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EXCURSION GUIDE AND ABSTRACTS

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ABSTRACTS

EXCURSION GUIDE

Abstracts

GENESIS, LITHOLOGY AND DATING OF SO-CALLED VALLEY SANDS IN SW MECKLENBURG (NE-GERMANY)

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In a geological surface mapping project four individual profiles were sampled between 2011-2012 at the North European Gas Pipeline trench (NEL). The study area is located c. 30 km south of the adjacent maximum distribution of the Weichselian inland ice within a periglacial influenced zone with valleys between higher-lying Saalian till morainic slabs. According to Brückner et al. (1960) and Krienke & Nagel (2001), the here presented profiles are located in mapped valley sand areas and representing the general regional glaciofluvial lithology and depositional period of Weichselian glaciation. In this region of SW Mecklenburg during the Weichselian glaciation (MIS-2) huge meltwater masses were discharged in broad outwash valleys between the higher till morainic slabs in SW Mecklenburg (Younger Saalian Glacial, MIS-6) generally in S/SW direction into the lower Elbe glacial valley (Fig. 1). The period of periglacial conditions was very important for the development of the meltwater valleys into today's river network. Since the late glacial period, the upper reaches of these relatively small streams have mostly developed from the glacial outwash deposits in the northern proximal parts and are often surrounded by younger Holocene valley sands and bog deposits, especially in their lower reaches.

Several sand layers from four investigated profiles were dated by Optic Stimulated Luminescence (OSL) on quartz grains (90-200 µm). The following, simplified descriptions do not include the excavated topsoil horizon (c. 0.3 m).

NEL 07-20 Zahrensdorf A-B; UTM ETRS 89 33.619354; 59.17897; c. 17m NHN:

The almost unstratified lower sand is classified as glacial meltwater deposit. The overlying fS(ms) horizon without coarser grains is classified as drift sand from the MIS-2. A low-thickness unstratified boulder-covered sand (20 cm) represents a clear layer boundary between the two OSL-dated drift sand horizons. The upper well sorted sand horizon (fine/medium sands) is classified as drift sand from the late Weichselian deglaciation period (Older Dryas?). The narrow age distributions of both OSL dated samples prove sufficient daylight exposure during deposition.

NEL 07-24 Schwartow C-E; UTM/ETRS89: 33.217107; 59.25533; c. 15 m NHN:

The ‘lower sand‘ layer (1.2-3.5 m) is interpreted as meltwater deposition from the MIS-2 by a fine grain distribution without coarser grains and one reliable OSL dating. This age classification "neutralises" a dating (MIS-3/4?) from hanging, unstratified meltwater sand with periglacial overprint.

NEL 07-30-Gehrum G-H; UTM/ETRS89: 33.212588; 59.25040; c. 25 m NHN:

The profile is composed of two sub-areas:

1. ‘lower sand‘ underlying Saalian glacial till on slope of morainic plateau to valley course:

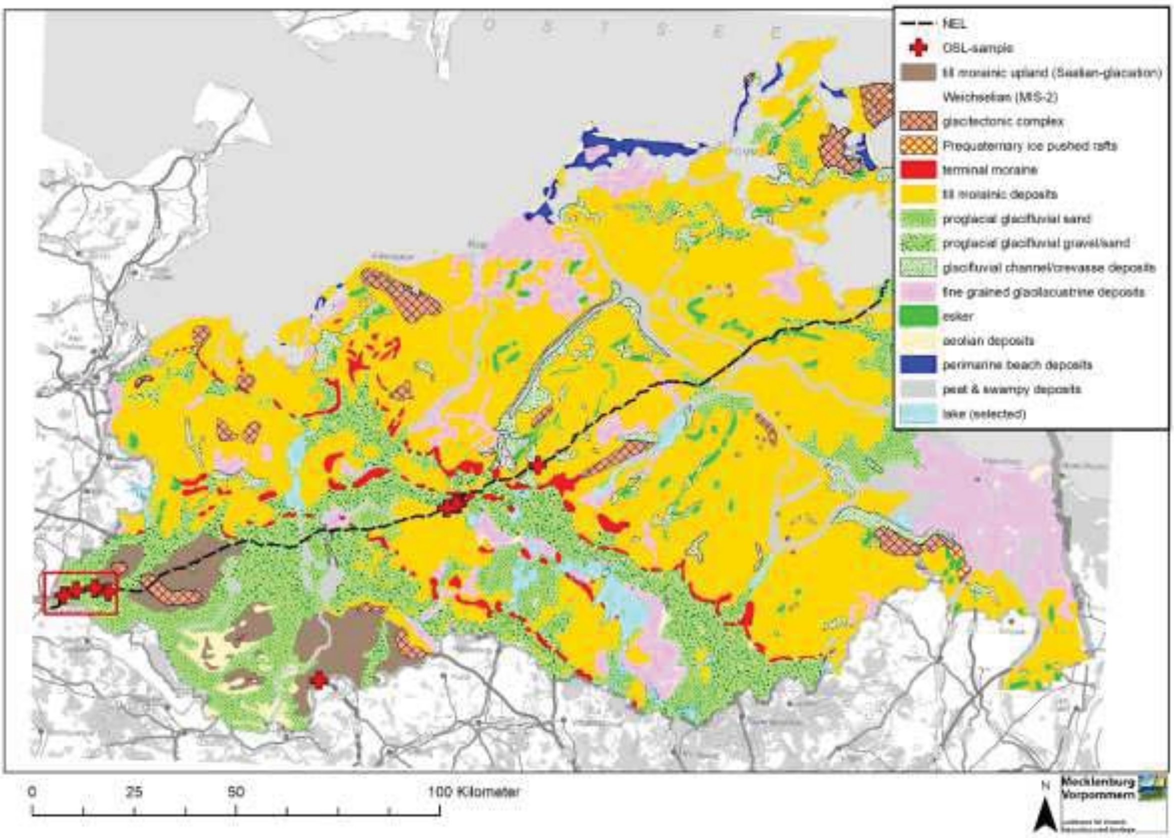

Fig. 1. Investigation area of Weichselian glaciofluvial valley sand, marked by red rectangle, plotted on general geological map Mecklenburg-Western Pomerania.

Both the hanging glacial till and the overlying sand were classified as Younger Saalian Glacial (MIS-6), confirmed by OSL dating.

2. upper ‘valley sand‘ in the valley/lowland area:

The lower sand is interpreted as meltwater sand (basin sand). The OSL age dating into the MIS-3/4(?) is presumably based on mixing with marginal lying Saalian glacial deposits. The hanging upper sand deposits can be classified as aeolian drift sand from the Weichselian glacial period (MIS-2) due to the well sorted grain size distribution of fine/medium sand and a well behaving OSL sample.

NEL 07-34 Bickhusen I-II; UTM/ETRS89: 33.209527; 59.23720; c. 12 m NHN:

The entire profile is composed of meltwater deposits and interpreted as meltwater formation from the Weichselian glaciation (MIS-2), despite two questionable OSL datings from the Middle Weichselian (?). The OSL age might by overestimated proven by the high age dispersions presumably based on incomplete bleaching of glaciofluvial reworked sediments of locally occurring Saalian glacial deposits, finally deposited during MIS-2.

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DROPSTONE DEPOSITION PROCESS – INSIGHT FROM COMPREHENSIVE NUMERICAL MODEL

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Due to gradual melting of free floating and drifting at the lake surface ice, clasts (dropstones) of all sizes are set free and eventually settle through the water column. They accumulate at the bottom sediments, producing an imprint (soft sediment deformation structures – SSDS) correlated with their kinetic energy related to their shape, size and the path they have traveled – the water column depth. Although the dropstones in glaciolimic and marine sediments have frequently been described by many authors (e.g Thomas and Connell, 1985; Gilbert, 1990; Brodzikowski and Van Loon, 1991; Pisarska-Jamroży et al., 2018; Van Loon et al., 2019), no previous studies based on numerical modeling has been addressed the dropstones deposition process in general. Here we present results of our comprehensive numerical model devoted to the relationship between dropstone size, water depth and resulting SSDS.

In aim to model the dropstone deposition process, two separate but complementary numerical methods has to be combine. First of them addresses impact velocity calculations, while the second one allow the investigation on the response of bottom sediments on pressure caused by impacting clast.

Velocity calculations: To calculate the clast's velocity at the moment when it reaches bottom sediments, we integrated numerically equations of motions in the dense medium considering three main forces acting on the falling through the water column dropstone: drag force, gravity and buoyancy. We used standard differential equation solver RKF45 (Shampine et al., 1976) and input parameters (drag coefficient, water density, dropstone density etc.) representative for studied physical situation. Final clast's velocity were calculated for different water column depth and dropstone's radii.

Bottom sediments response on pressure caused by impacting dropstone: To investigate the response of the bottom sediments to the pressure caused by an impacting dropstone, we use the iSALE2D code (Wünnemann et al., 2006), which is based on a hydrocode solution algorithm (Amsden et al., 1980) and which was originally developed for studies on hypervelocity impact cratering (Collins et al., 2004; Wünneman et al., 2006). The iSALE2D code includes an elasto-plastic constitutive model, fragmentation models, various equations of state, a strength model and a porosity-compaction model. It has been benchmarked against other hydrocodes (Pierazzo et al., 2008) and validated against experimental data (Pierazzo et al., 2008; Davison et al., 2011). In our models addressing the impact depth of a dropstone, the dropstone is resolved by 20 cells per projectile radius (CPPR). For the material model of the bottom sediments we use an equation of state (EOS) for quartz and the Drucker-Prager strength model with three different sets of parameters representing low-, medium- and high-strength sediments, respectively.

The presented comprehensive model allows the reconstruction of the depositional process of dropstones (which have been modeled in the present study to be spherical and homogeneous). The deformations caused by the impacting dropstone strongly depend on its diameter; the exact measurements of these soft-sediment deformation structures can also provide information about the impact scenario. There is a water depth that limits further increase of the settling velocity of a dropstone (and thus of its impact velocity); the velocity becomes constant after reaching this depth, which depends only on the dropstone size. For dropstones in basins that are deeper than the velocity-limiting depth, the reconstruction of the water depth is no longer possible.

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EVALUATION OF NERIS RIVER AND THEIR TRIBUTARIES OUTCROPS DYNAMICS USING GROUND-BASED AND REMOTE SENSING METHODS (FOR EXAMPLE OF SKIRGIŠKĖS OUTCROP)

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Outcrops of river banks are excellent objects for analyzing the composition of surface sediments, their structure or the age of sediments. In Lithuania, river bank outcrops began to be studied in the 19th century. The most accurate observations of dynamic changes in outcrops are made using ground-based geodetic methods. The classic methodology of such measurements is based on the fact that benchmarks are installed in the monitored area, whose spatial coordinates are determined from measuring stations installed in a stable area. By performing repeated measurements, it is possible to calculate and evaluate the dynamic changes of the outcrops. The application of drones (UAV) allows for quick and cheap survey of the earth's surface and identification of objects of interest. On the other hand, studies on the accuracy assessment of aerial images created by UAV are not yet widely carried out. The accuracy of aerial images of UAV is determined by many factors: flight height, camera image quality, design of the drone's flight path, georeference orientation methods, and others.

The study of the Skirgiškės outcrop of the Neris River (**Fig. 1)** carried out by the authors aimed at several goals: to determine changes in the surface of the outcrop in 2019-2022; compare the results of ground-based geodetic measurements and the photogrammetric interpretation of UAV aerial images; to evaluate the assessment of the possibilities of fixation of the outcrop sedimentary layers, using ground-based measurements and aerial images.

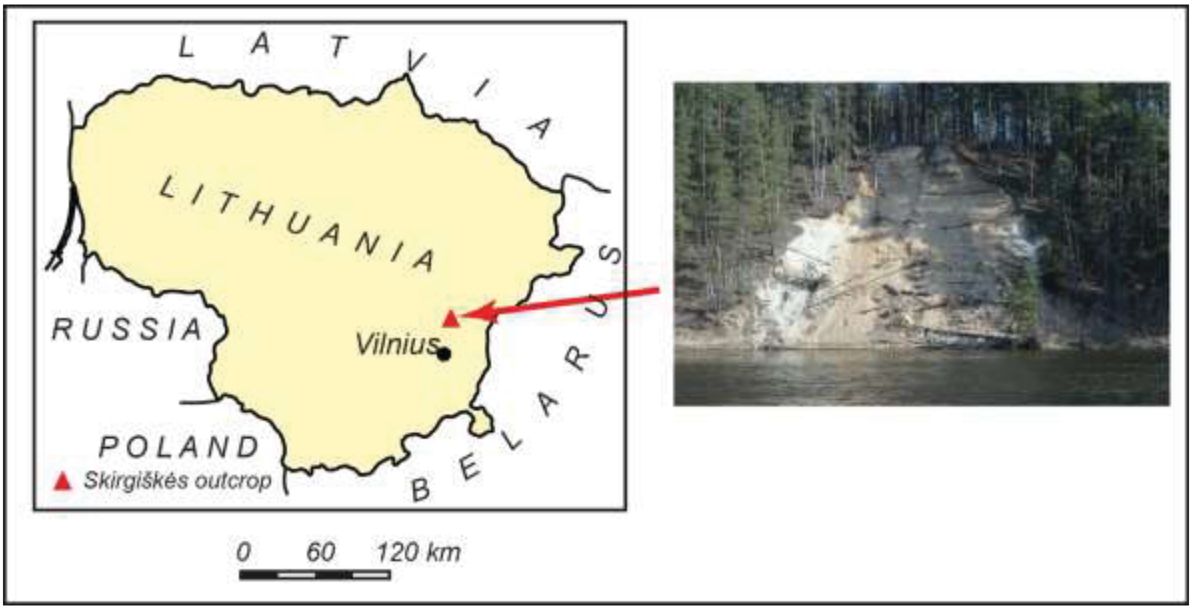

Fig. 1. The investigated area.

