures that develop within a layer, a member, or at their boundary, with the sharp collapse of individual layers and which are associated with liquefaction, viscoplastic flow, and slumping of weakly consolidated sediments (Lowe, 1975), are widespread in highly dispersed lacustrine deposits— rhythmically interbedded clays, silts, and sands. In recent decades, a large number of works have been published that analyze such formations (Obermeier, 1996; Owen, 1996; Alfaro et al., 1997; Moretti, 2000; Wheeler, 2002; Neuwerth et al., 2006; Moretti and Sabato, 2007; Van Loon, 2009, 2014; Deev, 2009; Gladkov et al., 2016; Lunina and Gladkov, 2016; Shanmugan, 2017; Vardanyan et al., 2018; Gorbatov et al., 2019a, b). In most English-language publications, such structures are called "soft-sediment deformation structures".

In this article, we denote such layering disturbances by the more convenient term "convolution." We denote the convolutions of the supposed cryogenic genesis by the term "involution", which is traditionally used in cryolithology. Due to the wide variety of mechanisms of convolution formation (seismic, hydrodynamic effects, gravitational instability, cryogenesis, etc.), lithological conditions of their occurrence, and their morphology, difficulties arise in determining the genesis of such formations. In particular, structures similar in morphology (Shanmugan, 2016; Gorbatov et al., 2021b), depending on the composition and type of stratification of the enclosing sediments, can be the result of completely different processes. The proposed approach to solving this problem is identification and comprehensive comparison of structural and lithological parageneses of convolutions in lacustrine sediments in regions with different levels of paleoseismological and cryogenic activity, which is **the aim of this study**.

For comparison, we chose the Baltic Shield, with its low level of paleoseismic and cryogenic activity; Northeastern Yakutia, with its widespread cryogenic deformations in the sediments of thermokarst lakes (alases) and relatively moderate seismic activity; and the Tien Shan, the lacustrine complexes of which were

Fig. 1. Sketch map of studied sections (shown by asterisks) in three regions considered in article. Unlabeled asterisk: outcrops on the southern shore of Lake Issyk-Kul.

formed under conditions of strong and frequent paleoearthquakes. Therefore, in the sections of lacustrine sediments of the Baltic Shield (Fig. 1), lithogenic convolutions should be expected (Gorbatov et al., 2019b; Gorbatov and Kolesnikov, 2019); in Yakutia, cryoturbation (Gorbatov and Kolesnikov, 2019; Gorbatov et al., 2021a); and in the Tien Shan, seismogenic convolutions, or seismites (Korzhenkov et al., 1999, 2018; Bowman et al., 2004; Deev et al., 2018).

Thus, comparison of the convolution structures in the selected regions will make it possible to trace the role of external and internal factors in the formation of layering disruptions, which will make it possible to identify the diagnostic features of various genetic types of convolutions. This determines the practical significance of research in paleoseismology and cryolithology.

The Baltic Shield is a region with low modern seismic activity, and the possibility of high-magnitude paleoearthquakes occurring here, in which seismogenic convoluted structures are formed, remains a controversial subject (Gorbatov and Kolesnikov, 2016; Gorbatov et al., 2017, 2020; Gorbatov, 2020). Therefore, correct diagnosis of convolutions and other types of deformation structures, which some researchers call seismites (Nikolaev, 2009; Biske et al., 2009; Van Loon et al., 2016; Shvarev and Rodkin, 2017; Shvarev, 2019; Shvarev et al., 2020), is important for an adequate assessment of the seismic potential of this region. This can be done by comparative analysis of convolutions of the Baltic Shield with similar structures in other regions. This problem is solved in the present study.

RESEARCH METHOD

Quaternary deposits have been studied in outcrops by detailed description, measurement, photography, and sketching. Convoluted structures were described separately, for which the following parameters were recorded (Fig. 2): thickness and lateral extent of deformation horizons, regularity of deformation structures, morphology and size of individual structures, fold shape, their asymmetry (inclination of the axial plane) and vergence, degree of penetration and isolation (presence or absence of pseudonodules), composition of deformed and host sediments, and nature of weakening deformation to the top and bottom of horizons (Korzhenkov et al., 2018; Gorbatov et al., 2021b).

When analyzing the lithological composition of sediments involved in deformation, the presence or absence of their unstable density stratification (occurrence of heavy on light sediments) in a weakly consolidated state was determined, which may speak to gen-

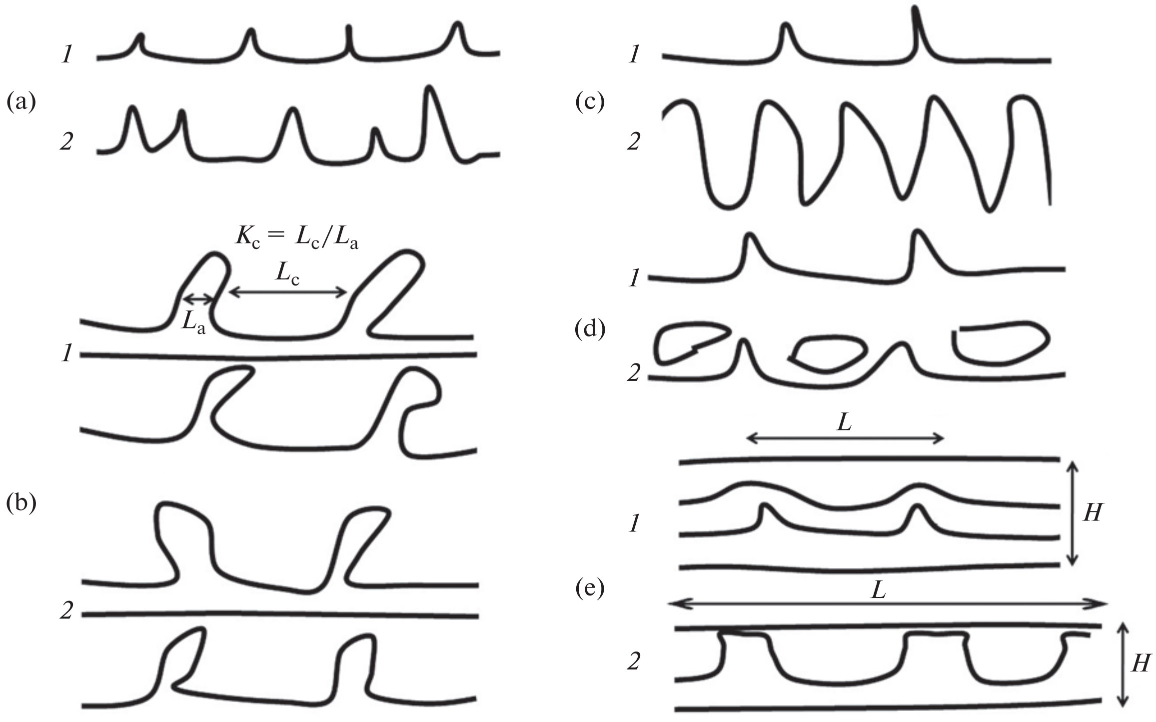

Fig. 2. Sketch map of main morphological parameters of convolutions. Numerals indicate magnitude of corresponding parameters. (a) Regularity (*1*, high; *2*, low); (b) vergence (*1*, expressed; *2*, absent); (c) degree of penetration (*1*, low; *2*, high); (d) *G*—insolation (*1*, absent; *2* present; i.e., there are pseudonodules); (e) fading of deformation towards roof (*1*, gradual; *2*, sharp). Lines show deformed and horizontal layers in convolution horizons; composition of layers is not shown. K_C, convolution synclinality coefficient; *H*, thickness of deformation horizon; *L*, its length.

esis of structures that is spontaneous or initiated by mechanical action. In the general case, we assumed that systems of "coarse-grained on fine-grained sediments " in a weakly consolidated state (e.g., sand-on-silt) usually have an unstable density stratification (Moretti et al., 1999; Gorbatov et al., 2021b). In the reverse order of the layers, respectively, the systems have a stable stratification.

