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Some features of deformation structures in an esker on the southern margin of the Fennoscandian shield

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Abstract

As a result of melting of the last ice sheet in the southeastern edge of the Fennoscandian shield, ridge structures called eskers were formed. One of these eskers is the subject of our study. We have identified both typical non-deformed sedimentary layers and specific intrusive mixture of sand and silt in the esker. The sand and silt were deformed with formation of recumbent and overturned folds, which indicate that they have experienced displacement in a ductile (wet) state. The formation of similar dislocations (diapir folds or glacial intrusion structures) can occur as a result of either dead ice melting or liquefaction during earthquakes.

Keywords: eskers, Fennoscandian Shield, liquefaction, neotectonics, palaeo-earthquakes, deformation structures, dislocations, intrusion

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1. Introduction

The latest of the Weichselian glaciations led to the emergence of a variety of glaciogenic landscapes. One of the main structures of these glacial landscapes are eskers which have been the subject of numerous studies from the late 19^{th} or early 20^{th} century (e.g., Davis, 1892; Crosby, 1902) to the last Peribaltic-2017 symposium (Sarala & Johansson, 2017).

Eskers are formed by material accumulation in crevasses, open channels and tunnels of an ice sheet or in subaqueous fans in lacustrine-glacial depositional environments (e.g., Banerjee & McDonald, 1975; Warren & Ashley, 1994; Karukäpp, 2005; Gruszka & Van Loon, 2011).

The primary stratification of esker sediments can be complicated by various glaciotectonic deformations, either directly related to the ice pressure on soft sediments, or to crumpling due to dead ice thawing out (e.g., Lavrushin, 1976; Morawski, 2003; Gruszka & Van Loon, 2011).

Also, the deformation of esker sediments is possible due to tectonic causes. The locations of large, extended crevasses (tens of kilometres long) in the ice sheet can be associated with scarps in metamorphic basement and movements along faults in the basement under the glacial bed (e.g., Harme, 1963; Penttilä, 1968; Ilyin & Lac, 1972; Biske et al., 1976; Lukashev & Ilyin, 1974; Chuvardinskiy, 1986; Karukäpp, 2005).

It is also known that movements along faults are often accompanied by earthquakes, which, in turn, cause the formation of various types of deformation structures (e.g., Nikonov & Zykov, 1996; Mörner, 2003, 2004; Nikonov et al., 2017; Druzhinina et al., 2017) also known as seismites (Seilacher, 1969; Alfaro et al., 1997; Montenat et al., 2007; Brandes & Winsemann, 2013; Van Loon & Pisarska-Jamroży, 2014; Druzhinina et al., 2017; Grube, 2017).

Identification and study of such structures that potentially have a seismic origin allows, therefore, to determine (ideally) the time and place of stress release within the reactivated geological structures, and thus to obtain new data on seismic hazard within stable platform areas.

In this article, we consider the preliminary results of an investigation of an esker, in which we found non-deformed sediments and deformed displaced squeezed sediments. Based on the observations made, we made assumptions about the possible mechanism for their formation and deformation.

2. Study area, materials and methods

We analysed geological maps of Precambrian crystalline basement and quaternary formations with ancient faults (Anischenkova et al., 1980) and compared them with a digital elevation model (DEM) topography. On the DEM map, we examined ancient faults, eskers and hydrology. We analysed the satellite imagery and identified quarries that crosscut the eskers. To characterize their morphology, we examined a profile perpendicular to the stretch of one particular esker. In the quarry, where the sandy material of the esker was deposited, we undertook additional excavations. We conducted observations on sedimentary and deformation structures, photographs and sketch-drawings. These observations were compared with previously published data.

The study area is located on the southeastern part of the Fennoscandian shield, 60 km west of Lake Ladoga. Here, according to geological mapping (Anischenkova et al., 1980) accompanied by drilling, Quaternary units overlie crystalline Precambrian bedrock, with a total thickness from a few metres to hundred metres (Fig. 1).