The single specific points of the outcrop were measured using the Trimble M3 Total Station device. Horizontal and vertical angles were measured with an accuracy of ±5", and distances - with an accuracy of ±3 mm. An UAV INSPIRE 1 with an X3 photo camera was used for the photo-fixation of the outcrop images. The photo-fixation was carried out by directing the camera's axis at an angle of 0, 60 and 90 degrees. From the obtained images create a digital relief model in which, using Pix4D software, the contour lines of the outcrop surface are drawn. The outcrop surface contour lines are drawn based on the results of ground-based geodetic measurements too, using the DXFtoFotoXY program (author Artūras Bautrėnas). The comparison of topographic plans allowed us to evaluate the quantitative changes in the outcrop surface. Here we present the change in the outcrop surface, which took place in 2021-2022 years (**Fig. 2**).

The research also highlighted some issues that demonstrate the potential of UAV imagery in outcrop surveys. The first problem is related to the accuracy of the results. The Pix4D photogrammetric software automatically generates a terrain model that has uneven accuracy (compared to the results of ground-based geodetic measurements) in individual parts of the model. This is related to relatively large height differences between the foot of the outcrop and its top (about 30 m). Another annoying factor is the deep river valley, whose high banks block part of the satellites and thus distort the three-dimensional terrain model. The absolute height readings of a UAV equipped with an RTK often do not match the readings of a precision GPS. To eliminate this problem, additional marks were used, with their absolute height accurately measured by precision GPS, and the image of the marks was captured on an aerial photograph. These two factors lead to the fact that the results obtained by ground-based geodesic measurements are much more accurate (**Fig. 3**).

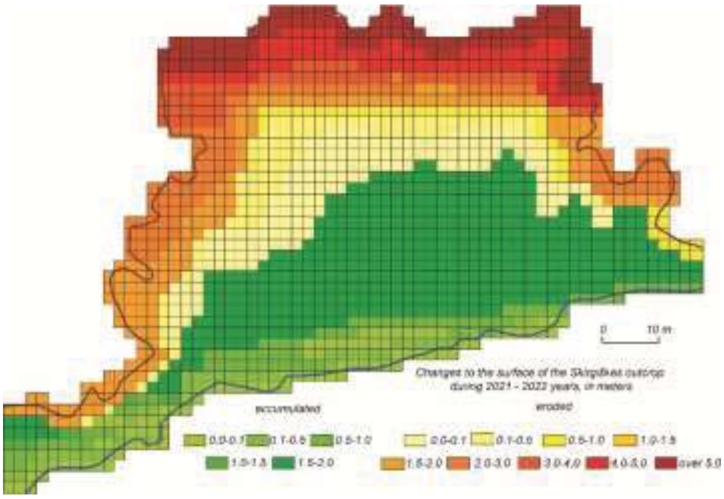

Fig. 2. Erosion and accumulation zones on the Skirgiškės outcrop 2021 – 2022 years (choropleth method).

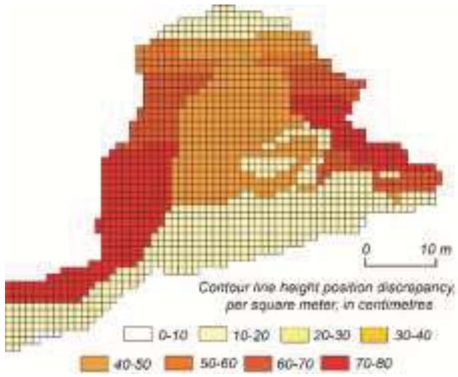

Fig. 3. Comparison of ground-based geod measurements and drone aerial imager Model results (2021 year).

UAV aerial photography is not entirely suitable for identifying outcrop sediment horizons. When capturing the surface of the outcrop, when the camera's viewing axis is perpendicular to the horizontal surface (0 degrees) and rotated 90 degrees, the sedimentary horizons could not be captured. After turning the camera at an angle of 60 degrees, the most contrasting layers of color came to light.

During ground-based geodetic measurements, the layer of outcrop sediments was clearly visible and their position over the entire width of the outcrop was accurately measured (**Fig. 4**). Fixing the layers revealed their texture and main granulometric characteristics (fine-grained, medium-grained or coarse-grained sand, gravel, pebble, boulders). The samples taken from the sediments of the layers made it possible to accurately determine their granulometric composition.

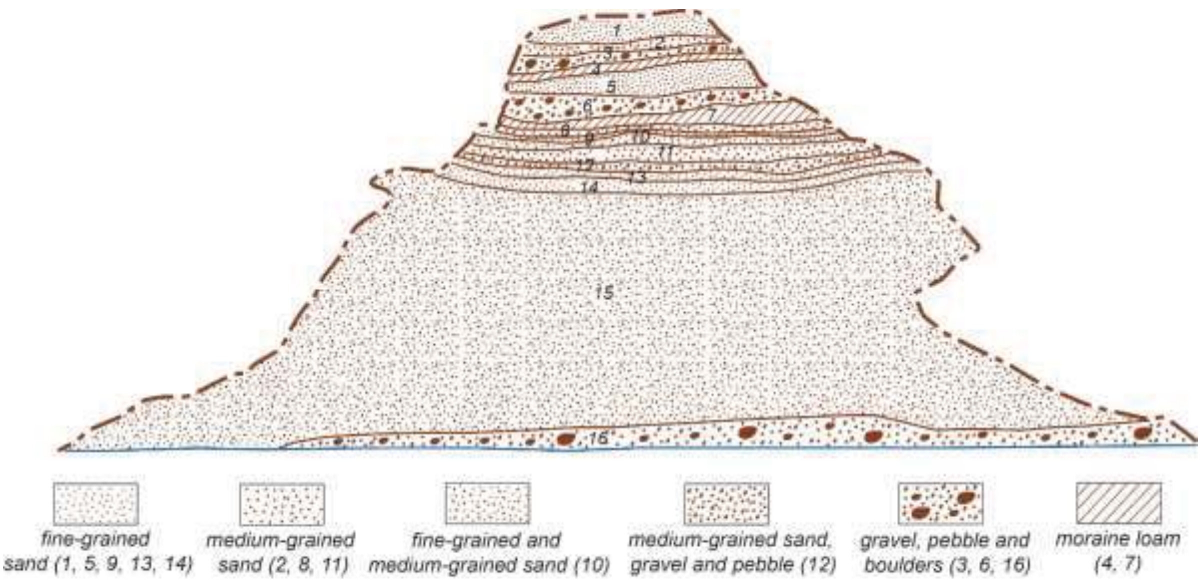

Fig. 4. Sediment layers recorded by ground-based geodetic measurements.

APPLICATION OF AERIAL PHOTOGRAPHS AND AUTOMATED GROUND-BASED MEASUREMENTS TO THE EVALUATION OF SAND GRANULOMETRIC COMPOSITION

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In order to assess the impact of meteorological and anthropogenic phenomena on the unstable surface, extensive dune studies have been carried out for many years. Various measures are taken to stabilize the dune surface. One of them is the installation of sand traps, the purpose of which is to reduce the blowing of sand. The aim is to develop a methodology that would help evaluate the effectiveness of sand traps. Ground measurements of dunes destabilize the dune surface and cannot be done frequently. Currently, measurements are performed 2-3 times a year, but the option of measurements every 2-3 months would be more optimal.

A special methodology has been developed for monitoring the effectiveness of sand traps, which includes three phases **(Fig. 1)**. During the topographic and aerial photogrammetric measurements, the cleared areas and their changes were evaluated, and during the topographic measurements, a microscopic granulometric analysis of the sand fractions was also performed.

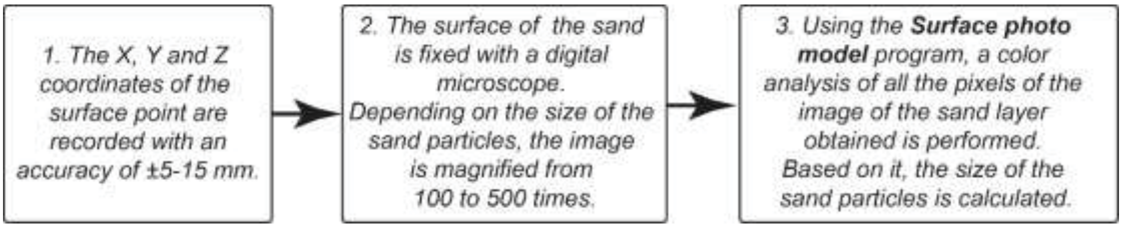

Fig. 1. Methodological research findings.

GPS device Trimble-R4 was used for ground-based topographic measurements, accompanied by photographing the surface of the sand with a digital microscope, allowing the image to be magnified up to 200 times. USB microscope and laptop connected to GPS Trimble-R4. During the measurement, the point position coordinates (X,Y,Z) and sand fractions were recorded. Additionally, after excavating the sand layer, sand fractions were fixed at a depth of 10 cm. The granulometric structure of the sand fractions of the deeper layer allows us to judge the possible swelling of the sand layer. Granulometric fixation was carried out at sand traps and in the open area of the dunes. In order to avoid breaking up the dunes, a mobile robot was used to measure the steep slopes and evaluate the sand granulometry **(Fig. 2)**. The robot chassis does not destroy the slope, it can move on steep slopes (up to 45°), it is equipped with a miniature microscope and a smartphone, with the help of which the surface deposits are recorded.

Fig. 2. A mobile robot.

The study included a complex comparative assessment of the accuracy and sediment granulometry of topographic plan and aerial photographs. An accurate ground-based topographic photo of the studied area was created using aerial images created by the INSPIRE 1 UAV and the grain size of the surface sand layer was recorded at coordinated points (granulometry). Automated creation of the terrain model was performed, which included the selection of pairs of measured points, interpolation between pairs of points, and determination of accurate horizontal positions. The selection of pairs of points was carried out based on the Delaunay triangulation methodology. The granulometric structure of sand fractions was fixed at 24 points near the installed sand traps. Over 300 digital photographs were taken with the microscope at various magnifications. Such fixation made it possible to assess the structure of the fractions of the studied sand layer under field conditions: the size of the sand particles and their relative amount in the studied sample. For this purpose, an original methodology for the evaluation of surface granulometry was created - *Surface Photo Model* (authors of the program Neringa Mačiulevičiūtė-Turlienė and Artūras Bautrėnas) **(Fig. 3).**

Fig. 3. Color analysis window of the *Surface Photo Model* program.

Fig. 4. A solid color background created in the Color Analysis window of *the Surface Photo Model* program.

This program allows you to perform photo-image analysis in two ways:

- Analyzing fixed colors of individual grains of sand
- Analyzing the background of the entire photo image.

In both cases, in the newly generated image, for better differentiation of sand grains, the different colors of the grains are changed to one freely chosen contrasting color. Since the colors of the sand grains and the background of the photo are not the same, in both cases the authors integrated a special algorithm into the program, which allows to calculate and automatically unify the selected colors. After leaving or rejecting the extracted colors in the newly created photo images **(Fig. 4)**, it is possible to calculate the amount of remaining objects (grains of sand) and the area covered by them.

The applied methodology proved itself and made it possible to draw some conclusions:

1. A comparison of the results of aerial photographs and ground-based geodetic measurements showed that the coordinates of the control points determined by the GPS Trimble device and calculated from the orthophoto model of the aerial photograph differ by no more than ±4-6 cm. Therefore, it can be said that in the future, the number of measured points of a topographic photo can be reduced by 2-3 times.
2. After evaluating the photos of sand particles taken with a microscope, it can be said that this methodology is suitable for sand granulometry studies. A comparison of the distribution of fractions in the sand column showed that the obtained results are little different from the results obtained after classical sand sieving.
3. With the help of a mobile robot, it is possible to fix the position of surface points on steep slopes without crushing them and to estimate the granulometric sizes of sand particles. It is possible to install anemometers in the robot to measure the wind speed, record and evaluate the sand deflation-accumulation processes in real time.

APPLICATION OF AIRBORNE PHOTOGRAMMETRY FOR THE MONITORING OF THE KARST PHENOMENA

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The monitoring of karst process in the North Lithuania Karst region started in 1997. The purpose of this monitoring is to evaluate activity on the development of karst process. One part of the activity was the registration of new karstic phenomena such as sinkholes. Registration of new sinkholes was carried out by direct inspection of the area in 1997-2018. The registration of sinkholes was time-consuming activity and the accuracy of this was rather low, in particular, it is difficult to detect every sinkhole. The registration takes place twice a year – in spring and in autumn and up to 30-50 sinkholes were detected each year during the period 1997-2018.

Lithuanian Geological Survey has started to use an unmanned aerial vehicle (UAV) senseFly eBee + RTK, its management and image processing software (eMotion - flight plan and operations, Pix4Dmapper - for image processing) in spring 2018. Before UAV mission starts, it is necessary to make a route, evaluate the influence of the existing air navigation barriers, landing and start positions, as well as evaluate the current landing conditions and possible obstacles at the UAV launch site. Fully processed material with Pix4Dmapper allows calculating volume, area, perimeter, etc. without using any additional software. The points of the generated digital surface have XYZ data, which allows analysing the data of the area of interest immediately. This method creates orthophoto maps of high resolution.