The general ability of sediments to form liquefaction structures, which depends on their particle size distribution, was also analyzed. It was believed that the easier the soils pass into a liquefied state, the more likely it is to detect lithogenic structures of spontaneous liquefaction in them, especially if there are no deformations in the slightly liquefied granulometric differences of the same section. Conversely, structures with external initiation of deformation processes form not only in sediments with a high liquefaction capacity, but also in grain-size differences, which are relatively less prone to such processes. It is known that fractions with a grain size of 0.01–1 mm (from medium-grained silt to coarse-grained sand) pass more easily than others into a liquefied state under external dynamic effects, while sediments with a grain size of less than 0.01 mm (clay, fine-grained silt) or greater than 1 mm (gravel, pebbles, boulders) are relatively poorly liquefied (Tsuchida and Hayashi, 1971; Obermeier, 1996).

An important diagnostic parameter of convolutions can also be the ratio of the viscosity of sediment layers during their deformation, which characterizes the synclinality coefficient K_C introduced by us (Gorbatov et al., 2021b): the ratio of the width of synclinal and anticlinal folds in the convolution horizon (see Fig. 2b). This conclusion follows from models of the formation of lithogenic (convective) and seismogenic structures in unstable stratified sedimentary systems (Artyushkov, 1963; Alfaro et al., 1997). If the viscosity of the underlying layer is higher than that of the overlying one, then convolutions are formed at the layer boundary (in the presence of an unstable density gradient), in which the width of synclinal folds is greater than that of anticlinal folds, and $K_C > 1$. For the inverse ratio of the viscosity of the layers, structures are formed in which the width of synclinal folds is less than that of anticlinal folds, and $K_C < 1$. If the vertical viscosity gradient is close to 0, then harmonic folds with $K_C = 1$ form.

Such ratios result from the fact that more viscous sediment, when penetrating into a less viscous one during the development of gravitational instability, tends to "break through" the latter with the formation of a narrow diapir-like fold, and less viscous sediment tends to deform first into a wide fold, then into a drop, or pseudonodule. With complete development of instability, layers of different densities will change places in the vertical section (the situation is more typical for liquids, not for liquefied sediments) and stratification will become stable.

The occurrence of the least compacted and viscous sediments on more viscous and consolidated sediments can be considered a normal and more common relation in a weakly consolidated sedimentary sequence. In this case, predominantly lithogenic convoluted structures with $K_C > 1$ can form. Conversely, structures whose formation is initiated by dynamic effects (seismic liquefaction, mechanical stresses during freezing and thawing of soils) are more often characterized by constancy or inversion of viscosity and $K_C \leq 1$. Thus, the K_C values and especially their scatter with respect to 1 pertain to the genesis of convoluted structures.

DESCRIPTION OF CONVOLUTED STRUCTURES IN THE STUDIED SECTIONS

Lacustrine–Glacial Complexes of the Baltic Shield

The studied sections of Late Quaternary lacustrine deposits of the Baltic Shield (Q_3), exposed in quarries represent relatively thin layers and lenses of lacustrine sediments in fluvioglacial and moraine complexes. The most characteristic features in the composition of these deposits are predominant sands and silts, the almost complete absence of clayey varieties, the complete absence of organic matter, fine banded bedding, widespread undulose and oblique-undulose textures, and the absence of dropstones. Lacustrine deposits of this type often have oblique enveloping bedding, which is due to the sloping relief during the sedimentation period.

Tirvas Section (Khibiny). In outcrops on the territory of the Tirvas dispensary, we investigated the structure of the proximal slope of a moraine ridge (Gorbatov et al., 2019b), which formed in the Early Valdai (Q_3^2) as a result of a prolonged stoppage of a glacial tongue in the valley of the Khibiny mountain range. From top to bottom along section, a gradual transition of the partially washed moraine into fluvioglacial sediments is observed, with layers and lenses of limnoglacial sediments (Fig. 3).

Layer *2* in Fig. 3 shows bedding of a fine-grained layer of lacustrine–glacial silty sand with a total thickness of 20–25 cm with thin interlayers of silt, deformed in the upper part of the layer with the formation of regular isoclinal, compressed, and fan-shaped anticlinal folds (tongues) 6–8 cm long an intervals 15–30 cm, overturned by uprising of the layer to the northwest, as well as wide synclinal folds. The folds gradually fade towards the base and are overlain by homogeneous sands with poorly discernible disturbed bedding unaffected by erosion. Spherical sand pseudonodules with concentric layering “hang” in the intervals between some folds. The protruding crests of anticlinal folds are not cut off and are overlain by homogeneous unlayered sands with a high silt content. The sand in the lower part of the layer has undisturbed, slightly displaced parallel-undulose bedding.

Polar Circle Section (Northern Karelia). A small quarry (Gorbatov et al., 2017; Rasskazov and Gorbatov, 2019), located 1.5 km from the Polar Circle station, reveals two layers (from top to bottom):

Layer 1 (0–120 cm), coarse-grained horizontally layered sand with layer-by-layer ferruginization, gradually transitioning into gravelly sand with individual boulders up to 20–40 cm in diameter. The overlies the eroded roof of gray sandy-silty deposits.

Layer 2 (below 120 cm) is a southward-dipping member of silty fine-grained sand with interlayers of silt and medium-grained sand, complicated by microfractures with an offset of 0.5–1 cm and fine flexures. The layer contains two horizons of shallow convolutions (Fig. 4), 7–16 cm thick, which formed at the boundary of 2- to 3-cm-thick silty interbeds and overlying sands. Upward penetrating textures predominate: tongues, flame textures, mushroomlike shapes, and ovoids. Convolutions are better developed in the lower horizon, in which the thickness of the silt interlayer involved in deformation is the largest.

Similar shallow convolutions have been noted at the boundary of silt covered by sands in the **Baryshevo** quarry (Leningrad oblast, right bank of the Vuoksi River) (Fig. 5). Just like in the Polar Circle section, in this outcrop, the layers of lacustrine sediments are inclined, while the axial planes of convoluted folds are oriented vertically, which may indicate the convective (rather than landslide) nature of the folds and primary nature of the inclined bedding of layers associated with enclosure of the slope during the sedimentation period. Convolutions in the Baryshevo section are combined with fairly widespread numerous faults, the formation of which may be associated with the melting of buried ice.

Sharvaozero Section (Northern Karelia). In the quarry of the same name, in a sequence of kame sediments, several areas were found where convolutions developed (Gorbatov, 2020). Among them are folds that did not develop at the lithological boundary, but in a homogeneous sequence of thinly bedded sandy-silty sediments (Fig. 6). The section of the deformation horizon is 20–120 cm thick 5 m long. Fold deformations are represented by straight and overturned (along dip) bedding and open anticlinal folds separated by wider synclinal folds with a lower amplitude. The amplitude of the former is 50–120 cm, and the horizontal distance between the axial planes is 50–100 cm.