In the study area (Fig. 1), in accordance with the data of the geological survey (Anischenkova et al., 1980), different types of landscapes are common: outwash plains and ridges (eskers). The eskers can be traced for a distance of more than 15 km with a width of up to several hundred metres. The relative height of the esker ridges averages about 10–20 m, and the slope angles often do not exceed 20–40°. Most of the long eskers have a well-defined NW-trending and a curved shape in cross-section (Fig. 1b). There are eskers both on the basement rocks and also on tills and interglacial sediments. The thickness of the esker deposits varies between 1.5–32 m. They are characterized by light yellow and grey colours of quartz-feldspar sands with cross-bedded and horizontal stratification containing gravel, pebble and boulder material. In some areas eskers are covered by glacial lake clays of the Baltic Ice Lake, while the recent deposits are lacustrine, alluvial and biogenic deposits lying on banded clays and older glacial and glaciofluvial formations.

The object of our study is located in the southeast of Kamennogorsk (before the Second World War – Antrea) (Fig. 1), to the west of Lake Borovskoe (Suuri Kelpojärvi) (N: 60.93090267°;

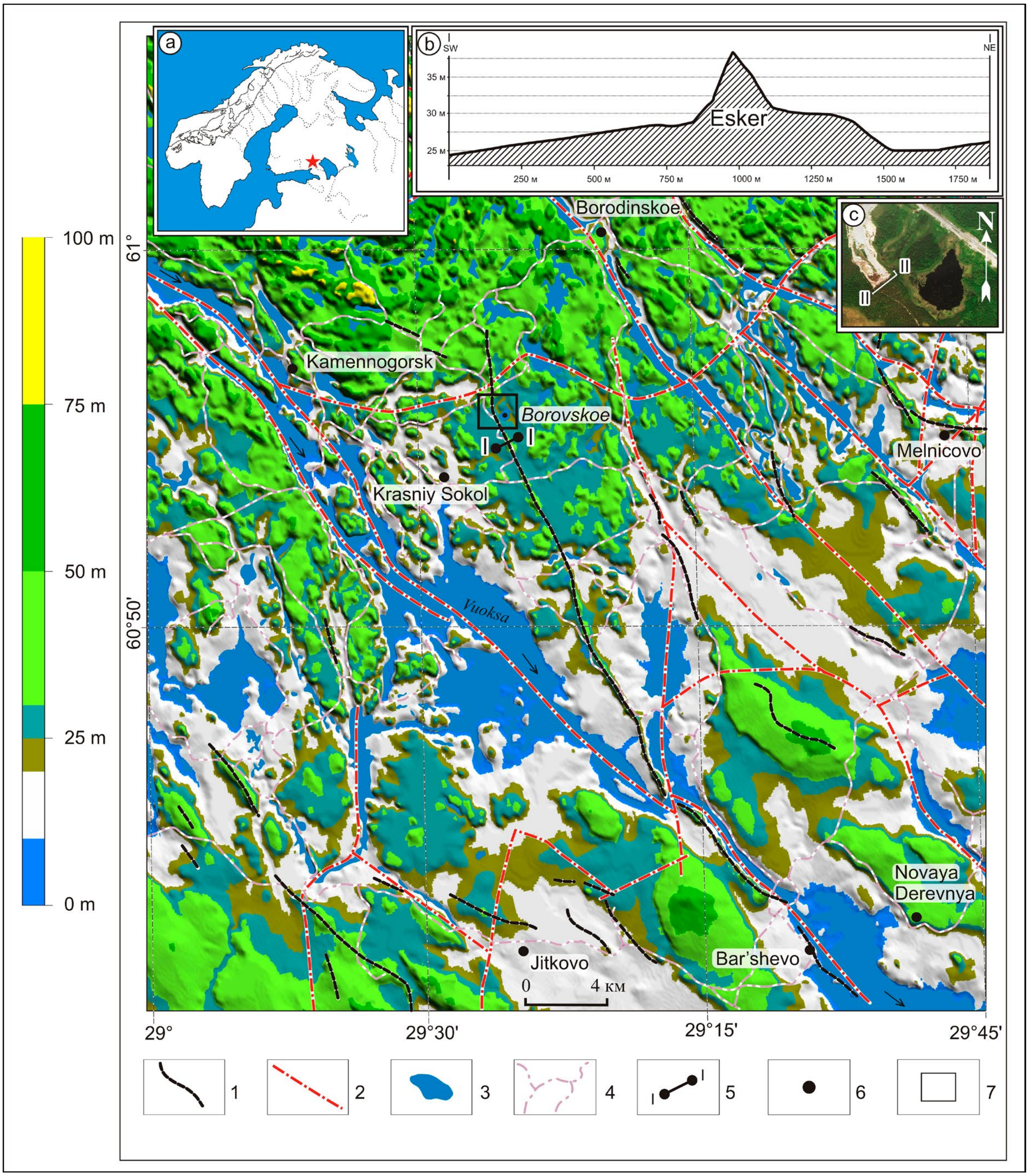

Figure 1. The DEM topography and hydrology of the study area with geological structures. a) Position of the study area within the Fennoscandian shield; b) topographic profile of the studied esker; c) a general satellite view of the quarry, II–II denotes the position of the wall of the quarry that cross-cuts the esker shown in Fig.2a. Explanations of the features: 1 – eskers; 2 – faults (observed and implied) in the crystalline basement, allocated based on results of the geological survey (Anischenkova et al., 1980); 3 – hydrological systems; 4 – roads; 5 – the position of the topographic profile I–I; 6 – the position of settlements and a lake in the study area; 7 – the position of the study area.

Editor's footnote: This figure has been updated after print with a minor clarification of the profile I–I. Scientific content has not been changed.

E: 29.31466242°) in the southeastern side of a large sand quarry section of an esker (Fig. 1a, b). The top (4–5 m) of the esker is exposed for observations. Orientation of the exposed part of the esker (Fig. 1c, II–II) is NE-trending and the location of our study is at the NE part of the esker.