Airborne photogrammetry facilitates registration of new phenomena in the North Lithuania Karst region. Usual flight height is about 160 m above the earth's surface and has 65% longitudinal/latitudinal overlapping. Flight area (Karajimiškis, Mantagailiškis, Drąseikiai, Naciūnai and Kirkilai areas) is about 6 square kilometers and a total 24 square kilometers per two years. Daumėnai area was also monitored a couple of times. During the period 2018–2019, more than 22 580 photos were done in all monitoring area.

It's possible to identify sinkholes with diameter up to 0.5 m (**Fig.1, Fig.2**) after data collection and processing procedures.

Fig. 1. The new sinkhole size is seen in the new orthophoto map in the Drąseikiai area: 0.5 m.

Fig. 2. The same sinkhole as in **Fig. 1**. (identified by UAV) occurred in April 2018 (photo by R. Kanopienė).

BREACHES IN COASTAL BARRIERS OF NON-TIDAL SEAS: PALEOGEOGRAPHIC ASPECTS

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Coastal barriers comprise ~13% of the world's shorelines (Stutz, Pilkey 2001; Buynevich, FitzGerald 2019). In non-tidal or minimally microtidal basins, some of the largest barriers include southeast Baltic Sea, northwest Black Sea, and west-northwest shores of the Sea of Azov (**Fig. 1**). The origin and evolution of these landforms is at least partially related to large fluvial systems (Paleo-Vistula, Paleo-Pregolya, Paleo-Nemunas, Paleo-Dniester, Paleo-Dnieper, Paleo-Southern Bug, Paleo-Molochnaya, and others), in a regime of complex Holocene sea-level fluctuations and short-term wave regime and hydrocalimatic factors. The geological age of non-tidal barrier lithosomes varies from 7.0-6.0 ky in the Baltic (Damušytė, 2011; Sergeev, 2015), 3.0-2.5 ky in the Pontic basin (Inozemtsev et al., 2019), and 1.5-1.0 ky for Azov Sea (Paleogeography…, 2019).

Fig. 1. Major barrier systems along non-tidal seas: *a – Black Sea (Pontic)*: 1 – Tuzla group baymouth barriers, 2 – Kinburn-Pokrovsky-Dolgiy, 3 – Tendra-Dzharylgach; *b – Sea of Azov*: 4 – Arabat Arrow Spit; 5 – Fedotov Spit – Biryuchiy Island; *c – Baltic Sea*: 6 – Hel Spit; 7 – Vistula Spit; 8 – Curonian Spit.

Throughout their evolution, non-tidal barriers were subjected to periodic storm breaching and overwash. The former results in ephemeral inlets (prorvas) and associated geomorphic features (**Fig. 2**). Some channels may turn into permanent inlets, but all have reversing currents and sediment transport patterns, though different in origin than tidal inlets. Similar to flood-tidal deltas, many breaches have associated depositional features (fans or surge deltas) in the back-barrier.

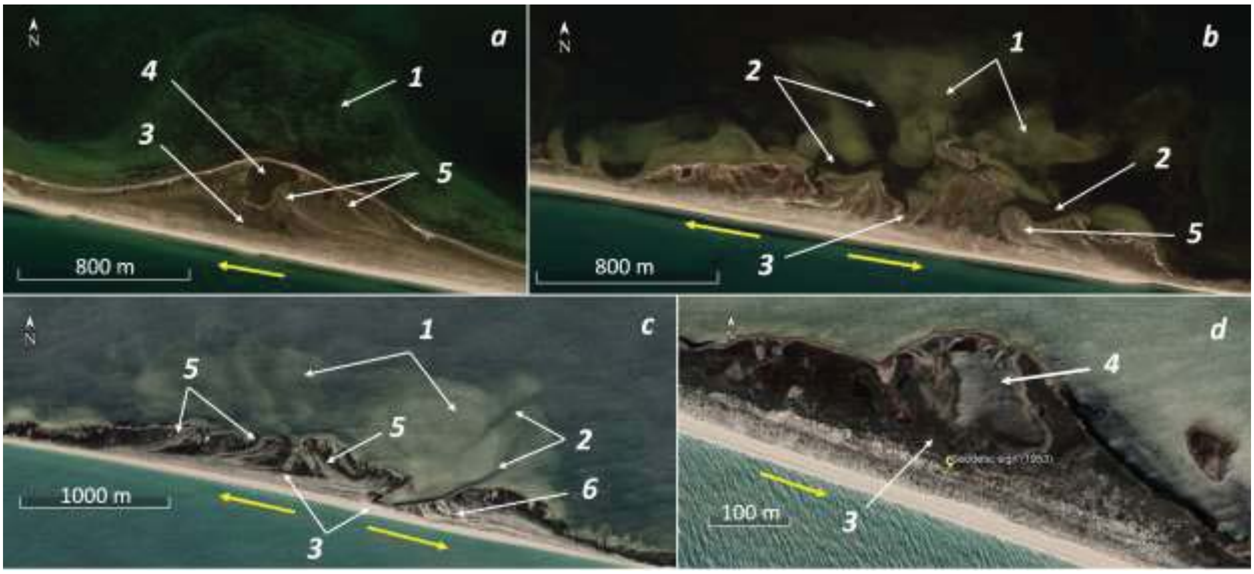

Fig. 2. A suite of morphodynamic elements of Tendra Spit: *a* – simple fan; *b* – complex fan associated with breaches of different ages; *c* – elements associated with actively migratring and re-established breach; *d* – semi-enclosed fan with a geodetic benchmark in front. Morphologic elements: 1 – relict suberged shoals; 2 – relict channels; 3 - sealed breaches; 4 – swales and remnant basins; 5 – recurved spits; 6 – ridge set truncations (yellow arrows show longshore transport direction).

These fan-like deposits and associated underwater shoals have important paleogeographic implications because their analysis allows not only to reconstruct the history of barrier evolution, but also aids in predictive models of coastal change in a regime of hydro-climatic shifts. A detailed assessment of the back-barrier flank of Tendra Spit (**Figs. 1** and **2**) shows systematic patterns of breach distribution, with a degree of morphostratigraphic variation. These are likely related to specific phases of barrier development, punctuated by storm impact. Simple widening (**Fig. 2 *a, d***) occurs along the western and eastern parts of the spit. Their morphology is likely a function of breach longevity, but with no or limited lateral migration This is the result of a dominant cross-shore transport. In contrast, complex fans (surge deltas) tend to occur in the central part of Tendra Spit (**Fig. 2 *b, c***). These openings have functioned for long periods of time and reveal substantial net alongshore migration, likely as a function of strong longshore transport.

Early researchers (Zenkovich, 1960; Pravotorov, 1966) have argued for active erosion along the seaward shoreline and landward migration (retrogradation) of barriers (cf. Buynevich, FitzGerald 2019). However, field data shed doubt on this interpretation. The average width of Tendra Spit does not exceed 70 m but can reach 400 m along its widened fan sections. Geodetic benchmarks installed in the beginning of 20th century show relative stability of these sections. One of such markers in the western section (**Fig. 2 *d***) is located 50 m from the shoreline, which differs little from its original position. This testifies to the stability of the shoreline. Analysis of satellite-based and GPS datasets aids in constraining the position of the Black Sea in the central spit segment. Shore-parallel beach ridges (**Fig. 2**), which front the recurve ridges associated with breach channels, are evidence of recent widening of the barrier (progradation; cf. Buynevich, FitzGerald 2019). These findings demonstrate that breach sites along non-tidal, wave-dominated barriers ultimately produce sediment-rich stable sections. Similar scenarios may have been common along paleo-barriers of the Baltic Sea basin, whereas modern systems are too wide and high to allow breaching and overwash.

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CLIMATIC VARIATIONS DURING THE LATE GLACIAL AND EARLY HOLOCENE IN LITHUANIA ACCORDING TO CHIRONOMIDAE RESEARCH

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The study of the postglacial climatic variations is currently an important scientific problem. Such studies using modern geochronological and climate reconstruction models are still scarce in the Eastern European region. Chironomidae - a diverse midge family, are often used for climate reconstructions as the major factor affecting their distribution is climate. Over the past decade a series chironomid based quantitative reconstructions of the mean July temperature in the south-easter Baltic region were carried out (Płociennik et al., 2011; Dzieduszyńska et al., 2014, Veski et al., 2015 etc.).

This study presents the first Chironomidae studies performed on Lieporiai (north Lithuania) and Čepkeliai (south Lithuania) sections. Mean July air temperatures were inferred using Fennoscandian calibration model (Luoto, Nevalainen, 2017).

Reconstructed Late Glacial mean July temperatures varies between 13–16 °C (Šeirienė et. al., 2021). Meanwhile in Poland reconstructed temperatures from Žabieniec bog ranges between 12–17 °C (Płociennik et al., 2011). Little lower temperatures were obtained from Kurjanovas Lake in Latvia – 1–14°C and Nakri Lake in Estonia – 10.5–13 °C (Veski et al., 2015). The highest temperatures during this period were registered in Kamyshovoye section, Kaliningrad (Druzhinina et al., 2020) and ranged from 16 °C to 19.8 °C.

Bolling interstadial is marked by the intense climate warming after the glaciers retreat from the territory and the mean July temperatures in Lithuania could reach ~14.8 °C. Similar temperatures were obtained from the Žabieniec bog (Płociennik et al., 2011). Sufficiently high temperatures for this period are fixed in the Kaliningrad – about 16 °C (Druzhinina et al., 2020), in the Netherlands – 14–16 °C (Heiri et al., 2007) and in west-central Europe (Magny et al., 2006). However, the reconstruction of Latvian and Estonian sections shows much lower temperatures of 11.8 °C and 11 °C respectively (Heiri et al., 2014; Veski et al., 2015).

During the Older Dryas cooling (GS-1d) the mean July temperature fell to 13.2 °C. Thus, the data obtained correlates well with that from Žabieniec bog and the data of the mid-Baltic (Heiri et al., 2014).

The highest temperatures of the Late Glacial were during the Allerod (GI-1a) and reached ~16 °C according to the Lieporiai section. Very similar results were obtained from the Poland and Netherlands (Płociennik et al., 2011; Heiri et al., 2007). Even higher temperatures of this period were inferred in Kamyshovoje section reaching ~19.8 °C (Druzhinina et al., 2020). The lowest values were obtained from the Latvia and Estonia, where they ranged from 13 °C to 14 °C (Heiri et al., 2014).

During the Younger Dryas (GS-1) cooling the temperature fell by 2 °C in Lithuania, but remained quite high ~14 °C. This temperature correlates well with the reconstructions in central Europe (50-55° N) (Heiri et al., 2014). Further north than Lithuania, much lower temperatures were fixed ranging between 10.5 °– 11 °C (Heiri et al., 2014), but here no significant temperature drop was recorded.

During the transition period from the Younger Dryas to the Preboreal our data indicate a temperature increase of about 2 °C. The same is also observed in other reconstructions from the Baltic countries (Heiri et al., 2014).

Beginning of the Holocene (Preboreal) is marked by gradual increase in temperature. It reaches 15–16 °C in both reconstructions of studied sections and correlates well with contemporaneous ones in western and central Europe (Magny et al., 2001).

During the Boreal, the temperature rise is observed in both sections: in Čepkeliai bog it reaches 18.4 °C, and in the reconstruction of Lieporiai Lake – 15.8 °C.

In summary, our temperature reconstructions correlate well with those obtained in neighbouring countries. The reconstructed amplitude of mean-July temperature variations is consistent with reconstructed in south-eastern Baltic region and proves the temperature gradient in the direction of the west-east, i.e., the retreat of the glacier. The reconstructed temperatures in the Early Holocene are slightly lower than the current temperatures. Reconstructions enable to fix short-term climate variations during that period.

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SPATIAL AND TEMPORAL CHANGES IN THE MODE OF TILL DEFORMATION UNDER A PALAEO-ICE STREAM DERIVED FROM MICROMORPHOLOGICAL DATA

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Subglacial processes under contemporary and past ice sheets attract a lot of attention, yet our understanding of the ice/bed interface remains fragmentary. Till micromorphology informs about its formation and deformation and therefore helps to decipher the nature of the subglacial processes and the origin of some active-ice landforms. Such landforms are especially abundant under fast-flowing ice streams where interactions between ice, water and the soft bed control the glacier dynamics and the land-forming processes.

In this study we investigated microstructures and clast microfabrics in tills generated under the Odra palaeo-ice stream, one of the most prominent land-based ice streams of the southern Scandinavian Ice Sheet. Specifically, S-matrix microstructures were mapped and interpreted in 17 thin sections, and 15 till blocks were investigated for X-ray microtomography (μCT). All samples were collected in trenches excavated in three drumlins. The most frequent microstructures were microshears indicating brittle deformation, and circular structures reflecting ductile deformation. The long axes of clasts mapped by μCT revealed weak clustering strengths and, occasionally, bimodal fabric pattern. There was no consistency in μCT fabrics in the vertical profiles, from one trench to another, and between the drumlins.

Our data indicate a spatial and temporal complexity of the subglacial processes likely modulated by porewater pressure fluctuations. Successions of brittle and ductile deformation events contributed to substantial homogenization of the till. However, the geometry of some microstructures suggests that only a thin layer of the till, in the range of centimetres, was experiencing deformation at any point in time. Finally, the lack of correspondence between the microclast orientations and the trend of the drumlin field suggests that the till pre-dates the drumlin formation, which is consistent with earlier studies in this area.

GEOHERITAGE OF KURTUVĖNAI REGIONAL PARK

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In this paper, we have used the term *geoheritage* after Brocx and Semeniuk (2007, p. 53). The authors' defined it in the following manner: "global, national, state-wide, and local features of geology, at all scales that are intrinsically important sites or culturally important sites offering information or insights into the evolution of the Earth; or into the history of science, or that can be used for research, teaching, or reference".