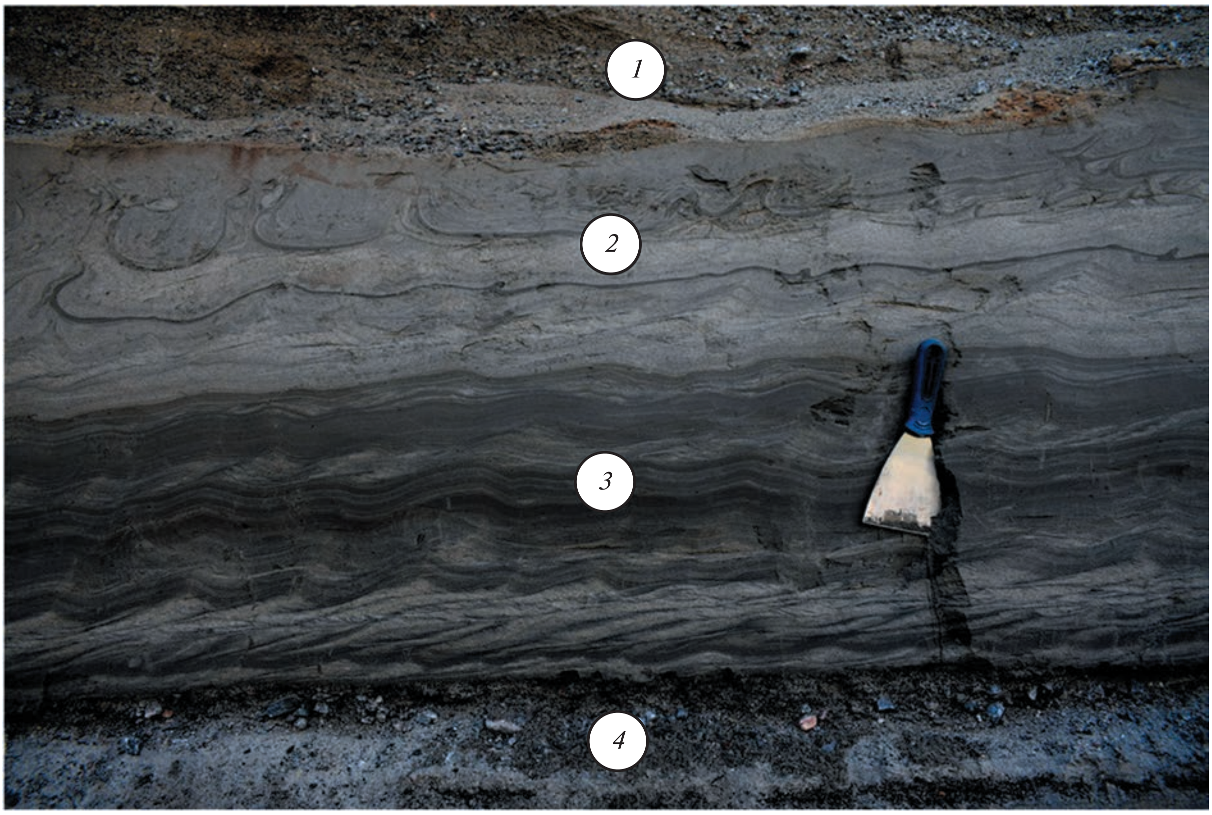

Fig. 3. Regular convolutions in lacustrine–glacial sediments at base of section of Kukisvum moraine ridge (Q_3^2), Khibiny. Photo by E.S. Gorbatov: *1*, sand and gravel deposits; *2*, fine-grained silty sand with convolutions in form of anticlinal tongues; *3*, dense silt with undulose bedding; *4*, gravel sand.

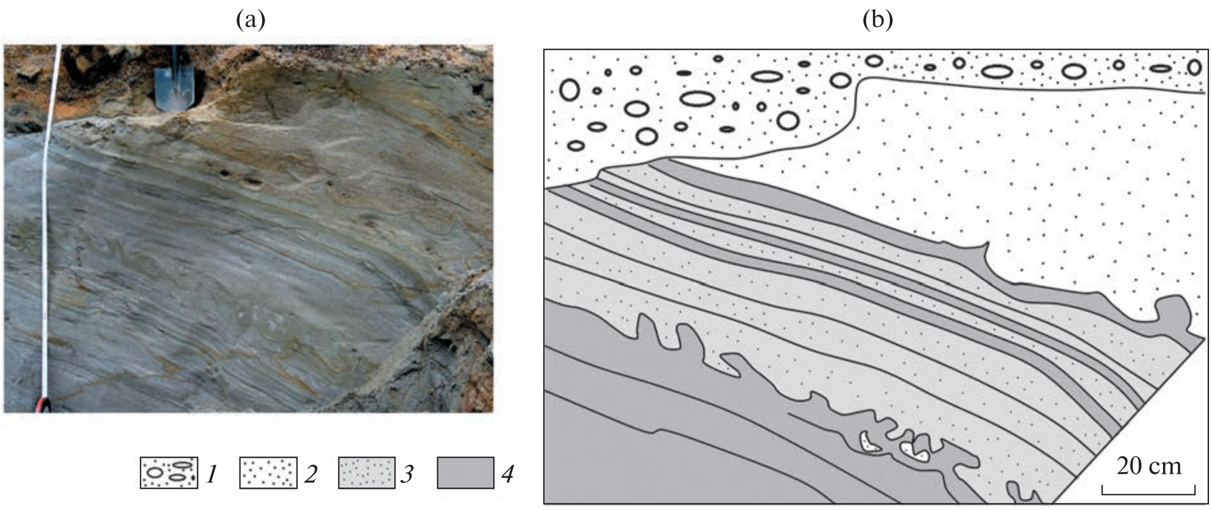

Fig. 4. Photo () and sketch (b) convolutions (two horizons) in primary-inclined member of sandy-silty sediments (Q_3^4) Polar Circle section (Northern Karelia). Photo and sketch by E.S. Gorbatov: *1*, sand–gravel–pebble deposits; *2*, unlayered medium-grained sand; *3*, fine-grained silty sand; *4*, silt.

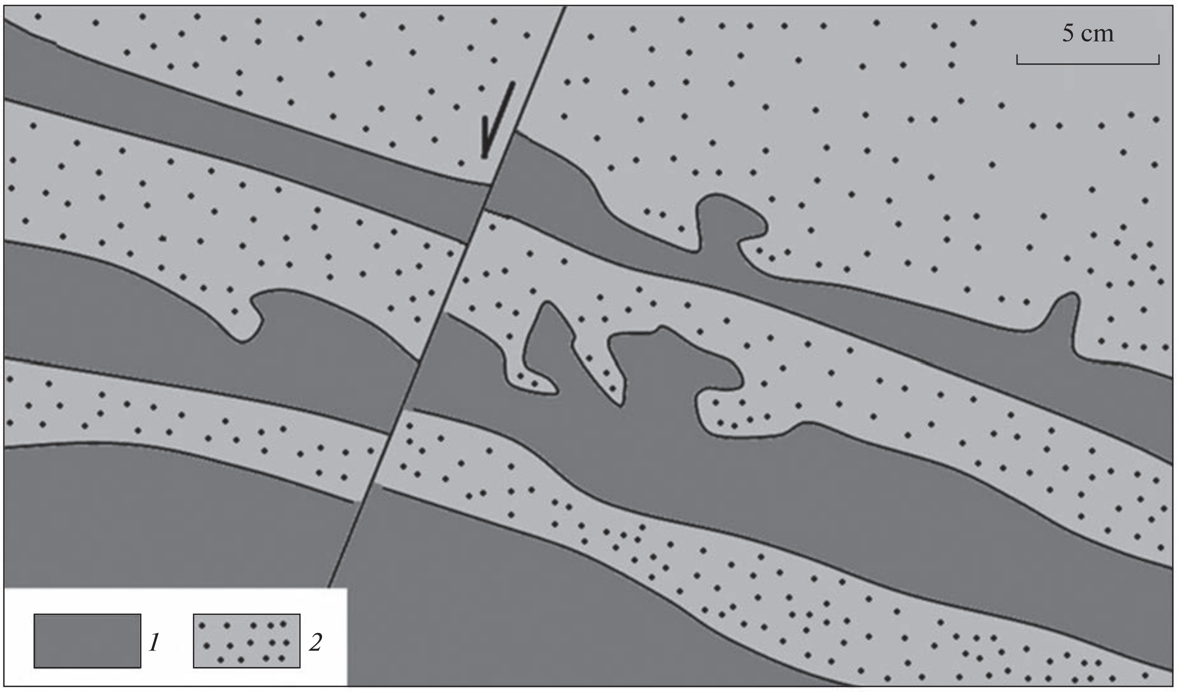

Fig. 5. Small convolutions in lacustrine–glacial sediments (Q_3^4). Baryshevo Quarry (Leningrad oblast), right bank of Vuoksi River. Deformations are noted at boundary of silty fine-grained sand (*1*), covered with medium-grained sand (*2*). Layers are displaced along normal microfault.

Some castle-shaped anticlinal folds vary from sharp to rounded from bottom to top along the horizon. Folding fades gradually towards the sole; deformations without erosion and enclosure of the protruding parts are overlapped by undisturbed layered deposits, and the deformations fade at different stratigraphic levels. Pseudonodules and homogenized deposits typical of other parts of this section are absent here.

Alas complexes of Northern Yakutia

In the structure of alas complexes (deposits of thermokarst basins) of the coastal lowlands of Yakutia, there are regularities characteristic of both typical lacustrine (deep-water, coastal facies) and periglacial sedimentation (varved bedding) (Kaplina, 2011; Gorbatov and Kolesnikov, 2019; Gorbatov et al., 2021a). At the base of the complexes are thawed (taberal) deposits of the ice complex, overlain by the subaquatic lacustrine deposits proper, and the section is crowned by subaerial deposits represented by autochthonous peat. In the composition of lacustrine sediments, clay particles are almost absent; silty and fine sandy particles predominate, which is associated with the peculiarities of cryogenesis during their formation (Fig. 7).