In the section with a height of about 8 m, exposed sands gradually change to a lesser extent silt and clay deposits with a unit of boulders. The sediment units have characteristic structures (Fig. 2):

A) At the central part of esker with erosional contact lies a conglomerate unit of well-rounded and well-sorted boulders, composed of magmatic and metamorphic rocks, with a total thickness of about 3 m (the central part (A) in Fig. 2a). In the conglomerates, a rough gradational stratification is noticeable – larger boulders underlie smaller ones. The contact is gradational; the dip angle changes from 15° to 5° to SW towards the central part of the esker.

B) Upward along the section and further along the strike to the central part of the esker, the unit of boulders is covered by sands with gravel and small boulder material. The contact with the unit of boulders is an erosional unconformity. The parallel stratification of sands (dip angle changes 15–20° towards SW) is consistent with the angles of incidence of the sides of the major depression in the central part of the esker. A total thickness of sands is about 2.5–3 m (the central part (B) in Fig. 2a).

C) Area of detailed study:

Unit No. 1: The upper 1.5 m of the section (under a soil) is composed of coarse-grained sands with fine gravel-pebble-boulder material and horizontal stratification (with drop stones, Fig. 2d). The lower contact with the unit No. 2 is erosional and has an angular unconformity.

Unit No. 2: Below unit No. 1, there are coarse sands with occasional silt and clay layers (thickness is about 10 cm) with lenses of gravel-pebble material (1.5–2 m in length). The sand layering is not horizontal, and is curved above the surface of a large boulder located below. The thickness of the deposits is from 0 to 3 m. In some areas (the left part of Fig. 2b, c) unit No. 2 has completely been wedged out. The unit No. 2 with erosional unconformity is in contact with various underlying strata – varved clays (unit No. 4), large boulders and deformed sands & silts (unit No. 5).

Unit No. 3: Below unit No. 2, there are medium- & fine-grained well-sorted sands (thickness is about 1.5 m), with less gravel and pebble material than in units No. 1 and 2, and parallel stratification with dip angles from 25 to 35°. These deposits are connected with unit No. 1 (the left part of Fig. 2b, c) and form a structural depression (about 10 m in length and about 5 m in height) with a large boulder.