The official legally protected geoheritage of Kurtuvėnai Regional Park includes 11 objects: 5 geological, 3 geomorphological and 3 hydrogeological objects (by State Service for Protected Areas under the Ministry of Environment of Lithuania, https://vstt.lrv.lt/). Besides, 4 geomorphological, 7 landscape and 1 hydrographic reserves have been established for conservations of erratic boulders, outcrops and landforms and landscapes of particular significance.

Valuable boulders of large size, interesting compositions and other extraordinary features represent most of the geological heritage objects. 3 geomorphological objects in the Kurtuvėnai Regional Park are designed to preserve localities with typical or rare landforms of relief bearing a great scientific and educational value. These objects are mostly hills, ravine and hollow. The author of this paper have decided to analyze the most famous areas in more detail.

Targiai Eskers. Targiai geomorfological reserve is situated in the southwest part of Kurtuvėnai Regional Park. It aims to preserve the only eskers in the park. Recent geological research revealed unknown features of these nature's monuments. Eskers' ridges stretch in northeast-southwest direction and are separated one from another by a rather wide, in some places boggy, lowering. The length of eskers varies from 300 m to 2 km, width of the basement 100-150 m, absolute high 130.0-145.3 m, relative height up to 12 m. Drilling of the most astonishing and longest esker has revealed that this esker consists of coarse grained sand and gravel of varying sizes. Total thickness of glaciofluvial deposits is up to 30.4 m. The basement of esker consists of compact till. We see only one third of this relief form on the surface of the earth. Drillings in the esker revealed that deposits vary very much and even six grain size of sand were ascertained.

The Pustlaukis Holes. The Pustlaukis Holes are situated in the western part of Kurtuvėnai Regional Park. The Pustlaukis Holes consists of very interesting and mysterious landscape forms. It's slopes are 13 meters high. On the southern and eastern slopes of the pit there is a pronounced terrace, and on the northern end there is a channel (narrowing). Another slightly smaller bowl is about 400 meters to the south. The provided collected data prove that the holes are of glaciokarst origin, and were formed in Alerod time (about 12 000 years BP). Palynological (pollen) surveys in the Half-Grove Pit shows how climate and vegetation had changed in the area. 11-12 thousand years ago pine and birch trees prevailed here, grass grew in abundance. 9 to 10 thousand years ago forests spread, grasses of various species disappeared; aquatic vegetation prevailed 8-9 thousand years ago; 5 to 8 thousand years ago a sudden increase in broad-leaved trees (oak, linden, elm) was observed; 3 to 5 thousand years ago dense spruce trees were formed. In the last climatic period, which has lasted for more than 3 thousand years, pine trees prevailed again in the environment of the Pustlaukis Holes (Mikulėnas et al., 1997).

Pustlaukis Holes should be regarded as part of national natural heritage with its implication for science, education and tourism. This geological phenomena should be involved into the List of official protected monuments of all Republic significance as geological monument.

Svilė Springs are among the most impressive in Lithuania. They are the largest in terms of area occupied and the third in terms of groundwater discharge. There are over a hundred springs in 1,8 hectare area, from which the 350-meter-long cold-water Svilė River flows. The water of Svilė Springs is fresh, tasteless, odorless, calcareous, of medium hardness. According to its chemical composition, it is magnesium calcium water of bicarbonate (Kadūnas et al., 2017).

The southern slope of the Venta-Dubysa tunnel-valley, where the springs of the Svilė erupt, may have been formed 15 to 16 thousand years ago.

Vėžaliai Stone, called Perkūnas**,** is one of the largest stones in Kurtuvėnai Regional Park. During the II World War German soldiers tried to dig up the entire stone, but most of it remained underground. The stone stands on the top of a high Perkūnkalnis Hill, in Šilkalnis Geomorphological Reserve. People say that the Devil was hiding under the stone, and Perkūnas thundered and split the stone in half.

Girnikai Hill, called Šikšto, Šventkalnis, in Kurtuvėnai Regional Park is exceptional. In the Kurtuvėnai hill massif dominate large and small, domed and flat-topped hills. Sharp-topped hills, like Girnikai Hill, are rare. Girnikai Hill absolute altitude is 183,1 m above sea level, relative height is 35-40 m. The hill is 400 m long and 180 m wide and extends north - west. Slopes are steep, up to 20 degrees. The slopes across the perimeter are of equal height and inclination, there are no carving by ravines or gullies. An extremely steep sloped top rises into the sky like a tower of a castle.

The three boreholes in Girnikai Hill revealed its internal structure. It is a typical complex (glacioaquatic) kame with a binary structure. According to whether kame deposits or sediments where deposited under conditions of flowing or still meltwater, they are classified as glaciofluvial or glaciolacustrine kame. The combined action of flowing and still glacier meltwater formed complex (glacioaquatic) kame.

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THE LATE WEICHSELIAN TO HOLOCENE VERTEBRATE BURROW SYSTEM OF PISEDE (NE-GERMANY) – NEW INSIGHTS FROM OSL DATINGS

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In the southwestern Baltic Sea area, the Scandinavian Ice Sheet (SIS) reached its Last Glacial Maximum during Marine Isotope Stage 2. From this position, the ice front retreated in general only interrupted by several short periods of readvance or stillstand during e.g. the Pomeranian (c. 20 ka) and Mecklenburgian Phase (c. 17 ka). Around 16 ka to 15 ka the SW Baltic Sea area and thus northeast Germany became ice-free. Terminal moraines, sandur areas, till plains, and glacitectonic deformed structures dominated this freshly deglaciated landscape in this part of Germany. Due to the general climate warming at the end of the Weichselian glaciation, plants and animals followed the retreating ice front with temporal and geographic distance. In this context, the Retzow-Gülitzer Heights, which were previously interpreted as a terminal moraine structure of the Mecklenburgian Phase (Janke et al. 1975; Nagel & Rühberg 2003), play an important role.

In in the end of the 1960s several excavation campaigns were organized by the Natural History Museum of Berlin to investigate an extraordinary burrow system in deformed glacilacustrine deposits, containing a very high content of fossils of different species (Heinrich 1975). For example, 160.000 amphibian and 17.000 rodent individuals were found in this system. The stratigraphic classification of the fossil content and thus also of the burrow system itself spans the period from the late Weichselian into the Holocene. However, there is no confirmation by absolute age dating apart from three uncalibrated conventional radiocarbon ages from charcoal of *Fagus sylvatica* L., which indicate a settlement of the burrow system at least within the last c. 2000 years (Heinrich & Jäger 1975).

The aim of the study presented here is to close this stratigraphic knowledge gap and to date the filled burrow system, as well as the surrounding glacilacustrine sediment by optically stimulated luminescence (OSL). The investigated section is located near Pisede (125 km NNW of Berlin, Germany) in the upper part of the former excavation site. The outcropping material consists of glacilacustrine sediment deposited in front of the advancing SIS. A subsequent glacitectonically deformation probably during the Gerswalder Substage, which is part of the Pomeranian Phase (Hardt & Böse 2016) formed the Retzow-Gülitzer Heights. The uppermost part of the standard profile is composed of a discontinuous till layer of Mecklenburgian age, which, however, does not occur in the investigated section. Four OSL samples were taken from the glacilacustrine sediments in which the burrow system occurs. For age assessment of the burrow system itself, two OSL samples from the burrow-fill were analysed. Based on the preliminary dating results, the following picture can be drawn: The glacilacustrine sediments in which the burrow system is located, were formed during the ice advance of the Pomeranian Phase around 21 ka, which is in excellent agreement with the age estimation in Hardt & Böse (2016). Afterwards, the youngest till layer was deposited, which can be associated with ice advance respectively ice stillstand event of the Mecklenburgian Phase. Based on the OSL ages from the burrow-fill, the initial period of burrow digging began shortly after the final ice decay phase at the end of the Weichselian (14.5±2.1 ka). During this time the southwest exposed slope of the investigated section might be settled by lemmings (*Lemmus lemmu*s) and ground squirrels (*Citellus superciliosus*; Heinrich & Maul 1983), which are typical tundro-steppe species (Popova 2016). These may have been the first builders of the burrow systems, which were subsequently reused by a whole series of other species.

The results illustrate that OSL dating of burrow-fills and surrounding sediment could be an important tool to reconstruct bioturbation activity in periglacial environments. In addition to this absolute age chronology, future studies on fossil remains from the Pisede burrow system provide insights that help determine the palaeogeographical distribution of certain vertebrates in the late Weichselian to Holocene.

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THE HISTORY OF MID-TO-LATE HOLOCENE ENVIRONMENT DYNAMICS: NEW MULTY-PROXY STUDY FROM THE EASTERN BALTIC REGION, W LITHUANIA

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Peatlands of the Nemunas River Delta have been subject of numerous investigations comprising various aspects of the environmental history in this part of Lithuania. Being one of the largest in this territory, Aukštumala raised bog have been an object of scientific investigations since 1902, when it was firstly described in the famous monograph by German botanist Weber (Weber, 1902). Nevertheless, not so much is done discussing the Mid-to-Late Holocene environmental history here thus an additional multi-proxy data including archaeobotanical and archeological one is required for the reliable reconstruction of palaeoenvironment history in the Eastern Baltic region.

In order to reconstruct the main patterns of the Mid-to-Late Holocene environmental dynamic, complex studies of biotic and abiotic variables were held. The study area is located in the Nemunas River Delta, within the territory of the Aukštumala raised bog stretching eastwards from the coast of the Kuršių Marios (Curonian Lagoon). Two parallel 2.37 and 2.40 m depth sediment cores (A1D and A2D) cores were taken for which palaeobotanical (plant macrofossil, pollen-spores), lithological (loss-on-ignition (LOI), magnetic susceptibility), chronological (^{14}C), geochemical and various statistical studies were proceeded.

Based on the results of the multi-proxy data six distinct stages yielding a 6000- year record of the environmental dynamics have been established. The initial period of sedimentation (before 5900 cal yr BP) was marked by the flourishment of *Alnus* and poor herbaceous representation in the context of the vegetation composition. Simultaneously, the highest value of SO4 with higher admixture of the terrigenous matter was noted. Recorded characters of the particular environmental proxies points to increasing wetness that correlates well with the wet interval noted all along the European territory at that time (Langdon et al., 2003; Edvardsson et al., 2012; Grindean et al., 2015; Stančikaitė et al., 2019).

Dryer period was noted between 5900-5000/ 4800 cal yr BP. An onset of this interval is marked by the decreasing representation of wetland plants and extinction of *Alnus glutinosa* macrofossils' from spectra. However, recovering of the aquatic plants (i.e. *Potamogeton*) at about 5400 cal yr BP points to the hypothesis of rapidly increasing water table. This change is consonant with the prevalence of the plants tolerating wet soil (i.e. *Alnus glutinosa* and *Potentilla palustris*), however surrounding forest still dominated by coniferous indicating dry habitats. No changes were fixed in geochemical record, except insignificant decrease in SO4 value.

Between 5000/4800–4300/4100 cal yr BP the site transitioned to a lake which gradually changed to an open wetland. The transition is marked by the decrease of *Alnus glutinosa* and

Pinus while *Betula* gains more ground. However, since 4400 cal yr BP *Betula* rapidly decreases and *Pinus* takes over. Simultaneously first finds of *Picea* macrofossils are observed. Increasing water table is confirmed by an increasing representation of the water plants in macrofossil spectra. Indicated fluctuations may have been caused by an increasing precipitation, synchronous with the cooler climatic regime recorded in the eastern Baltic region at the time (Seppä, Poska, 2004).

In the beginning of the next period (4300/4100–3200/3000 cal yr BP) water plants gradually disappeared, and territory was occupied by wetland plants, *Andromeda polifolia*, in particularly. Differences marked in A2D core, support a hypothesis that newly spread vegetation blocked water outflow and lakes appeared within the territory. At that time surrounding forests were vegetated by temperate trees (i.e. *Tilia*). However, at about 3200–3100 cal yr BP *Tilia* curve shows a decrease, though representation of other temperate trees is rather steady. Collected data support the hypothesis of wetland extension. This interval also is marked by increased NO3, P and variable Cl, F also SO_4 values.

During the final period (3200/3000–2100/2000 cal yr BP) intermediate wetland blocks gradually changes to raised wetland according to data available. Surroundings of the newly formed lakes are occupied by *Alnus*, *Menyanthes trifoliata*, also Poaceae which could partly consist of *Phragmites* type vegetation. Interval is marked by increased Cl concentrations. Since about 2100/2000 cal yr BP vegetation gradually changes from intermediate to raised wetland. This is marked by the appearance of Cyperaceae species and gradual occupation of the territory by *Sphagnum* and Ericaceae representatives. Noted changes connected with raised wetland vegetation degradation may have been triggered by human interference, including land-use practices, peat exploration and land reclamation. Some of these changes significantly correlate with an increased levels of NO3, P, SO4, and Cl values.

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AGE ASSESSMENT OF GLACIOTECTONIC COMPLEXES BY LUMINESCENCE DATING – A CASE STUDY FROM THE JASMUND PENINSULA (SW BALTIC SEA)

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There are many studies on glaciotectonic complexes with Pleistocene age in the south-western Baltic Sea area (e.g. Pedersen, 2005; Gehrmann & Harding, 2018). However, the investigation of the chronological evolution of these complexes bears some difficulties due to the lack of directly dateable material. The age assessment is mostly based on indirect dating of under- and overlying undeformed deposits. Thus, the challenge is to find suitable material for direct dating. Pedersen (2005) described the development of glaciotectonic piggyback basins filled with syn-tectonic deposits. We assume these deposits to provide the potential for directly dating of the evolution of glaciotectonic complexes.