The most characteristic feature of this type of sediments is the presence of pseudomorphs along polygonal wedge ice (PWI). Most often they are wedge-shaped. In the upper part of the alas complex, strongly dislocated layers in the form of involutions are quite often encountered (see Fig. 7); their formation is apparently associated with cryogenic processes in the active layer, during which stresses increase sharply, causing sediments of different density to move (Kostyaev, 1964). The section of the complex is crowned by a peat layer, reflecting the basin's subaerial evolutionary stage.

The involution horizon in Fig. 7 formed at the top **of the alas complex at the mouth of the Omolon** River and is confined to a lithological boundary with an unstable vertical density gradient (sand-on-silt). Judging by the change in the morphology of folds from bottom to top along the horizon (in the bottom $K_C \gg 1$ and better pronounced narrow anticlinal folds, both types of folds developed in the roof and $K_C \approx 1$); in the upper part of the liquefied sediment sequence, the viscosity was constant, which can be a typomorphic feature of deformations under the action of cryogenic processes.

Involutions (Fig. 8) formed under conditions of liquefaction of the upper part of the sequence, 20–30 cm thick, as a result of thawing of the frozen sediment layer, and the vertical gradient of sediment viscosity was high, just like during faulting, which we identified on the Baltic Shield.

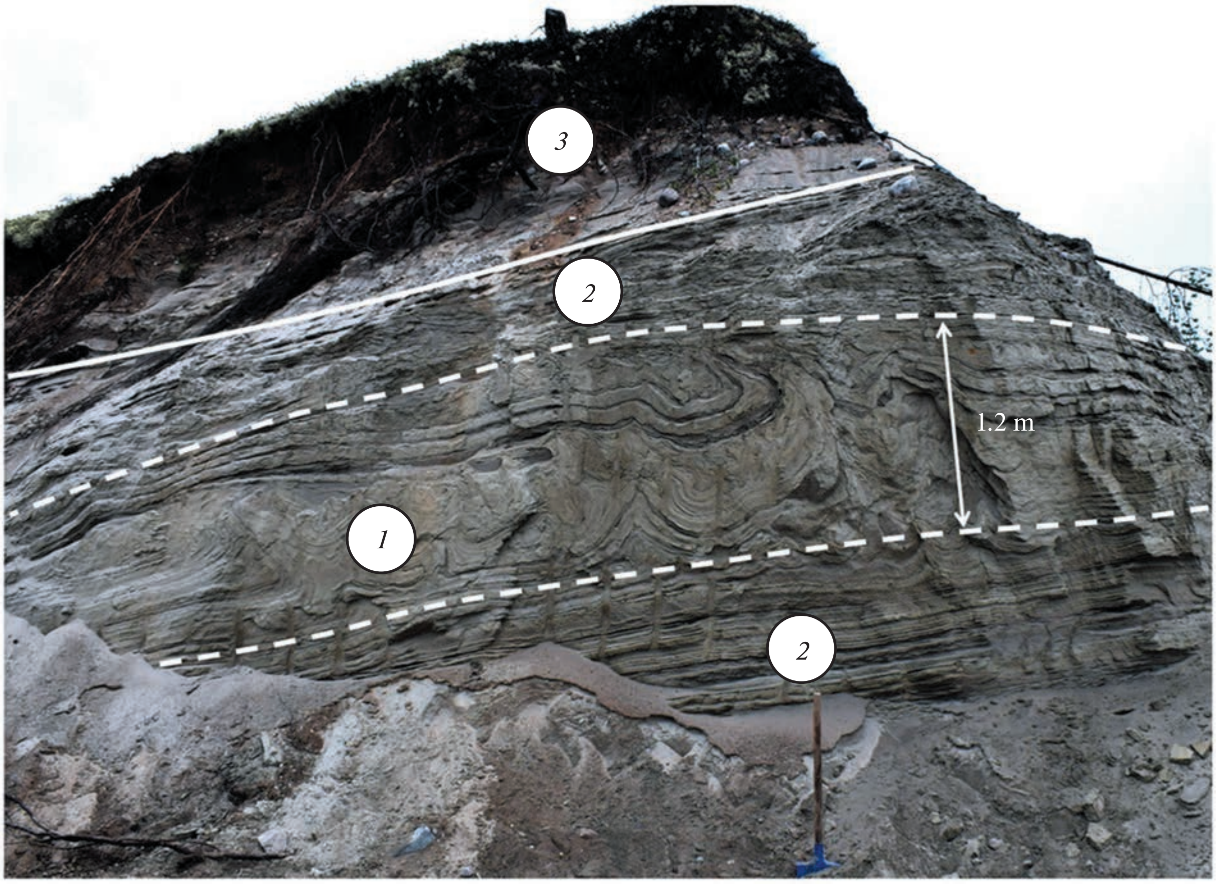

Fig. 6. Horizon of large folds (*1*) in homogeneous sandy–silty (Q_3^4) limno-kame sediments over- and underlain by undeformed sediments of similar composition (*2*), lying under sand–gravel–pebble material (*3*). Sharvaozero Quarry, Northern Karelia. Photo by E.S. Gorbatov

Lacustrine and Lacustrine–Alluvial Complexes of the Issyk-Kul Basin (Tien Shan)

Quaternary accumulations in the Issyk-Kul neotectonic basin include a wide range of deposits: from fine lacustrine clays to alluvial coarse-clastic deposits and giant moraine blocks (*Korzhenkov et al.,* 2018). These deposits accumulated in lacustrine, beach, and alluvial environments as a result of cyclic migration of facies with fluctuations in the level of the paleolake. The bedding in lacustrine complexes is predominantly horizontal, undulose (ripple signs), and, less frequently, oblique. Since sedimentation took place in a large lake basin, the layers are preserved along strike, the primary boundaries between layers are most often horizontal, and the oblique bedding, as a rule, has a secondary character, caused by tectonic imbalance.

Among the undisturbed lacustrine sediments, the horizons of seismogenic convolutions (seismites), repeating in the sections, are sharply distinguished, associated with seismic sediment liquefaction as a result of vibration effects during strong paleoearthquakes. These structures differ markedly from the convolutions of the Baltic Shield and the involutions of Yakutia.

The involvement of relatively weakly liquefied sand and gravel deposits under the silt in an outcrop near the village of Kosh-Kol (Fig. 9) indicates significant seismic impacts during earthquakes with $M \geq 5.5$. In an unnamed outcrop on the southern shore of Lake Issyk-Kul (Fig. 10), coarse-clastic sediments could not have liquefied at all, but passively "sank" into the lacustrine silt quicksand, ultimately resulting in seismites in the form of giant pillows. In connection with the poor exposure of the horizon, the most characteristic structure is shown in the extended convolution horizon. The layering of lacustrine sediments (dashed lines) is deformed, which indicates their seismic liquefaction and subsidence. The inset in the upper left corner of Fig. 10 shows a schematic diagram of the formation of convolutions of the studied section as a result of the "sinking" of pebbles into the quicksand of lake sediments with the formation of pillows (this process is indicated by the synclinal and conformal structure of the bedding of silts under the pillows) and the pressing of silts in the anticline between pillows