Unit No. 4: Varved clay with boulder unit. The initial thickness of the clay unit was not less than 30 cm, and the length of the clay layers was not less than 2 m. At the top of the excavation pit, at the contact zone of units No. 4 and 2, there is a large (about 1 m in length) metamorphic rock boulder. Varved clay is brecciated in the lower left part of the excavation pit (contact zone of unit No. 3) and is strongly dislocated (contact zone of unit No. 5). At the contact zone of units No. 3 and 4 (Fig. 2e, f), the dip angle of sands in the unit No. 3 stratification is concordant with the dip angle of stratification of varved clay. Slightly upwards, the varved clay is brecciated (the left part of Fig. 2f). Above, we can find a “tongue” of sands in varved clay (non-laminated sands take space inside the clay (the central part of the contact)), and above – the sand strata rests on the varved clay strata (at the top of Fig. 2f). In the contact zone of units No. 4 and 5 (the right part of Fig. 2e, f) we found another type of contact. The lamination of the varved clay is curved (with dip angles from 60 to 90°), and not brecciated. The lamination is accordant to the sand & silt sediments (unit No. 5), which indicates ductile type deformation in wet conditions. Taking into account that the stratification of clays was originally horizontal, and that the layering at the contact with the unit No. 5 is practically vertical in places, it can be assumed that the displacement amplitudes were several metres.

Unit No. 5: Unit with sand and silt with gravel material and boulders is characterized by a strong and complicated dislocation of layers in the bottom