In the presented study, we focus on the formation of the Jasmund Glacitectonic Complex (JGC) on the island of Rügen (NE Germany). Gehrmann & Harding (2018) extensively described the multi-stage evolution of the JGC, which exact chronology is still under debate (Lüthgens et al. 2020). In the southern part of the JGC Plonka et al. (2021) identified syn-kinematic sediments deposited in a piggyback basin. These strata are not dated so far. In order to test the applicability of the basin infill for luminescence dating we present a set of OSL ages. The samples were taken from glaciolacustrine and alluvial fan sediments deposited between ice margin-parallel thrust-bounded ridges formed during the formation of the JGC (Plonka et al. 2021).

Since the depositional environment was close to the ice margin and the transport distance of the sediment was most likely quite short, partial bleaching of the luminescence signal might be a general issue. With the potential luminescence dating of these syn-kinematic sediments it would be possible to reconstruct the genesis of the JGC for the first time.

A comparison of our data with existing age data related to the evolution of the JGC will contribute to a better understanding of the regional dynamics of the Scandinavian Ice Sheet (SIS) in the research area.

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HISTORY OF TWO CLIFF PALEOLAKES (POLISH COASTAL ZONE) BASED ON THE POLLEN AND CLADOCERA ANALYSIS

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The increase in the water level of the Baltic Sea and the abrasive processes are the cause of uncovering of numerous paleolakes on the coastal cliff. The origin of most of the lakes on the Poddąbie - Smołdzino section was connected with the process of deglaciation on the foreland of the terminal moraine of the Vistula Glaciation dated by Rotnicki and Borówka (1994) on 14500-14300 year BP. These lakes were formed in depression created after deglaciation and filled with water from melting glaciers. Further development of the lake depend on aeolian processes and marine abrasion occurring with varying intensity during the Holocene (Florek et al. 2010).

The studies were carried out on two sites (Debina and Poddąbie) located in the central part of the Słowińskie Coast in Northern Poland. The results of palynological and subfossil Cladocera analysis of the sediments together with geological data document the dynamic changes in the environmental conditions that occurred as a result of the transition from cold to warm climate.

Dębina reservoir was created in the Late Glacial period. In the initially cool, proglacial lake, the lake muds and gyttja were deposited. The species of Cladocera identified in this period (bølling / allerød) indicate a deeper, oligotrophic reservoir. Cooling in older dryas caused inhibition of the development of fauna in the reservoir. The climate change at the beginning of the Holocene improved the habitat conditions in the Dębina paleolake, which is reflected in the growth of zooplankton biodiversity and the rich pollen content of aquatic plants. Climate change i.a. warming and intensification of melting processes in areas occupied by permafrost (Błaszkiewicz 2005) also contributed to the creation of a second reservoir near Poddąbie. Initially there was a relatively high water level in the reservoir. Then, during the preboreal period, there was a decrease in water level with a marked increase in trophic level, which was recorded in pollen records. At that time, developed lowland bog of the rushes character with the domination of sedges (*Cyperaceae*) and the marsh fern, which documents the high share of spores of the species *Thelypteris palustris*.

The distinguished phases of paleolakes development (three zones in the profile from Dębina and five in the profile from Poddąbie) illustrating the evolution of the studied aquatic-mire ecosystem. In the following periods trophic level in the reservoir increased, there were also significant fluctuations in water level leading to periodic transformation of reservoirs in peat bogs. Gradually, the drop in water level and the intensification of the erosion processes led to terrestrialization of the paleolake. The research allowed to reconstruct the history of the cliff reservoirs during the Late Glacial and early Holocene, which - as a consequence of regression of the sea-land border zone due to climatic and geological processes - are now becoming irreversibly damaged.

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PLEISTOCENE SEISMITES IN THE SOUTHERN PERIBALTICUM AREA - THE GREBAL PROJECT SUMMARY

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The overall objectives of the GREBAL project were to investigate the sedimentological traces of earthquakes (seismites) within Pleistocene successions and to combine seismic activity with the particular stages of Fennoscandian Ice Sheet development. The studies performed consist of (1) field work conducted in river valleys, coastal bluffs and sand / gravel pits in NE Germany, N and W Poland, Lithuania, Latvia, Estonia; (2) sedimentological analysis (logging; lithofacies analysis; grain size analysis; structural measurements and analysis) as well as microstructural analysis of soft-sediment deformation structures (SSDS); (3) collection of samples for OSL dating and acquisition of absolute geochronological data, (4) numerical analysis of glacially-induced stress state changes and its implications for GIA-induced earthquakes (Pisarska-Jamroży et al., 2019a; Steffen et al., 2019), (5) numerical modeling of seismites development in water-saturated sandy and silty sediments (Bronikowska et al., 2021).

Seismites were interpreted within glaciolacustrine / lacustrine and fine-grained fluvial sediments on the basis of characteristic textural and structural features as well as stratigraphic position in the sequences supported by OSL dating results. Seismic activity did accompany Saalian and Weichselian glaciations, and occurred in different periods of glacial cycle – during or after deglaciation (Belzyt et al., 2021; Van Loon and Pisarska-Jamroży, 2014; Van Loon et al., 2016; Pisarska-Jamroży et al., 2019a; Pisarska-Jamroży and Woźniak, 2019) and during ice-advance periods (Pisarska-Jamroży et al., 2018, 2019b). Earthquakes caused by the reactivation of deeply rooted pre-Quaternary faults due to stress state changes and/or glacial earthquakes were the most probable sources of interpreted seismic activity. Low to moderate seismic activity connected with glacial loading cycles should be considered and discussed as one of possible trigger mechanisms for liquefaction-induced SSDS observed within sections currently or formerly covered by an ice sheet. Moreover, glacigenic earthquakes are discussed at some study sites (Pisarska-Jamroży et al., 2019b Woźniak et al. 2021).

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LIQUEFACTION AND RE-LIQUEFACTION SEDIMENTOLOGICAL IMPRINTS IN PLEISTOCENE SEDIMENTS

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Liquefaction phenomenon can leave imprints in water-saturated, loosely packed fine-grained sediments (cf. Obermeier, 1996; Vanneste et al., 1999). During liquefaction, the water-saturated porous silty and fine-grained sandy sediments undergo sudden loss of intergranular contacts (Obermeier, 1996; Youd, 2003). As an effect the sediment behaves as a plastic mass (Van Loon et al., 2020). The occurrence of majority sedimentological features caused by liquefaction (e.g. injection structures, load casts, flame structures and pseudonodules) are restricted to the uppermost few decimetres below the respective ground surface, i.e. palaeosurface (Obermeier, 1996).

Liquefaction phenomenon causes an increase of grains packing and a decrease of sediment hydration, resulting in sediment solidification (Youd, 2003). Sediments that have already been liquefied are highly resistant to re-liquefaction (repeated liquefaction of the same sediments). However, re-liquefaction of the same sediments is possible if the compaction after initial liquefaction does not exceed 10%, especially in water-saturated, loosely packed sandy and silty sediments (Alberto-Hernandez and Towhata, 2017). The unique sedimentological traces of re-liquefaction phenomenon were recognised in a few study sites in Pleistocene sediments in the area south of the Baltic Sea (Woźniak et al., 2021; Belzyt et al. 2021; Pisarska-Jamroży et al., in review). A re-liquefaction phenomenon was responsible for e.g. disintegration of some larger soft-sediment deformation structures (SSDS) into smaller ones, reorientation of previously formed SSDS as well as development of the second generation of injection structures infilled by previously formed, dispersed and reoriented SSDS.

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FEATURES OF THE AREA FORMATION OF MIDDLE AND NORTHERN LITHUANIA LOWLANDS

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In Lithuania, the multi-layered formation of the Last (Nemunas, Weichselian) Glacial deposits was determined by the active stages and phases of glacier advance and retreat. The absence of reliable biostratigraphic and geochronological data, palaeodynamic parameters of sedimentation, usually cause problems in determination of deposits genesis, stratigraphical subdivision and correlation of Pleistocene sections.

The formation of the Last (Nemunas, Weichselian) glaciation deposits was investigated in the outcrops by taking samples from till for investigations of graine-size and petrographical composition. The petrographic compositions of pebbles were analyzed according to the A. Gaigalas methodology (Gaigalas, 1979; Gaigalas, Melešytė, 2001) and using the following categories: crystalline rocks, sandstone, Devonian dolomite and dolomitized rocks, Ordovician and Silurian limestone, Devonian and Permian limestone, and a group of other rocks. Clast fabrics were also taken from outcrops in the glacial till. The orientation and dip of long axes of 50 macroclasts with elongation ratios of ≥ 3: 2 were measured in outcrops using a geological compass and applying methods outlined by A. Gaigalas (Gaigalas, 1979; Gaigalas, Melešytė, 2001). For the investigation of intertill sediments between Grūda and Baltija tills, analysis of spores, pollen, graine-size and organic material was performed.

Data on geological mapping, hydrogeological and mineral exploration boreholes from the Geological Fund of the Lithuanian Geological Survey were used to study the structure and composition of morainic plains. Morphometric parameters of MSGLs in Lithuania have been determined by cartometric measurements from topographic maps (1:10 000). A digital elevation model (DEM) with 2 m spatial resolution was used for microform analysis of some small places (Kivyliai, Kupriai, Baisogala, Viešintos and Kėdainiai) in Middle and Northern Lithuania. The copyright of the DEM belongs to the Lithuanian Geological Survey under the Ministry of Environment. The composition of MSGLs and the thickness and sedimentological characteristics of depositional units were determined. Macroclast fabrics were also taken from excavated pits and outcrops in glacial till.

The carried investigations and the results obtained led to several conclusions: 1) The deglaciation of the Last (Nemunas, Weichselian) Glaciation between the Grūda and Baltija stages, according to the Balbieriškis outcrop investigations, was characterized by a pronounced interstage warming with a characteristic development of vegetation from the cold polar to the forest, then gradually returning to the cold polar vegetation. Sediments contained considerable number of redeposited spores and pollen; 2) The investigation of the ridged relief of the morainic plain in NW part (Naujoji Akmenė area, North Lithuania) showed that it is characterized by features of mega-scale glacial lineation (MSGL) forms, indicating active movement of the glacier. No association with sub-Quaternairy palaeosurface features was observed in the layout of MSGL forms; 3) Typical MSGL forms in Mūša-Nemunėlis Morainic Plain (North Lithuania) and the relicts of MSGL forms in the Nevėžis Morainic Plain (Middle Lithuania), as well as narrow and concentrated orientation of the long axes of the macroclasts and the degree of mixing of the moraine material (till) positively correlate with the velocity of the sliding glacier.

AEOLIAN DEPOSITS, BURIED SOILS AND CARBONATES IN DUNES OF LITHUANIA

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New preliminary data was obtained carrying out project entitled „Ichnological and sedimentological evidence of late glacial and Holocene environmental changes in the eastern part of the European Sand Belt". The continental dunes prevail over the coastal ones in the territory of Lithuania. The coastal dunes are widespread in the Curonian Spit while the area of continental ones is largest in the east southern Lithuania (**Fig. 1**.)

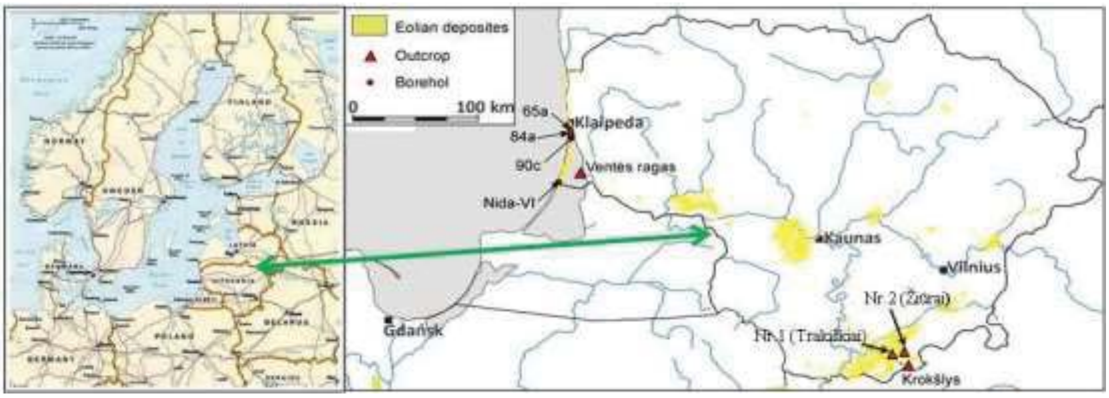

Fig. 1. A map showing the location of the studied sedimentary sequences in aeolian deposits in Lithuania.

Examining the internal structure of continental and coastal dunes we could judge about a renewal of aeolian processes. The paleosoils buried in sand reflect periods of dunes stabilization while overlying sand beds indicate a renewal of aeolian processes. All these processes are reflected in the complex internal structure of dunes. The carbonate content (calcite and dolomite minerals) was determined for aeolian sediments. The results obtained show that carbonate content in buried paleosoils is higher than in aeolian ones (**Fig. 2a, b**).