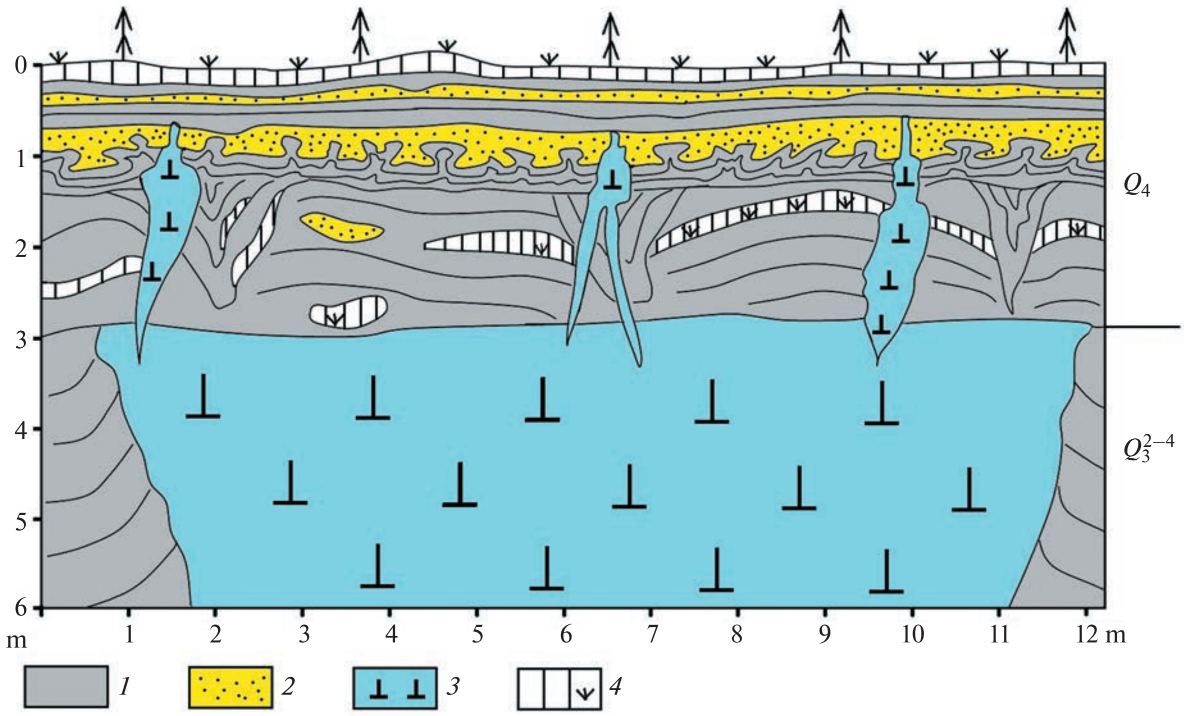

Fig. 7. Structure of section of Quaternary deposits with preserved horizon of cryogenic fold deformations (cryoturbations). Location: mouth of Omolon River (NE Yakutia). Sketch by S.F. Kolesnikov. Genesis and age of deposits: ice complex (Q_3^{2-4}); alas deposits (Q_4). Lithology: *1*, silt; *2*, fine-grained sand; *3*, polygonal wedge ice; *4*, peat with wood residues.

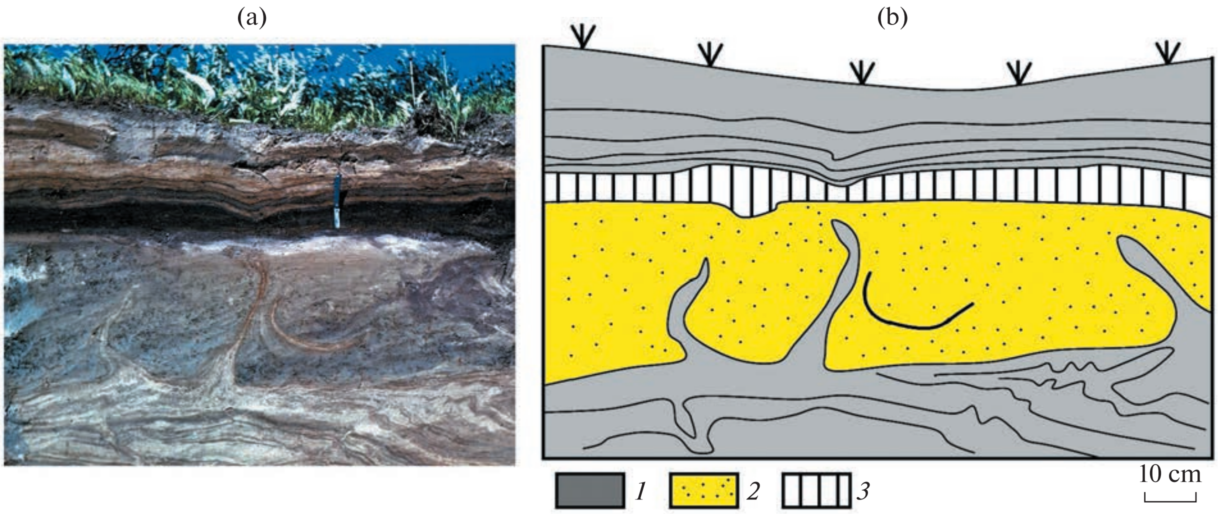

Fig. 8. Cryogenic fold deformations (involutions) in upper part of Holocene section (Q_4); alas deposits of Northern Yakutia: (a) photo by S.F. Kolesnikov; (b) sketch by E.S. Gorbatov: *1*, silt: *2*, fine-grained sand with unclear stratification; *3*, peat. Flattening is noted in layered sediments underlying involution. horizon.

In another outcrop (Fig. 11), regular folds of variable morphology with high penetration of layers are noted, in particular, a columnar synclinal fold with a horizontally displaced lower part, and a single pseudonodule.

The anticlinal folds are accentuated by the negative microrelief in the surface of the outcrop, formed by the spilling of loose sand. For these folds, K_C = 0.6–1.7; i.e., the parameter is scattered in the vicinity of 1. Stratification of sediments during the deformation

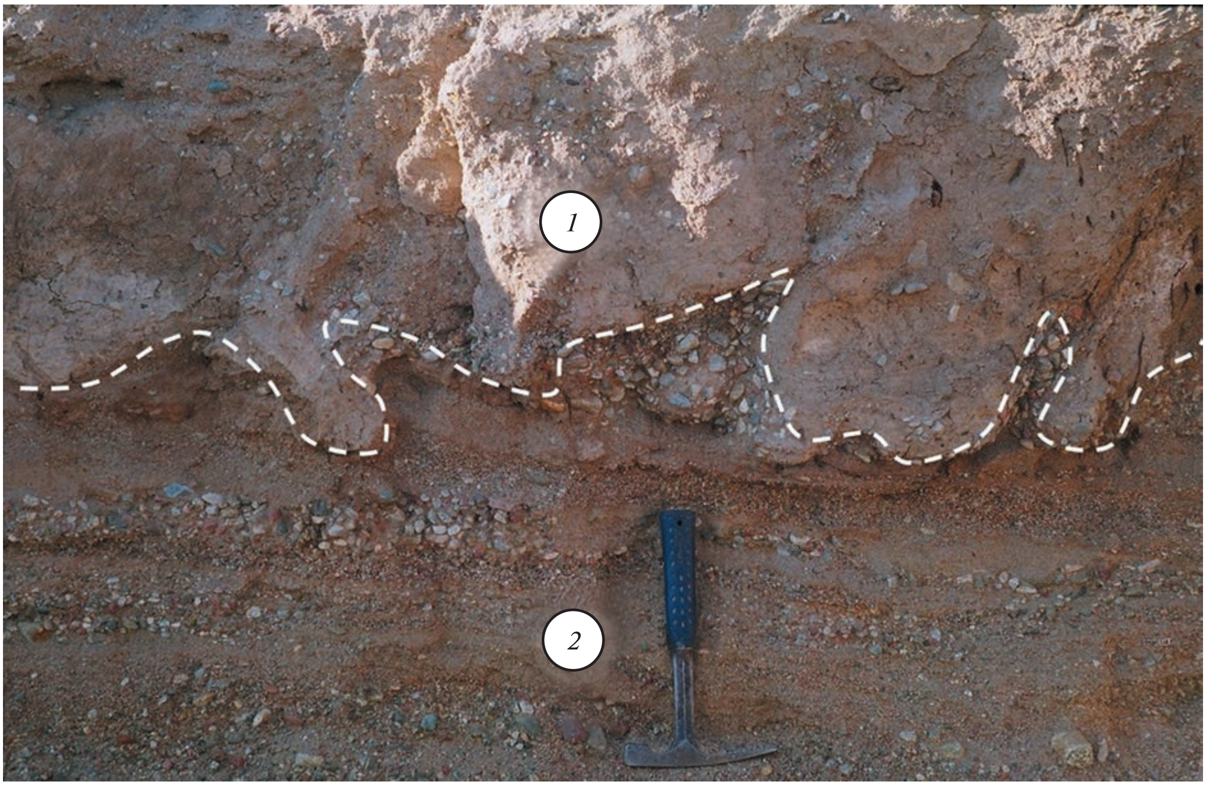

Fig. 9. Seismites in lacustrine sediments (Q_{3-4}) exposed near village of Kosh-Kol in northwestern Issyk-Kul. Photo by A.M. Korzhenkov Layers: *1*, clayey silt; *2*, interbedded coarse-grained sand and gravel. Dotted line shows lithological boundary. Low-liquefiable coarse-clastic deposits of layer *2* are pulled into deformation, which indicates strong seismic impact.