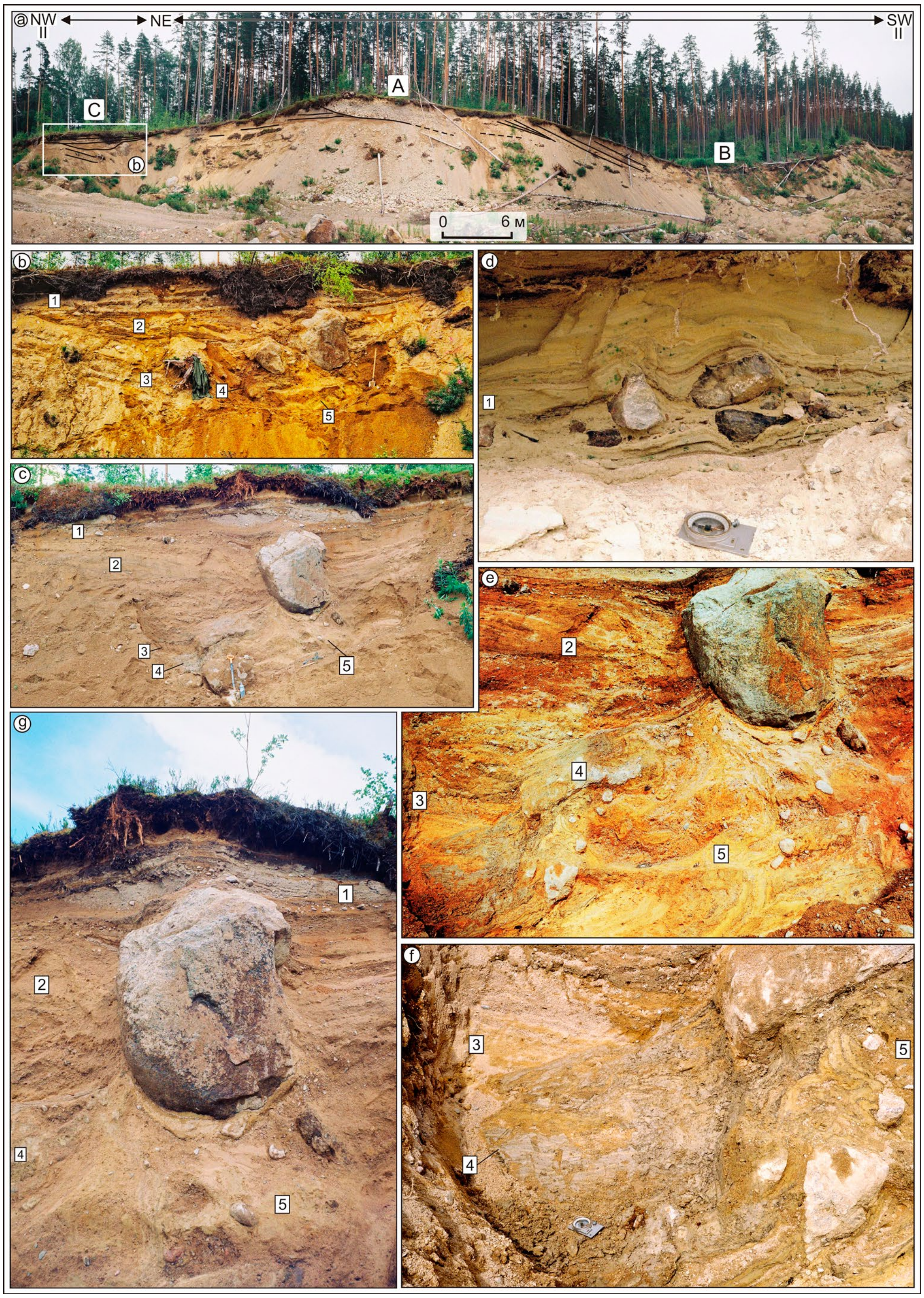

Figure 2. The structural features of the study area. a) position of the wall of the quarry that cross-cuts the esker shown in Fig. 1c – white rectangles with letters denote the major units (see text); b) and c) the esker slope before (b) and after excavation (c). White rectangles with numbers denote the minor units (see text); d) drop stones from unit No. 1; e) general view of the excavation – white rectangles with numbers denote the minor units (see text); f) details of the contact of varved clay unit (No. 4) with sands (unit No. 3); g) details of deformation of lamination (unit No. 5) under a large boulder.

Editor's footnote: This figure has been updated after print with a correct positioning and clarification of the major (A–C) and minor (1–5) units. Scientific content has not been changed.

and left part of the excavation pit (Fig. 2e, f). Among the well sorted fine-grained sand and silt material, isometric segregations of coarse and poorly graded sand and gravel material are encountered, as well as small angular and rounded boulders, ranging in size from 3–4 to 10–15 cm. Here, one can observe complex recumbent and overturned folds. In some areas (the central part of unit No. 5), folds are poorly visible. In separate sections, the curved, crumpled bedding of the folded sand and silt sediments in the contact zone of the unit No. 4, is conformal with the curved, disconnected stratification of the varved clay. In some places, it crosscuts it (Fig. 2e, f). Detailed observations of the unit No. 5 and boulders show that under the boulders there are fragments of the original layering (layered sands) of the deposits. Lamination is curved and follows the bottom of the boulder (Fig. 2, g).

3. Results and discussion

Based on the observations (in some areas so far, only preliminary), we can assume following origins for the sedimentary strata:

A) The well-rolled, well-sorted boulders (the central part (A) in Fig. 2a) which form the upper part of the esker, were deposited with the erosional contact in an aquatic environment with high dynamic activity. This is evidenced by the thickness of large rounded boulders forming densely packed congestions. The reduction of the boulder size in the upper part of the section is a result of the decrease in the activity of the hydrodynamic regime of the aquatic environment.

B) Upwards in the section and along the strike (the central part (B) in Fig. 2a), the boulder unit is covered with sands of detritus material, the stratification of which emphasizes the major depression in the relief of the esker. The formation of this depression and inclination of layered sands is presumably associated with the processes of dead ice thawing out and the formation of gravifossums or kettle-fill depressions (e.g., Hayward & French, 1980; Gruszka & Van Loon, 2011), but this issue requires additional more detailed studies.