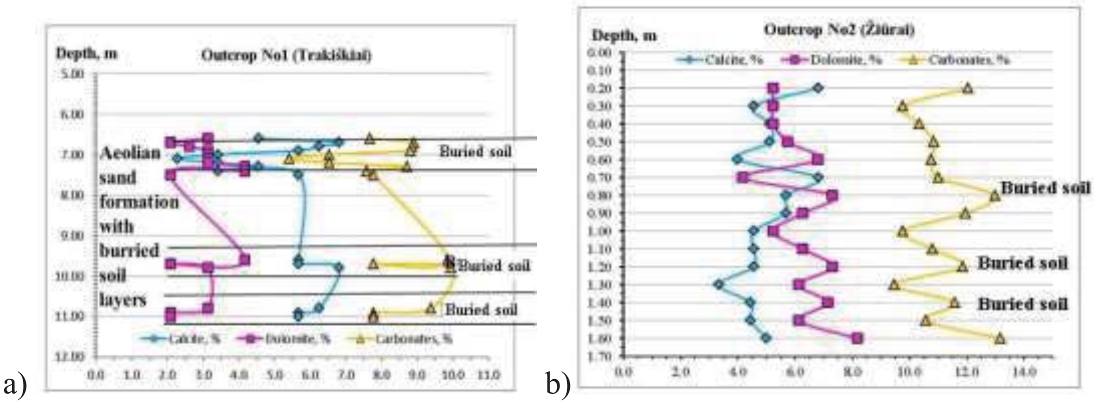

Fig. 2. Carbonates in aeolian sediments and buried soils from outcrop Trakiškiai (a) and outcrop Žiūrai (b).

The carbonate content could be used as a criterion for very thin or poorly preserved buried paleosoils. Moreover, the criterion could be used not only for outcrops samples but also for the ones taken from drill-cores (**Fig. 3**). (Rudnickaite E., 2019).

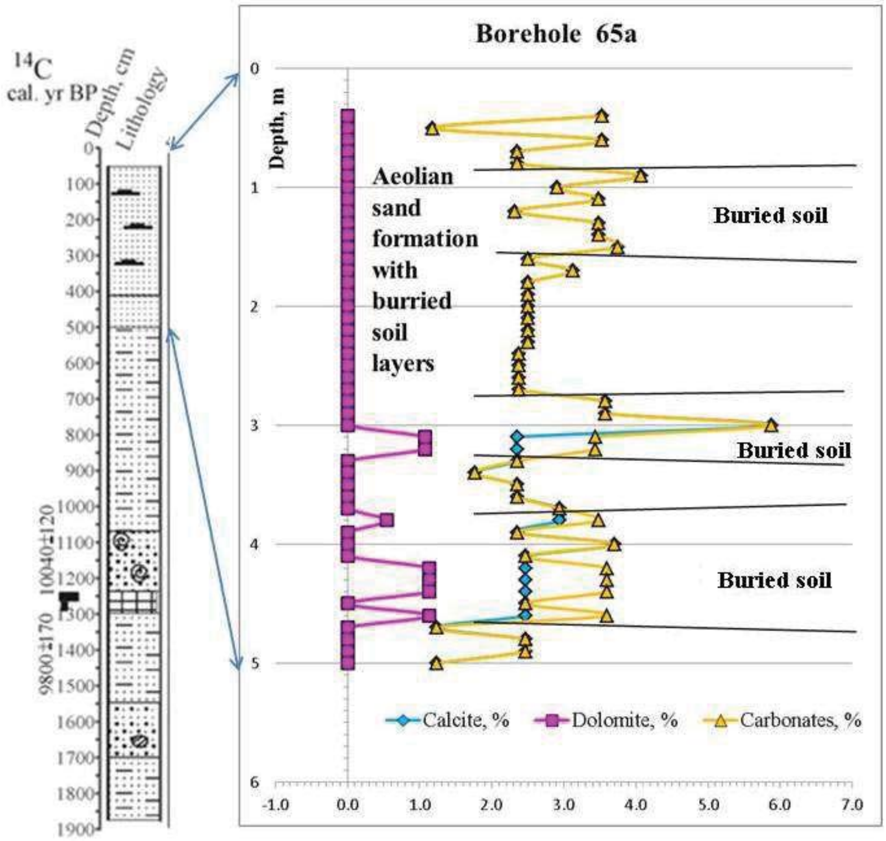

Fig. 3. The carbonates in aeolian sediments and buried soils from borehole 65a.

The studies will be followed by fossil and bioturbations textures, sedimentological and stratigraphical analysis which will be based on optically stimulated luminescence (OSL), radioactive carbon dating technique, geophysical and statistical methods. As a result it will enable us to establish spatial dynamics of aeolian sediments and integrate it with the results of ichnological analysis.

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THE BURIAL OF LATE GLACIAL LAKES IN SOUTHEASTERN LITHUANIA

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Ūla River Valley crosses the outwash plain formed in front of the former ice margin South East from the distal slopes of Baltic highlands of Pomeranian stage of the Last Glaciation. Deposits in the distal part of the outwash plain are drifted forming high dunes in many places.

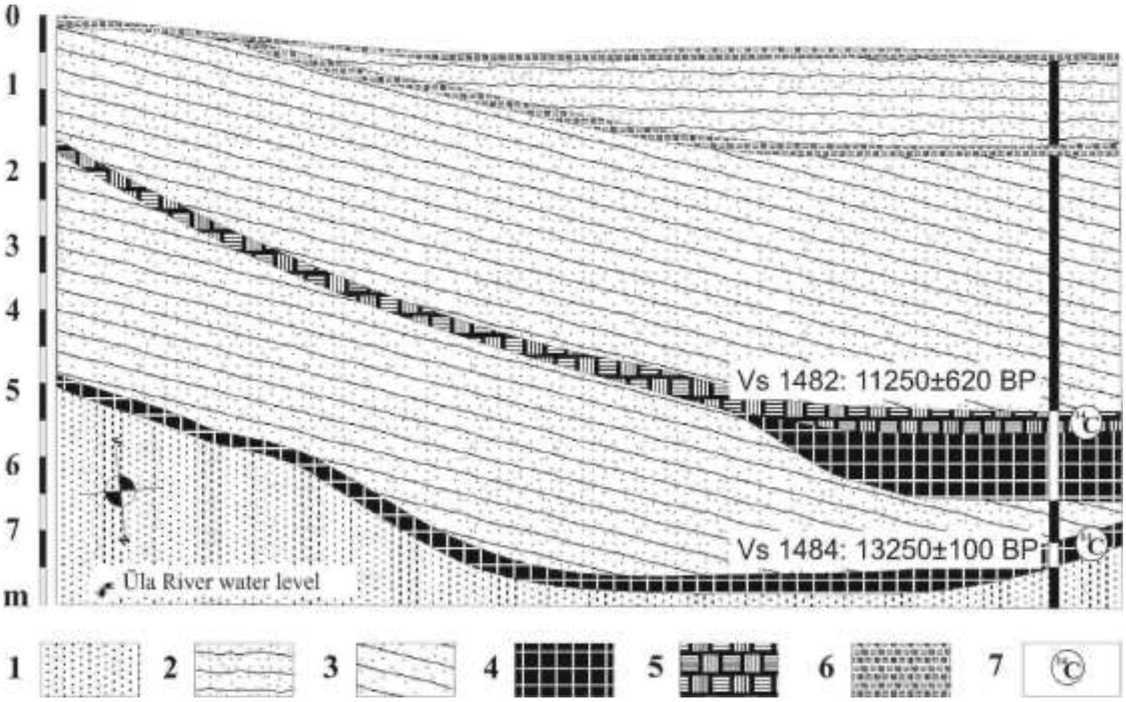

Fig. 1. Lithological sequence of Paūliai outcrop: 1 – massive sand, 2 – sand subhorizontally bedded, 3 – sand diagonally bedded, 4 – gyttja, 5 – lake marl, 6 – soil, 7 – radiocarbon dating (Barzdžiuvienė, V., Šinkūnas, P., Mažeika, J., 2004).

In the Ūla River Valley, there are several outcrops with the sandy deposit sequences which include peat, gyttja and calcareous sediments interbedded in between the sand layers **(Fig. 1)**. A quite long history of sediment stratigraphical interpretation exists, but the question of sediment origin is also interesting, especially if to relate it with the interpretation of the palaeogeographical history of the region.

Results of a sedimentological and palaeobotanical study of the sediment beds, which are well visible in the ground-penetrating radar profiles **(Fig. 2)**, suggest that deposition of organic and calcareous sediments took place mainly during Alerod interstadial - warmer and wetter Late-glacial time into some water basins, the origin of which can be interpreted as glaciokarst or paraglacial river erosion. The infill of sand is interpreted to be related to colder and dryer Younger Dryas time due to the intensification of slope erosion and aeolian processes which probably continued during the Holocene as well. The climatic changes had caused the change in the sedimentation pattern, however, the sedimentation of individual sequences rises many questions the answer of which can serve the key to regional palaeogeographical interpretations.

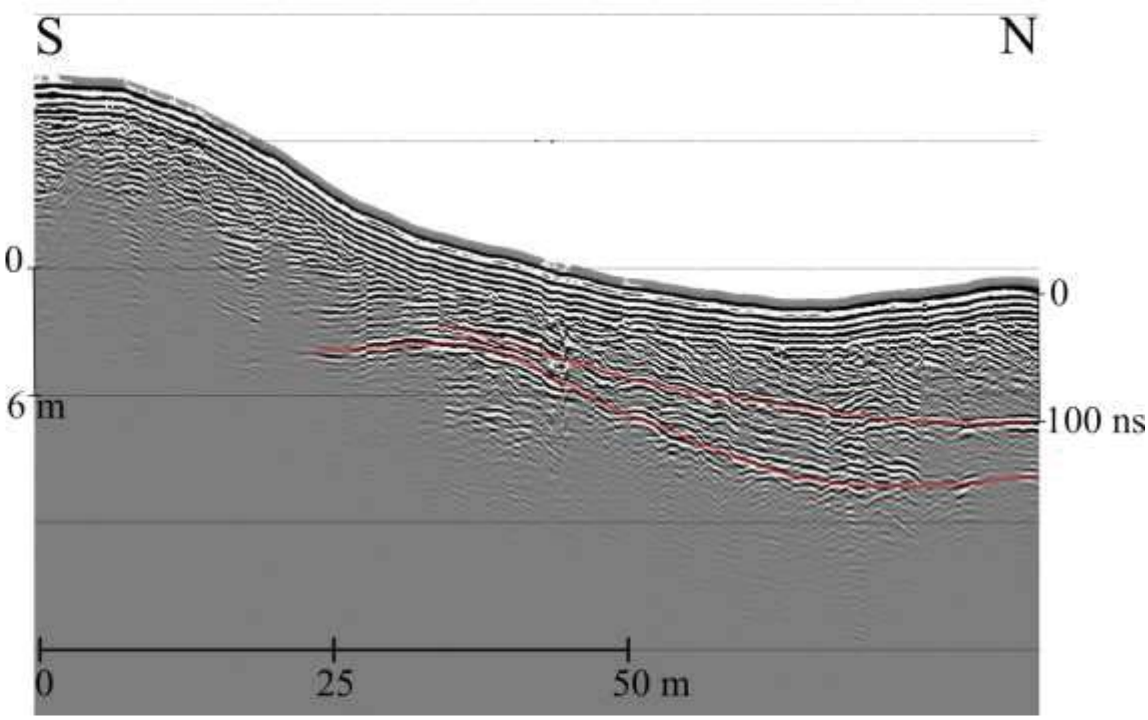

Fig. 2. Ground-penetrating radar profile close to the railway bridge near Zervynos village.

Acknowledgements

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TERRAIN RUGGEDNESS INDEX (TRI) AND SLOPE ANGLES (SA) OF LANDFORMS OF INSULAR AND MARGINAL MORAINIC HIGHLANDS (BASED ON THE LIDAR DATA) OF THE LAST AND PRE-LAST GLACIATIONS, CASE OF LITHUANIA

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LIDAR based digital elevation models of the representative patterns of morainic highlands of the Last (Weichselian) and pre-Last (Saalian) glaciations in Lithuania were constructed and Terrain Ruggedness Index (TRI) and slope angles (SA) were calculated.

The SA and TRI were calculated for the pattern areas which size were 16X16 km and their central smaler parts (size 5x5 km). Slope angles and TRI in each pattern area were calculated from DEM using QGIS software (www.qgis.org) and the maps of distribution of these parameters were compiled.

The terrain ruggedness index (TRI) was developed by Riley et al. (1999) to express the amount of elevation difference between adjacent cells of a DEM. It calculates the difference in elevation values from a center cell and the eight cells immediately surrounding it. Then it squares each of the eight elevation difference values to make them all positive and averages the squares. The terrain ruggedness index (TRI) is then derived by taking the square root of this average. This parameter is calculated using formula: $TRI = Y\left[\sum\left(x_{ij} - x_{00}\right)^2\right]^{1/2}$, where x_{ij} – elevation of each neighbour cell to cell (0,0).

The steepest slopes and highest TRI was determined for the marginal morainic highlands of the Last (Late Weichselian) glaciation.

The TRI and SA parameters display the highest maturity of the relief (Jacobsen and Platen-Hallermund 2013) and this property was determined for the southern slope of the Žemaitija insular highland and the Medininkai highland of the Saalian age. This indicates the similar age of both highlands.

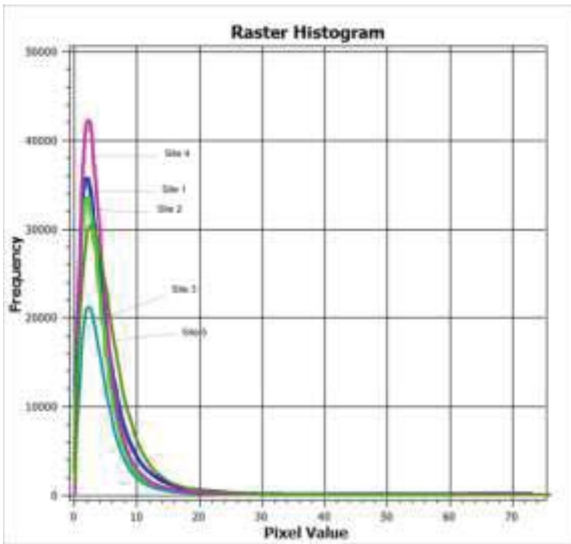

Fig. 1. Raster histograms of the slope angle values of the pattern areas 1 to 5.