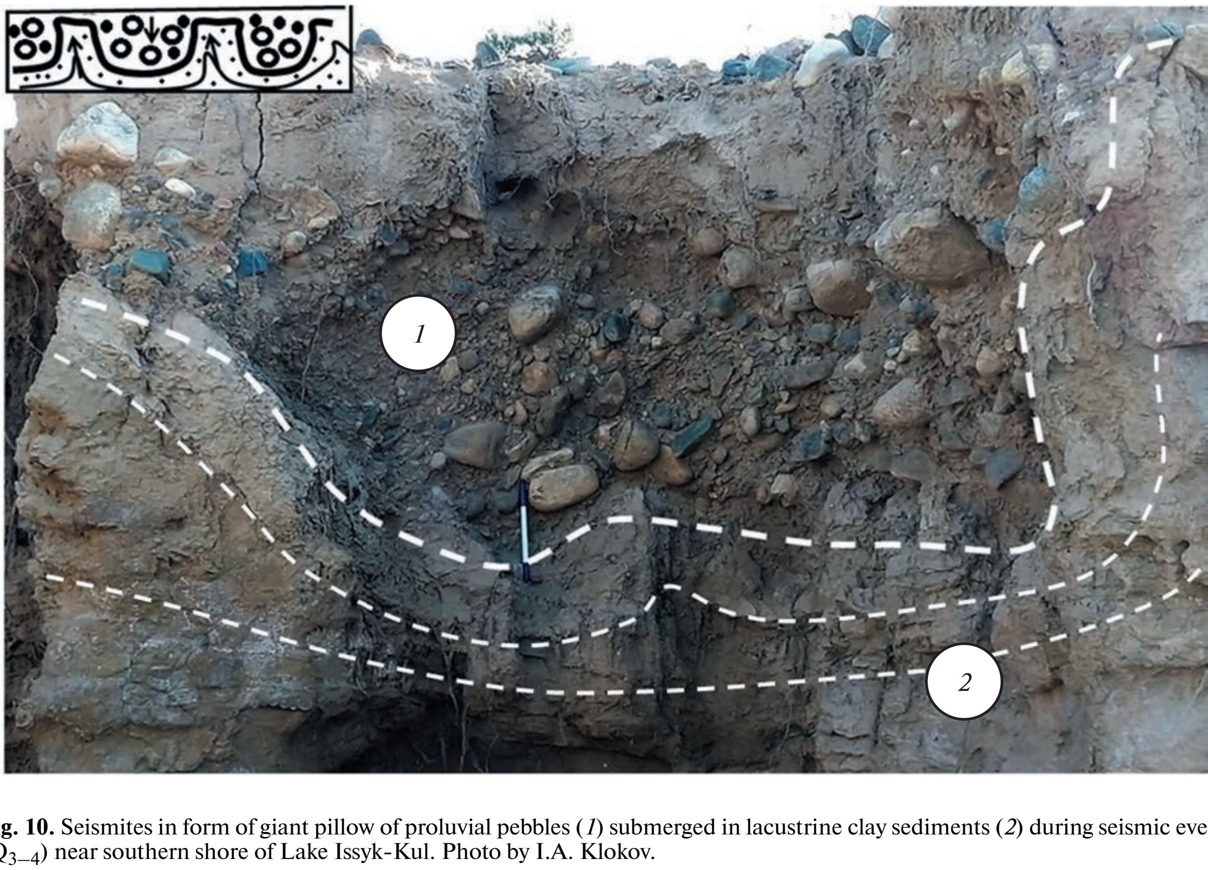

Fig. 10. Seismites in form of giant pillow of proluvial pebbles (*1*) submerged in lacustrine clay sediments (*2*) during seismic event (Q_{3-4}) near southern shore of Lake Issyk-Kul. Photo by I.A. Klokov.

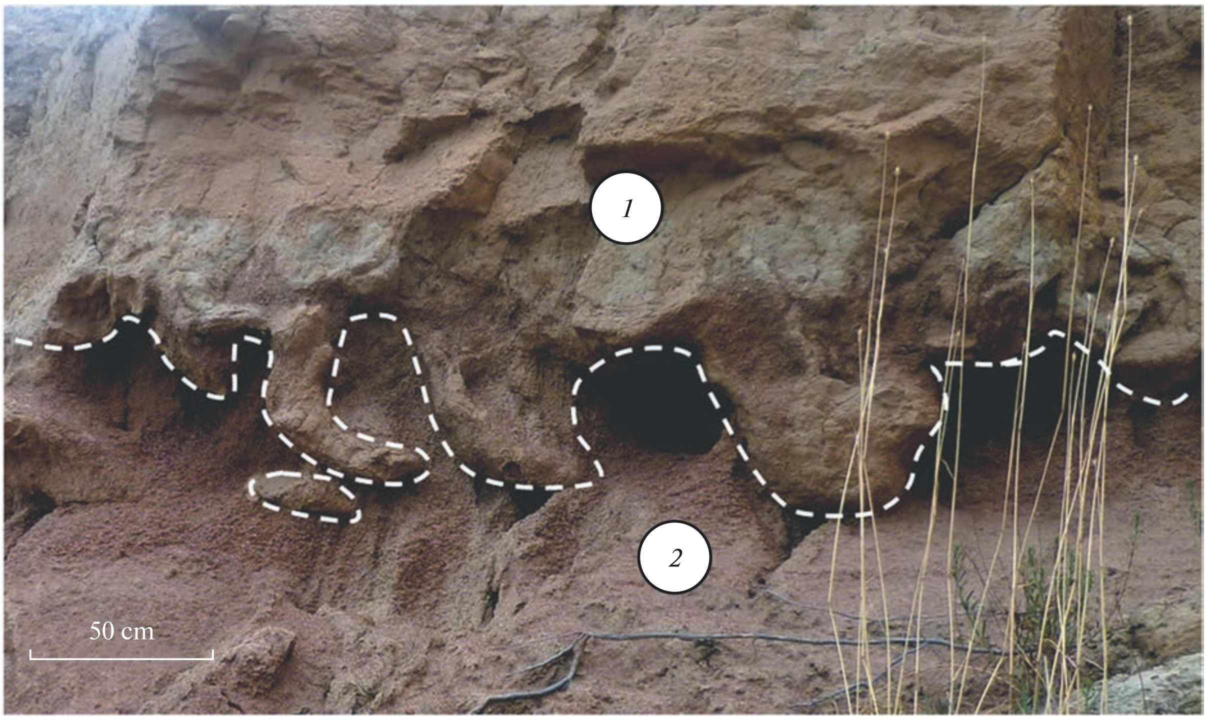

Fig. 11. Large seismogenic convolutions that resulted from mutual penetration of seismically liquefied marls (*1*) into underlying sandy sediments (*2*) of Lake Issyk-Kul (southern shore, Q_{3-4}). Photo by I.A. Klokov.

period was stable along the vertical density gradient, since the sediment dispersion in the overlying layer is greater than in the underlying one.

RESULTS AND DISCUSSION

Table 1 presents a comparative description of the bedding conditions, morphology and structural features, composition and density stratification of sediments, and the predominant genesis of deformation structures in the regions under consideration, taking into account data on the sections in this study and our other publications (Korzhenkov et al., 2018; Rasskazov and Gorbatov, 2019; Gorbatov et al., 2021b) is presented in Table 1.

As follows from Table 1, the fundamental differences between the convoluted structures of the three regions consist not only in different morphologies of structures, but also in the different grain size ranges of sediments involved in deformation and the nature of their density stratification as convolutions form.