C) Area of excavation and detailed observations:

Units No. 1–2: These units were also formed in the aquatic environment. These strata with erosion unconformity fill a depression with a large boulder in the central part. The erosion is indicated by the contacts of sand with varved clay (unit No. 4), and the deformed sand and silt unit No. 5. At the contact with the unit No. 4, layers of silt and clay material have been formed within sands due to erosion.

Unit No. 3: The medium- and fine-grained well-sorted sands with parallel stratification were deposited in the aquatic environment with a low hydrodynamic mobility. This is indicated by the absence of a significant amount of gravel and detrital material in the layers, and good sorting of the sands. In the contact zone of the units No. 3 and No. 4, the stratification of sands (unit No. 3) follows the stratification of varved clay (the bottom of the contact zone), rests on the stratification of varved clay (the upper part of the contact zone) or non-stratified sands fulfil the space of the clays (the "tongue" at central part of the contact zone). The angular, brecciated fragments of varved clay have been deformed in a brittle way, indicating a more advanced process of dehydration and lithification of the varved clays. In the contact zone of units No. 3 and No. 5, we find a different type of contact. The stratification of varved clays is folded, which reflects another type of deformation. The stratification of the clays follows the stratification of sand and silt in unit No. 5, which indicates ductile deformation in wet conditions.

Unit No. 4: This is the varved clay with the boulder unit. The size of the lake in which the varved clay was formed remains unknown.

Unit No. 5: Detailed observations of the unit No. 5 (sands and silts with gravel material and boulders) show that under the large boulder the original stratification of sands is curved according to the bottom of the boulder. Conversely, we can conclude that the sands and silts retained their plasticity, but were able to withstand the considerable weight of the boulder. The unit No. 5 is characterised by a strong and complicated dislocation orientation of the silt layers with recumbent and overturned folds. Sands and silts show typical soft-sediment deformation structures (e.g., Feng, 2017; Rogers, 2017; Shanmugam, 2016, 2017), which reveal the ductile type deformation and intrusion. The presence of small boulders and gravels among the sands indicates that the intrusion was accompanied by a high driving force (Topal & Ozkul, 2014), capable of moving this clastic material. Taking into account that the stratification of the varved clay was originally horizontal and at the contact with the unit No. 5, the layering is practically vertical in places, it can be assumed that the displacement amplitudes (of intrusive movement) were several metres.

Relationships of the units No. 3–5 indicate synchronous intrusion of unit No. 5 and deformation of clays (unit No. 4) and filling of the lower part of the depression with sands (unit No. 3). The intrusion of the diapiric unit No. 5 was accompanied by deformation of the banded clay and was accompanied by the accumulation of unit No. 3.

The formation of units in the excavation area occurred in several stages: A) stage of deposition of the sand and silt (unit No. 5) and varved clay (unit No. 4); B) stage of diapir intrusion of sand and silt with pebbles and small boulders mixed into the clay and wet sand sediments (unit No. 3); C) "drop stone" stage of burial of a large boulder (detached from floating ice) in a sand and silt mixture (unit No. 5); D) stage of erosional unconformity and deposition of sands (units No. 1–2).

The mechanism (explanation) for the formation of the sedimentation depression, in the central part of which is a sand and silt intrusion that was squeezed upwards, probably can be the mechanism similar to the emplacement of magmatic intrusions. In such cases, the ascending movement of magma and the introduction of large sills are accompanied by a simultaneous deflection of the geological structures overlying the locus of magmatism (Grout, 1918). In the case here, the force for the simultaneous vertical growth of the sedimentary diapir and filling of the depression by sediments can be associated with the thawing of dead ice in the central part of depression according to the development models for kettle-fill (Hayward & French, 1980) and gravifossum (Gruszka & Van Loon, 2011) structures. In wet conditions, the waterlogged sediments experienced liquefaction and acquired the ability to move upward, simultaneously with the filling of depression by sands (unit No. 3).

Another possible mechanism for the formation of a sedimentary diapir intrusion is liquefaction during earthquakes (e.g. Gradziński et al., 1976; Audenard & De Santis, 1991; Alfaro et al., 1997; Druzhinina et al., 2017; Mörner, 2017). After the accumulation of the units No. 3–5 as a result of the earthquake shock and the development of liquefaction, the wet sands and silts were moved into the sands (unit No. 3). In this case, sand and silt sediments are "seismite" deposits, which have been the subject of numerous publications in recent years, as cited above.