Table 1. Statistical values of slope angles (degrees) in the pattern areas.

Area	Minimal	Maximal	Mean	Standard deviation
1 Plateliai	0	73,18797	4,628472	4,116221
2 Varniai	0	84,3384	4,002275	3,334261
3 Vištytis	0	81,67053	4,406875	3,703286
4 Medininkai	0	80,58797	4,061586	3,234437
5 Tauragnai	0	81,8672	5,352742	4,278851

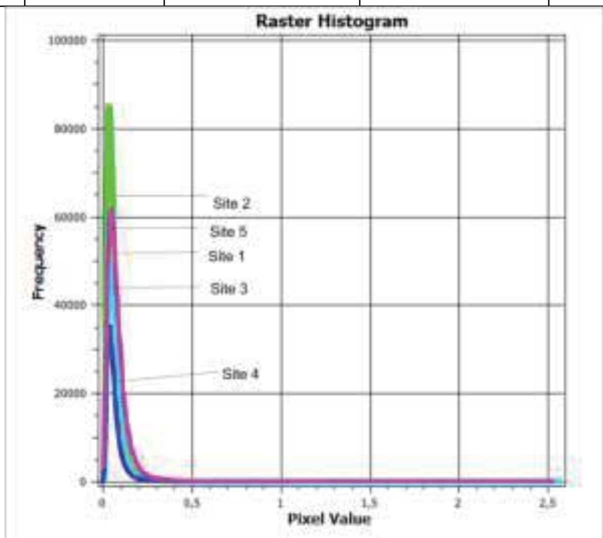

Fig. 2. Raster histograms of the TRI values of the pattern areas 1 to 5.

Table 2. Statistical values of TRI in the pattern areas.

Area	Minimal	Maximal	Mean	Standard deviation
1 Plateliai	0,000101	2,073198318	0,070947342	0,058347278
2 Varniai	0	2,569648743	0,061103541	0,047057817
3 Vištytis	0	2,568226814	0,068531411	0,052687617
4 Medininkai	0	1,053409576	0,063147387	0,044667232
5 Tauragnai	0	2,530132294	0,079818553	0,059252521

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CALCITE CEMENTATION IN THE GLACIOFLUVIAL DEPOSITS AS A RESULT OF SUBGLACIAL PROCESSES (KOCZERY SITE, E POLAND)

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Low-temperature water shows a great ability to dissolve carbon dioxide and enrich solutions with dissolved calcium carbonate. During the freezing of water molecules, the concentration of dissolved compounds in the remaining part of the solution increases until it becomes saturated, and crystallization occurs (Drozdowski, 1991). Even a relatively small increase in their concentration is sufficient to induce the precipitation process (Sharp et al., 1990). Carbonates are therefore easily dissolved under subglacial conditions and may recrystallize under favourable conditions.

The calcium-carbonate cement was found in the uppermost part of glaciotectonically-deformed coarse-grained glaciofluvial sediments of the Saalian age (MIS 6), at the Koczery study site, eastern Poland. Deposition of these sediments was controlled by the occurrence of permafrost (Mleczak et al., 2021). It is concluded that the enrichment of solutions with carbonates and their reprecipitation occurred under subglacial conditions. The mechanisms responsible for the latter were the horizontal and vertical pressure caused by ice sheet, the differences in pressure of the solution circulating beneath the ice sheet and the freezing of water (both water film beneath ice sheet and water present in the subglacial active layer of permafrost). Precipitation of calcite cements within the studied glaciofluvial sediments occur only in forelimb of folds evolved during glaciotectonic processes. The higher the inter-limb angle of folds, the thicker the cement.

The thickness of calcite-cemented zone varies from 2-5 cm (**Fig. 1A**) to even 70 cm, and can be divided into two parts: (1) bottom, thicker part, where grains of different lithology (approx. 70-75%) are cemented by micritic, isopachous and equant sparitic cements; equant spar predominates and the growth of its crystals proceeding from the surface of grains towards the centre of pores can be observed (Fig. 1B), and (2) upper, thinner part, with micritic cement (approx. 90%; **Fig. 1C**). Contact between these two parts of cement is undulating and grains of the framework present at this border are partially surrounded by both types of cement. In places the boundary is marked by secondary precipitated manganese oxides (**Fig. 1A**). The morphology of the cements exhibit that calcite precipitated in phreatic conditions. This process occurred in the zone limited by the freezing front from the top and the frozen ground from below. Differences in pressure induced upward movement of water towards the freezing front. This is evidenced by vertical arrangement of micritic cement surrounding the grains (**Fig. 1D**) which resembles a series of streaks or fringes. Their shapes refer to the vertical interaction of the forces responsible for cryosuction (cf. Vogt & Corte, 1996).

Moreover, the oxygen and carbon stable isotope composition of calcite-cement was analyzed. The calcite is characterized by $\delta^{18}O$ values changing in a narrow range from -6.9 to -6.2‰ (V-PDB), and the $\delta^{13}C$ values varying from -9.0 to -5.5‰ (V-PDB). No significant differences in the isotope notation between micrite and sparite were observed, which suggests similar host water parameters.

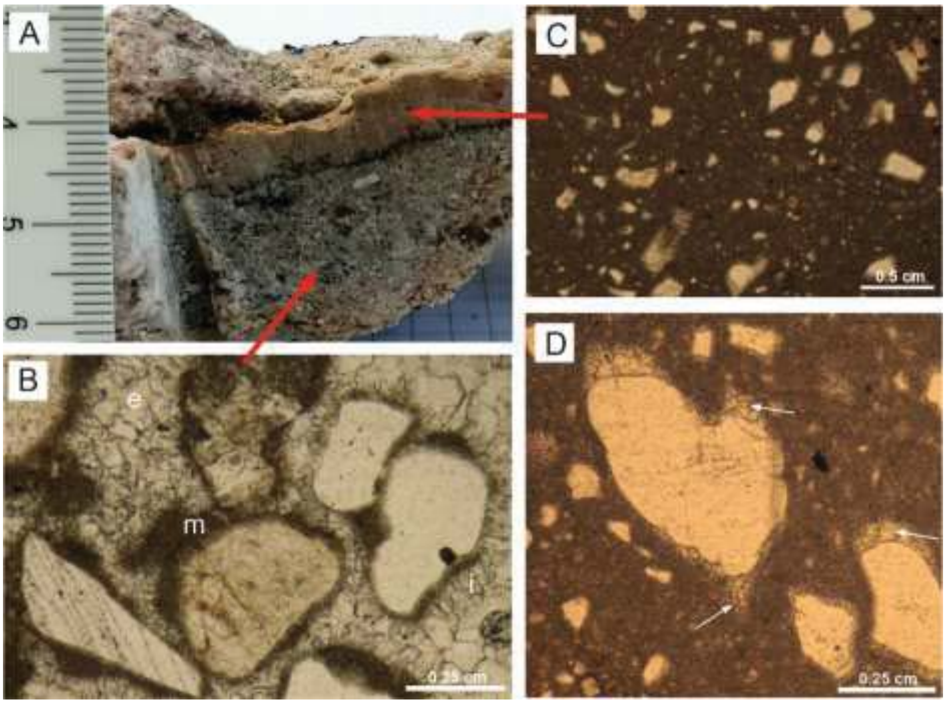

Fig. 1. Characteristics of studied carbonate cements. A – Fragment of conglomerate with calcium-carbonate cements. Two layers of cementation zone can be observed. B – Cements within bottom part: m – micritic, i – isopachous, e – equant. C, D – Micritic cements within upper part with **s**treaks of microsparite cement surrounding the grains (white arrow).

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CORRELATION OF EROSION-DEPOSITION CYCLES OF EXTRAGLACIAL RIVERS DURING THE VISTULIAN ON THE EXAMPLE OF THE MIDDLE VISTULA AND PROSNA RIVERS

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The evolution of fluvial systems is mainly controlled by three factors: bedrock tectonics, changes in the level of the erosion base and climate change. The area of the extraglacial part of the Polish Lowlands and the Southern Poland Uplands belt was characterised in the Vistulian by relative tectonic stability, in contrast to mountainous areas or the range zone of the last glaciation. Also, changes in the position of the erosional base had little effect on fluvial processes, mainly due to the distant location of the estuarine zones and the practical isolation from the aggradation/erosion impulses resulting from these changes. This means that the main factor controlling fluvial processes in the extraglacial zone was climate change.

Studies of fluvial systems operating during the Pleistocene in Europe indicate that adaptation of fluvial systems to ongoing environmental change only occurs after certain threshold values are exceeded (Vandenberghe, 2002). The degree of vulnerability of rivers to change is also determined by their size (Starkel et al., 2015). Hence, sedimentation style and the chronology of change are key elements conditioning the correct reconstruction of palaeoenvironmental and palaeogeographic changes in fluvial environments.

In order to test how extraglacial rivers of different sizes reacted to climatic changes during the last glaciation, the valley of the Prosna River in its lower reaches and the middle section of the Vistula River above the mouth of the Wieprz River were selected. The studies included sedimentological studies (lithofacies analysis, textural features of sediments, palaeocurrent measurements), analysis of periglacial structures, and age dating of sediments based on luminescence and radiocarbon methods. Surveys were carried out at 7 key sites. Two main aggradation cycles of trough sediments were found in the Vistula River valley and 3 cycles in the Prosna River valley. The sediments of all aggradation cycles were deposited in the sand-bed environment of the rift river. The results of the dating of these sediments indicate that they formed in different periods of the Vistulian. This allows us to assume that the size of the fluvial systems played a decisive role in their response to climate change. The fluvial system of the Vistula was characterised by greater inertia. Climatic cycles, which did not exceed several thousand years, did not affect changes in the proportion between erosion and aggradation and sedimentation style. In contrast, the Prosna fluvial system was characterised by greater susceptibility to millennial climate change.

Acknowledgements
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THE PALAEOENVIRONMENTAL STUDY OF THE SOUTHWESTERN PART OF THE CURONIAN LAGOON INFERRED FROM DIATOM DATA

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Based on new palaeogeographic data, we consider the development of the coastal zone in the southwestern part of the Curonian Spit, Kaliningrad Region, Russia. The data are appropriate to contribute to the general concept of the Curonian Spit development and shed light on the question of ecosystem formation in the coastal zone of the Curonian Lagoon.

During the study, a 0,9 m core of bottom deposits was collected in the Russian sector of the Curonian Lagoon (N 54°57'55,6", E 20°32'50,00"). The diatom analysis was performed for 31 samples according to the accepted methodology (Battarbee, 1986). The species composition was determined using the taxonomic identification keys (Krammer, Lange-Bertalot, 1988, 1991 a,b; 1997). Based on AMS radiocarbon dating for 4 samples, the absolute age of the studied deposits and sedimentation rates were calculated. The dates were calibrated by means of the IntCal2020 calibration curve (Reimer et al. 2020).

Considering the boundaries of the Holocene period (Walker et al., 2018), the formation of bottom sediments took place in the Middle and Late Holocene (6900-460 cal yr BP). Since the period after 7500 cal yr BP, the inflow of sea waters did not occur in the studied lagoon area (Damušytė, 2015), meanwhile, there was an accumulation of peat-gyttja material during the period of 6900-6000 cal yr BP. The rate of biogenic accumulation was not high (0.43 mm\yr).

As we could derive from the species composition, the diatom complex developed in a shallow coastal zone of a freshwater basin that underwent periodic water-level fluctuations. Most of the diatom taxa belong to the oligohalobous-indifferent group, indicating the low salinity of the lagoon waters. At the same time, the pH of the basin was high (> 7), which is confirmed by a large number of the epiphytic diatom species from the *Fragilariaceae* family that prefer alkaline conditions.

At the next phase of the lagoon development (6000-460 cal yr BP), the sedimentation conditions changed as could be seen by the deposition of gyttia. The accumulation rate decreased more than 40 times up to 0.02 mm\yr. The hydrological conditions were unstable at the beginning of this stage as it may have been inferred from such facts as a large number of fragmented diatom valves, a decrease in the concentration of epiphytic species, and the sporadic presence of sponge spicules. Hereafter, from 5500 cal yr BP, the general concentration of diatoms started to decline. This abrupt decline in amount of the periphytic *Staurosira inflata et var*. is most likely to be associated with the high water turbidity. The described changes may have been evidence of increased hydrodynamic activity. This period coincided with rising water levels and flooding of the coastal area.

During this phase of the Late Holocene, there is an increase in the total number of diatom valves that matches the period of 2800-680 cal yr BP. We associate this with the gradual increase in biomass accumulation and productivity in the study basin. The sedimentation rate was 0.05 mm/yr during this stage. The percentage of the planktonic diatoms (*Aulacoseira spp*., *Stephanodiscus spp.*) rose. We also record mesohalobic species *Actinocyclus normanii* that appears in the sediments since this period and might mark the changes in the trophic environments of the basin. Most likely, the studied area was influenced by the river runoff drained into the Curonian Lagoon.