Analysis of the morphology of deformational structures also made it possible to identify the characteristic paragenesis of convoluted forms in each of the regions (Fig. 12).

For sediments of the Baltic Shield and Northeastern Yakutia, a condition was established for spontaneous formation of a convolution (unstable stratification and high liquefaction of sandy–silty sediments); however, whereas in the first region structures are formed with an increase in the viscosity of sediments from top to bottom ($K_C > 1$), in alas complexes, the viscosity in the deformation layer remains constant ($K_C \approx 1$ for most regular folds), which may be a sign of deformations with a cryogenic origin (see Fig. 12b, *b*). In the Tien Shan, due to stable density stratification of soils, convolutions were unable to form without external dynamic influence); deformation involved, among other things, low-liquefied (or unliquefiable) coarse-grained soils; the viscosity of sediments here could have both increased and decreased (which is a typical of lithogenic structures) with depth (since K_C can be either greater or less than 1—see the section Research Method), there are horizontal shortening folds (see Fig. 12d) unassociated with the flows of liquefied soils.

To confirm the parageneses of convolutions in the three regions, a two-dimensional diagram of relation of K_C and thickness of convoluted horizons was used (Fig. 13). In this diagram, we identified the fields corresponding to structures of spontaneous (lithogenic), cryogenic, and seismogenic genesis; the three fields of points on the diagram correspond to different regions. Since the selected fields barely intersect, such diagrams can be used to analyze the genetic type of convoluted structures.

As follows from the diagram, for the structures of the Baltic Shield and Yakutia, the scatter of the synclinality coefficient is 0.6–6 and 0.9–15, respectively, and is noticeably shifted towards $K_C > 1$, while for seis-

Table 1. Comparison of convoluted structures in lacustrine sediments of considered regions

Sediment genesis, region	Peculiarities of bedding and structure of deformation horizons	Morphology and structural features of convolutions	Composition and density stratification of deformed sediments	Main process of convolution formation
Lacustrine–glacial complexes of Baltic Shield	Thickness 5–120 cm, lateral length up to 10 m, recurrence in section 1–5 horizons/m. Protruding parts of folds, as a rule, are not washed out and are covered by homogeneous material of upper part of horizon	Flamelike structures, pseudomodules, pillows, regular folds. Anticlinal folds are more compressed than synclinal folds. $K_C = 0.6–6.0$	Sediments of limited grain size range with highest liquefaction capacity: from silt to medium-grained sands. As a rule, deformations occur in sand-on-silt systems with density inversion	Spontaneous convective instability with landslide component
Alas complexes of Northern Yakutia	Thickness 20–100 cm, lateral length up to several hundred meters, recurrence in section, 2 horizons/m. Roof folds are not eroded	Frequently: regular, straight fan-shaped or flat-topped folds with $K_C \approx 1$. Less frequently: individual strongly compressed anticlinal folds with K_C up to 15	Sediments with highest liquefaction capacity: from silt to fine-grained sands (no other grain-size differences). Deformations occur in sand-on-silt systems with density inversion	Cryogenic mixing and convective instability
Lacustrine–alluvial complexes of Issyk-Kul basin (Tien Shan)	Thickness 15–200 cm, lateral extent up to several hundred meters, recurrence in section 0.1–10 horizons/m. Roof folds can be either eroded or uneroded	Flame structures, pseudomodules, columnar structures, diapirs, harmonic folds. $K_C = 0.5–2.0$. Vergence in horizons of one section coincides more frequently	Sediments of a wide grain size range, with both high and low tendency to liquefy under vibration effects: from clays to pebbles. Deformations occur in systems with both reverse (sands-on-silts) and direct (silts-on-sands) density gradients	Seismic liquefaction and flexural dislocations under vibration effects

mites, this indicator is less variable ($K_C = 0.5–2$) and is scattered symmetrically about the value $K_C = 1$. The average thicknesses of the horizons of the studied convolutions also differ: these values are minimal for the Baltic Shield (5–20 cm), take average values for the Tien Shan seismites (30–60 cm), and are maximum for the alas complexes of Yakutia (40–85 cm).

DISCUSSION

Let us consider the possible genesis of the studied structures. The main mechanisms by which deformation horizons form in weakly lithified subaquatic sediments include underwater landslide processes (Botvinkin, 1962; Alsop et al., 2016); pore pressure fluctuations in sediments initiated by seismic waves (Sims, 1975; Hempton, Dewey, 1983; Scott, Price, 1988; Deev et al., 2009; Lunina, Gladkov, 2016); bottom currents, waves (Botvinkin, 1962; Alfaro et al., 2002), and turbidity flows (Allen, Banks, 1972); spontaneous convective mechanisms during sediment density inversion, including during rapid sedimentation (Artyushkov, 1963; Kostyaev, 1964; Anketell et al., 1970; Molina et al., 1997); and cryogenic processes (van Vliet-Lanoë et al., 2004; Gorbatov et al., 2021a).

Since the studied lacustrine sediments have predominantly horizontal or slightly inclined bedding, and there is no correlation between the intensity of deformations and angle of inclination of the layers, it is possible to exclude the underwater landslide formation mechanism as the main one. Only in the Sharvaozero section are convolutions confined to a homogeneous thin-layered sequence with completely preserved bedding (see Fig. 6), which allows us to suggest a landslide genesis of dislocations.

Hydrodynamic effects on lacustrine sediments are also excluded in most sections, since the bedding of the studied sediments is mainly horizontal or oblique, which corresponds to quiescent sedimentation conditions. The effects of turbidity flows on sediments are also excluded, since folds of this genesis are distinguished by vergence in the dip of the sequences and the presence of swirling spiral shapes. Thus, the most probable formation mechanisms for the convolutions in the studied regions are spontaneous convective instability, cryogenesis, and seismic liquefaction.

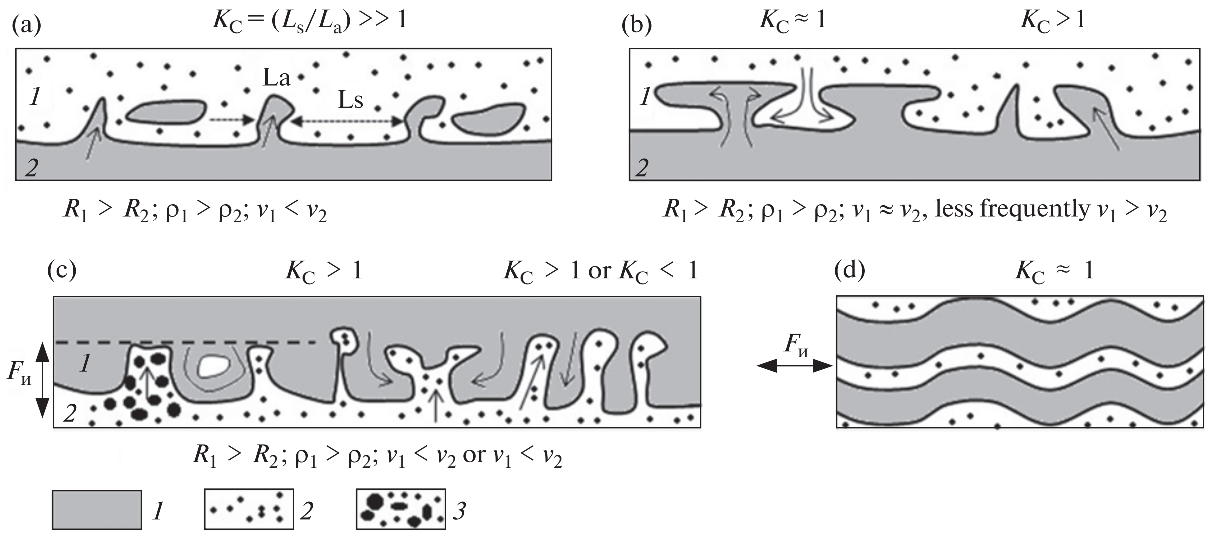

Fig. 12. Sketch of structural parageneses of convolutions and relation of lithological composition and physical properties of stratified lacustrine sediments in their deformation in studied regions. (a) Baltic Shield (lacustrine–glacial sediments); (b) NE Yakutia (alas complexes); (c) Tien Shan (lacustrine and lacustrine–alluvial complexes, liquefaction convolution paragenesis); (d) same, lateral compression convolution paragenesis under seismic impacts; *1*, silt or clay; *2*, sand; *3*, gravel with sand. Arrows show direction of liquefied sediment flow. F_{and}, vector of inertia under seismic impacts; K_C, coefficient of synclinal folds, characterizing relation of layer viscosities during deformation ($K_C > 1 \rightarrow \nu_1 < \nu_2$, $K_C < 1 \rightarrow \nu_1 > \nu_2$); R, sediment grain size; ρ and ν, density and viscosity of poorly consolidated sediments, respectively.