The contributions of these mechanisms can be assessed in different ways. Often earthquakes are triggers (Lu et al., 2017) for further redistribution of sediments. In thic case, earthquakes could have disrupted the wet sediments and initiate the growth of a diapir through the varved clay.

Similar phenomena of vertical injections of material, called, e.g., glacial protrusions or clastic dikes, have repeatedly been described in the geological literature (e.g., Diller, 1890; Gradziński et al., 1976; Lavrushin, 1976; Nikonov & Zykov, 1996). In the case of such injection structures, they develop straight contacts with enclosing dry strata (brittle type of contacts) and curved contacts (ductile type) form due to interaction with soft wet sediments. Similar soft sediment deformed structures (SSDS) are the subject of closely related studies by various researchers, and are important due to their potential relationship with earthquakes (e.g. Shanmugam, 2016, 2017; Mörner, 2017).

The formation of injection structures is possible in a variety of glacial environments – from the high-pressure conditions of active ice to the environments of melting of passive and dead ice (Lahee, 1961; Gradziński et. al., 1976; Lavrushin, 1976; Edwards, 1986).

All possible origins cannot be assessed with a high degree of probability due to a limited amount of evidence at the initial stage of the study. For some of the questions we can only give conjectural answers. For example, the question about the environment of the esker formation (tunnel fill in active ice or a fluvial ice-channel fill in stagnate ice) can only be answered tentatively due to the small size of the excavation.

However, given that a large part of the esker sediments are represented by sands, at least the varved clay and occasional large boulders (with the exception of the boulders in unit A) were formed at a distance from the margin of the ice sheet, where the hydrodynamic activity was weakened. Probably, it was a lacustrine environment (lakes, streams, deltas or floating ice with boulders (drop stones)). Perhaps stagnant ice (kettle-fill depression) was present in the central part of the esker (A in Fig. 2a).

The study of the structure of the eskers makes it possible to estimate the history of their formation due to seismic activity caused by superposing of vertical (isostatic) and horizontal tectonism. However, the degree of influence, as well as the distance to which this influence extends, is a matter of debate. In our case, in the study area, in direct contact with the esker, confirmed faults in the Precambrian basement are not known (Fig. 1). However, they are found at some distance. Therefore, in this particular case, we can assume either an indirect or direct weak influence from earthquake generation (presumably associated with the fault zones). To confirm such an assumption, new discoveries of dislocated strata within this and adjacent eskers would be needed. The intensities of the hypothetical dislocations would have to increase from esker to esker along the direction towards the fault zones. Calculations of seismite formation in relation to the distance from the epicentre of the earthquake would also be needed (Hilbert-Wolf & Roberts, 2015). If our reasoning is correct, the age of the identified dislocated soft-deformed sediments can be used to correlate them with the generation of known seismic events recorded in the Fennoscandian shield (Mörner, 2017). The final answer for the formation of the dislocations revealed by this study requires additional research, accompanied by more extensive excavations.

4. Conclusions

Analysis of the results from an esker in the southern margin of the Fennoscandian shield allows us to draw the following preliminary conclusions. We have found a mixture of silts and sands with gravel and boulders with recumbent and overturned folds in the esker. The presence of ductile type contacts with surrounding sediments indicates an intrusive origin for the sand and silt mixture in a ductile (wet) state, which further led to the formation of a depression structure. We suggest the formation of these structures in relation to both melting of stagnant ice (kettle-fill type of structure) and liquefaction of the underlying sediments, mobilization and intrusion into the overlying strata. The liquefaction mechanism often accompanies seismic phenomena (e.g., Gradziński et al., 1976; Audenard & De Santis, 1991; Alfaro et al., 1997; Mörner, 2017). Recognizing the manifestations of possible seismic processes in the sedimentary record will help to obtain new additional information on tectonic activity in the area.

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