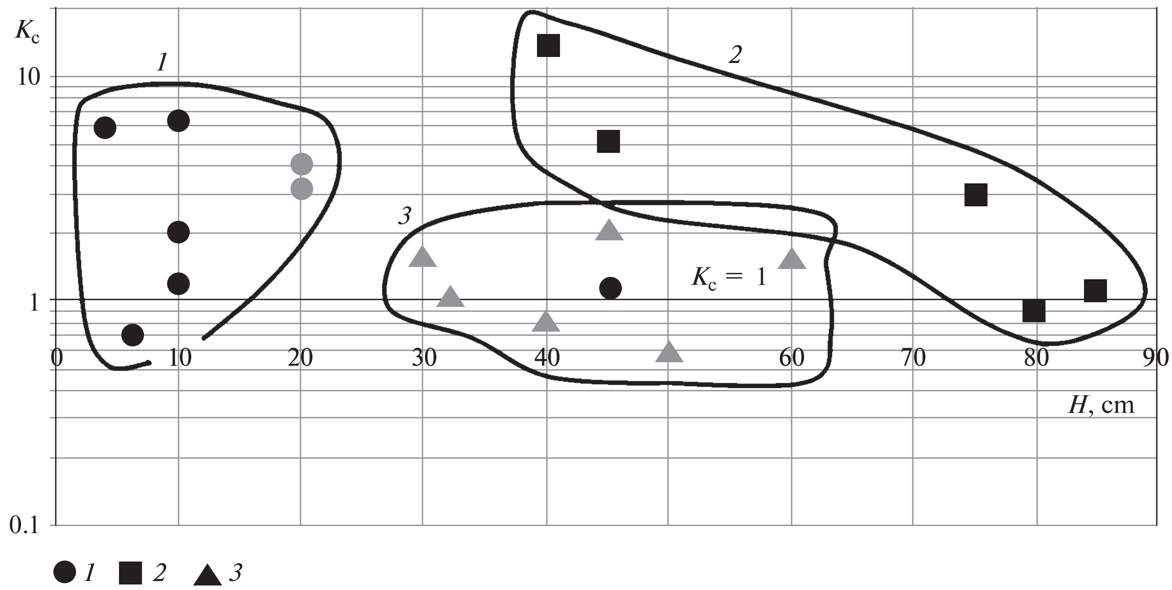

Fig. 13. Diagram of relation of synclinality K_C and thickness H of convolution horizons in studied regions. *1–3*, Measurements and fields on diagram corresponding to regions and genetic types of structures: *1*, Baltic Shield (lithogenic deformations); *2*, Yakutia (cryoturbations and lithogenic deformations); *3*, Tien Shan (seismites). Black dots, measurements of parameters of convolutions that occurred during unstable stratification of sediments; gray dots, during stable stratification. Scale on *y* axis is logarithmic.

In the sediments of the Baltic Shield, convolutions are very rarely encountered in the same section with cryogenic structures and faulting, such as soil veins and small postcryogenic schlieren textures. They are far from always timed to sedimentation hiatuses (as in the case of involutions in alas complexes), during which freezing and deformation of soil strata could have occurred. Therefore, in our opinion, these structures are mainly lithological in nature and are associated with spontaneous soil liquefaction processes during sedimentation under inverse density gradient conditions.

The differences in the vertical sediment viscosity gradient during the formation of liquefaction structures revealed from analyzing the morphology of convolutions of the Baltic Shield and Yakutia may be associated with different soil physical conditions. In lacustrine–glacial complexes, deformations occurred even in subaquatic conditions, when the sediment composition changed from fine to coarse, while their consolidation gradually intensified downsection. Therefore, the viscosity in the deformation layer also increased from top to bottom, as evidenced by the high K_C of convoluted folds (see Research Method). In alas complexes, fold deformations formed in a more consolidated sequence after the completion of subaqueous sedimentation and freezing of sediments (evidenced by their clear confinement to the tops of noncoeval alas complexes), under conditions of a layer with seasonal thawing of soil strata. When the frozen soil thawed, adhesion between particles in the active layer abruptly dropped to insignificant values and the transition of soils into a liquefied viscoplastic state occurred from top to bottom.

Thus, the degree of soil liquefaction remained relatively unchanged in the vertical section. This explains the small viscosity gradient of sediments during their deformation (for most structures), indicated by folds with proportionally developed synclinal and anticlinal folds and K_C close to 1. Thus, low K_C values of folds can serve as a typomorphic feature (structural indicator) of deformations in cryogenesis conditions.

The convolutions of the Issyk-Kul basin stand out the greatest against the folded structures in the other two regions. They are distinguished by the faulting at boundaries with a direct vertical density gradient and in coarse-clastic poorly liquefiable (or, unliquefiable) sediments (similar structures are described in (Korzhenkov et al., 2018)), large morphological diversity of folds, the presence (in addition to folds) of mutual intrusion of layers and harmonic horizontal shortening folds (also seismic in nature), and a relatively symmetric spread of $K_C \sim 1$.

These features unambiguously indicate the formation of structures due to external seismic impacts under conditions of large variations in sediment composition and physical properties. Comparison of these structures with lithogenic convolutions of the Baltic Shield and cryogenic convolutions of Yakutia makes it possible to develop additional diagnostic criteria for seismites and cryogenic disturbances versus other types of atectonic disturbances (Gorbatov et al., 2021b). In (Wheeler, 2002; van Vliet-Lanoë et al., 2004; Van Loon et al., 2020), attempts were made to develop criteria for such structures, but they did not completely analyze the relationship between the nature of deformations and sediment composition and physicomechanical properties. Our work partially fills this gap.

CONCLUSIONS

(1) In the sediments of glacial lakes of the Baltic Shield and thermokarst lakes of Yakutia, convolutions (regular folds, loading signs, pseudonodules) occur only in the most liquefied fine-grained sediments and tend towards lithological boundaries with unstable density stratification (sands-on-silts), which suggests the possibility of their spontaneous formation during lithogenesis.

(2) It was found that convolutions in the alas complexes of Yakutia (divergent folds with $K_C \approx 1$) formed in a sequence with a lower vertical sediment viscosity gradient than convolutions in the glacial lacustrine complexes of the Baltic Shield (compressed anticlinal folds with K_C up to 7.5), which can serve as a sign of formation of the former under cryogenesis conditions.

(3) In the highly seismic region of the Tien Shan, convolutions often formed with stable density stratification of sediments, and poorly liquefied coarse-grained soils were also involved in deformation, which justifies the seismic initiation of liquefaction processes.

(4) The greatest morphological diversity of convoluted structures of the Issyk-Kul basin (regular folds with $K_C = 0.3–2.5$, columnar and mushroom structures, diapirs, harmonic folds) is associated with a greater variability in the composition of sediments and their physical properties during the formation of deformations versus the other two regions.

(5) The identified parageneses of convoluted structures in regions with different levels of paleoseismic and cryogenic activity make it possible to distinguish typomorphic features of fold deformations of lithogenic (unstable stratification, $K_C > 1$, high positive sediment viscosity gradient), cryogenic (unstable stratification, $K_C \approx 1$, low vertical viscosity gradient) and seismogenic (variable density stratification, K_C greater or less than 1, variable viscosity gradient) genesis and develop a method for identifying them in subaqueous sedimentary complexes.

(6) Analysis of the diagram of the synclinality coefficient and thickness of convolution horizons proposed in the study (see Fig. 13) for the given sections (three virtually nonintersecting fields were revealed) shows that such diagrams can be used to diagnose the genesis of convoluted structures.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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