According to previously published literature (Damušytė, 2015; Kaminskas et al., 2019), no seawater inflow entered the lagoon's southern part during the Middle and Late Holocene. This fact is confirmed by the homogenous composition of the diatom complex with slight fluctuations in its percentage. In this case, the Curonian Spit most likely developed as an aeolian body during this stage, separating the southern lagoon part from the Baltic Sea. Based on this statement, we can infer that the rise in the water level in the lagoon was not caused by the transgression of the post-Litorina Sea during this period. The most probable reason is, presumably, the increase of the river runoff of pra-Neman and other smaller rivers drained into the lagoon.

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PHYSICAL PROPERTIES OF AMBER AND OTHER FOSSIL RESINS AS AN INDICATOR OF THEIR ORIGIN AND BURIAL CONDITIONS

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Fossil resins are a polymeric material of natural origin with unique biological, physical and chemical properties. The geological history of natural resins is reflected in their physical and chemical properties. Heat, pressure, oxygen, microorganisms, water, sedimentation, and diagenesis are processes that have chemically altered resin exudates over the years. What we know today is that fossil resins arose because the organic functional groups in the terpenes of the resins were affected by these substances.

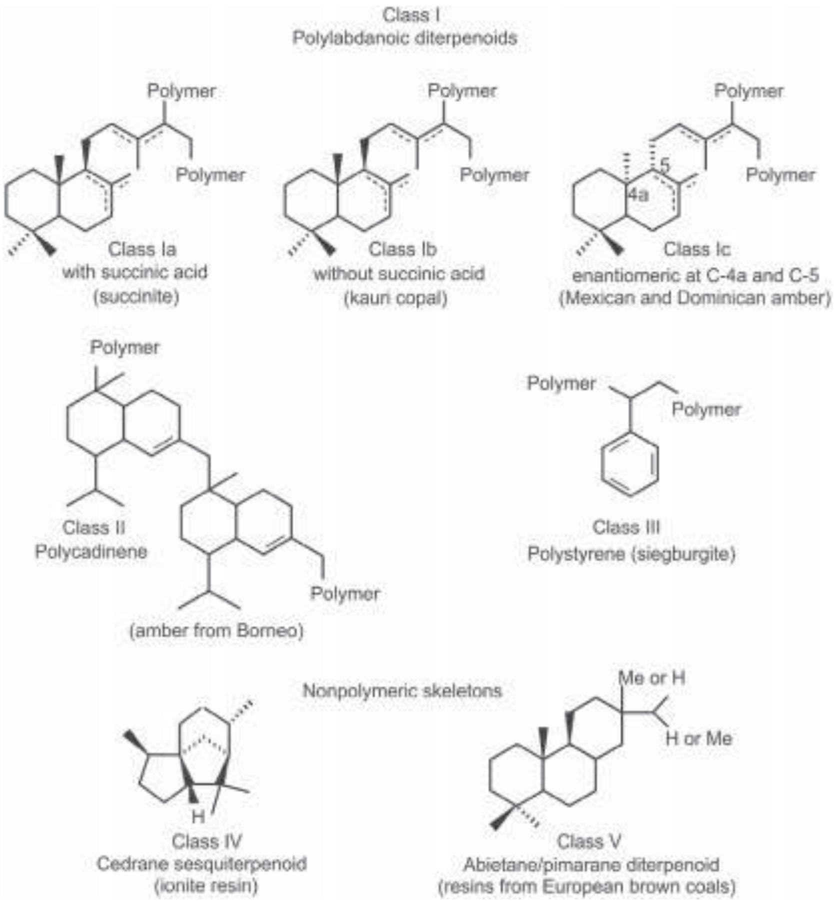

Fig. 1. The classification of the resins are proposed on the basis of their main chemical components (Drzewicz et. al., 2016).

Amber and other fossil resins are brought from older sediments during the Quaternary, so the aim of the study was to determine how their physical properties, such as microhardness, density, and degree of ultraviolet-induced fluorescence emission, depend on their age and geological burial and deposition conditions.

Microhardness, appearance, and fluorescence properties have been found to be consistent with past geological and paleoenvironmental conditions. Microhardness is closely related to the chemical structure of fossil resins, which depends on the botanical source **(Fig. 1)**. Changes in physical parameters are also influenced by the geographical location, the environment and the burial and geological conditions in the reservoir.

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ALTERATION OF SEDIMENTATION CONDITIONS IN THE SE BALTIC SEA DURING THE HOLOCENE

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Sandy sediments of the Late Glacial and Holocene prevail in the Lithuanian coastal zone of the Baltic Sea, including the underwater area. Various grain sized sandy sediment layers varies from a few decimetres to a few ten meters and in some places contain interlayers of organic sediments. This sediment thickness was formed during different stages of the Baltic Sea development and are important objects for palaeobotanic and geochronological investigations intended to reconstruct geological evolution of the SE Baltic.

The sediment core 66376 ($20^0$51.028’ E; $55^0$22.277’ N) was analyzed in detail with the aim to describe environmental changes in the shallow offshore area after the Weichselian Glaciation. The core length is 5 m and it is drilled at the 29.6 m b.s.l. in the Lithuanian marine water area during the geological mapping (scale 1:50 000) in 2017 (leading institution is Lithuanian Geological Survey). The radiocarbon dating, pollen and diatom analysis was applied for the interval 1.9 – 5.0 m because at that depth sandy sediments contain interlayers of organic sediments (peat and gyttja). The upper part (1.9 m) of the core consists of various grained sand. Measurements of magnetic susceptibility (MS) and loss of ignition (LOI) were made entire the sediment core.

According to diatoms the interval 1.9 – 4.9 m can be subdivided into four diatom zones (DZ). The bottom sediments (DZ1, 4.0 – 4.9 m) consist of sand with peat remnants and gyttja interlayers. Relative abundant of diatoms and number of species is small, benthic diatoms predominate up to 95% in sediments. Freshwater – brackish diatoms *Epithemia adnata*, *E. gibba*, *E. sorex*, *E. turgida*, *Amphora ovalis*, *Gyrosigma attenuatum*, *Staurosirella martyi* and freshwater *Ellerbeckia arenaria* are the most abundant. Single benthic brackish – fresh diatoms were detected also.

Upwards, the core (1.9 – 4.0 m) is composed of the layering of fine−grained sand and organic sediments and fine sand enriched in organic matter. According to diatom cluster analysis it is distinguished three diatom zones (DZ2 – DZ4) in the mentioned interval but composition of diatoms is similar and characterized by: 1) very small amount (2 – 10%) of brackish and brackish – fresh diatoms; 2) varying in a great range of fresh – brackish and freshwater diatoms; 3) highly variable content of benthic and planktonic diatoms. The most abundant benthic fresh – brackish species are *Epithemia adnata*, *E. turgida*, *E. sorex*, *E. gibba*, *Staurosirella martyi* and its content decreases upwards. Amount of species from the same group *Amphora ovalis*, *A. copulata*, *A. pediculus* is less and remain almost similar in zones DZ 2 – DZ 4. Percentages of the benthic fresh – brackish diatoms *Fragilaria heidnii* var. *istvanfyi*, *Pseudostaurosira brevistriata*, *P. brevistriata* var. *inflata*, *Planotridium lanceolatum* have increasing tendency upwards the core. Planktonic fresh – brackish diatoms are represented mostly by *Stephanodiscus rotula*, *Aulacoseira ambigua* and the most abundant freshwater is *Aulacoseira islandica* (up to 68%). Brackish benthic species *Fallacia forcipata* and brackish – fresh *Cocconeis scutellum*, *Cocconeis pediculus*, *Cymatopleura elliptica* makes up only a few percent. Diatom composition in the zones DZ 2 – DZ 4 indicates freshwater – brackish shallow environment. Very low content of benthic brackish diatoms probably shows littoral zone of the sea.

Pollen composition is not very changeable throughout the investigated sediment interval (1.9 – 5.0 cm). AP constitutes 75-90% of the pollen sum. *Pinus* (up to 80%) and *Betula* (up to 50%) predominate. *Corylus* pollen increases up to 5% in the upper part of the section. Pollen of Cyperaceae and Poaceae represent herbs. Pollen analysis of the investigated sediments indicates growth of mixed birch-pine forest, which was replaced later by mixed pine-birch forest. The identified vegetation cover is similar to the Early Holocene, i.e. Preboreal (I LPAZ) and Boreal (II and III LPAZ).

Radiocarbone (^{14}C) analysis of organic sediments were done at the depth of 2.3–2.35 (peat), 2.8–2.92 (peat) and 3.7–3.8 (gyttja) meters; the determined age is 11510–11260, 11350–11180, and 12240–11600 cal years BP respectively.

Results received on the basis of complex investigations are controversial: palynological and geochronological data maintain assumption that sedimentation took place during the Younger Dryas – Boreal, whereas diatom analysis indicate possible sedimentation in brackish environment. Moreover, in the uppermost part of section, until the depth 1.9 m, the shells of marine molluscs Macoma and Ceratoderma have been identified during the visual description of core. Very frequent alteration of peat, gyttja and sand interlayers at the depth of 1.9 – 5.0 m is indicating that peat and gyttja, what have been formed in peatbogs and, possibly, in small lakes, later were re-deposited in the littoral zone of the sea and it happened during the Litorina Sea transgression. Very variable amounts of fresh – brackish and freshwater diatoms, as well as benthic and planktonic possibly indicate gradual transgression of the Litorina Sea. Brackish species *Fallacia forcipata* and *Cocconeis scutellum* indicate the brackish Litorina Sea environment, as they are common for this stage in the SE Baltic Sea (Kabailienė, 1999). Therefore, brackish diatoms are found in organic sediments, which usually forms in freshwater basin. Baltic basins level at the very end of Late Glacial (Younger Dryas), i.e. since the Baltic Ice Lake drainage about 11.7 ka BP, was significantly lower than altitude of the core 66376 (29.6 m below the current sea level) (Bitinas et al., 2003; Žulkus et al., 2015). Thus, the continental conditions with lakes and peatbogs prevailed in the surroundings of investigated core at that time. The similar situation was during the Yoldia Sea and Ancylus Lake stages (Žulkus, Girininkas, 2020), until the beginning of Littorina Sea transgression that manifested about 8.5 ka BP (Andren, 2011).

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Excursion guide

Stop 1. SLĪTERE LIGHTHOUSE: PANORAMA OF THE SLĪTERE NATIONAL PARK

The lighthouse was built between 1849–1850; however the area historically, since the eleventh century, has been a site of plunderers who lit misleading signal-fires to confuse passing ships, causing them to run aground, once wrecked they would be raided of their cargo. The site of the lighthouse may have been an ancient holy place as old maps refer to the locality as Temple Mount (*Domkalns*), and Church Hill (*Baznīckalns*). Towards the end of the nineteenth century Baron Osten-Sacken cut-down a number of trees; making this a key-location spot for fishermen in the area; which is why the 24 metre stone lighthouse was built there between 1849–1850. The lighthouse is located in the Slītere National Park, which now maintains the lighthouse and its surroundings. The light has a focal height of 82 metres above sea level, making it the highest light in Latvia until it was deactivated in 1999. The lighthouse is the second oldest in Latvia, the oldest being that of Ovisi which first entered service in 1814.

The source of information and photo: Wikipedia.

Stop 2. SLITERE NATIONAL PARK AND PĒTEREZERS NATURE TRAIL

Slitere National Park is located in the Northern Kurzeme peninsula washed by the Baltic Sea. The park is known for its incredibly beautiful vista – courtesy of the sea, broadleaf forests, bogs, wetlands, boreal forests and swamps.

Pēterezers nature trail (3,4 km) starts as a forest path crossing the former narrow gauge railway or the so called Little-train track of North-Kurzeme which in the past connected Dundaga and coastal villages with Ventspils and Talsi and operated between 1916 and 1962. The route continues through a unique nature formation that does not exist anywhere else in the world – the system of dunes and lowlands (*kangari* and *vigas*), which were formed around 6000 years ago, when the Baltic Sea was emerging in the area. Here you shall face few steep ups and downs with long stages of staircases. When more than half of the route is behind, the trail finally comes to its most interesting and nicest point – a wooden boardwalk along the marshy *vigas* known as *Pīļu Dīķis* (the Ducks' pond) and *Pēterezers* (Peter's Lake), which is the home of rare plant and animal species. In the *viga* of Pēterezers 25 protected plant species can be found. The trail finishes with a well-trodden path through the pine forest.

The source of information and photos: Internet.

Some geological information about geological structure of this region, mostly about the ancient liner dunes, are available in a few publications.

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Stop 3. COASTAL PROCESSES AT THE CAPE KOLKA

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Cape Kolka is located at the top of the Kurzeme (Kurland) peninsula northern part. It separates the Baltic Sea (Irbe Strait) and Gulf of Riga. Cape Kolka as a major foreland represents partial barrier to longshore sediment drift (Eberhards, 2003). Coastal processes at Cape Kolka are not directly affected by any major hydrotechnical structures or other human activities except for inefficient small-scale coastal protection structure 200 m to the west from Cape.

Formation and geological history

Below the Quaternary near the Cape of Kolka there are the sedimentary rocks of the Middle Devonian – dolomite marls, clays, dolomites and gypsum. The surface of the eroded Devonian rocks, located at a depth of 59-63 m, is covered by the glacial deposits of the Upper Pleistocene (Ulsts, 1998). Above the thin layer of moraine, a layer of glaciolimnic clay has accumulated, reaching a considerable thickness (~ 20 m). The sediments of the Baltic Ice Lake were eroded away during Lake Ancylus or the Littorina Sea, when the area was exposed to waves and longshore currents as the water level of the basin fluctuated (Ulsts, 1998; Eberhards, 2003). The sediments formed during the Ancylus Lake consist of several meters of clay and silty clay.

Littorina sediments are 35-40 m thick and mark a period of very intense accumulation in the history of Kolka area and northern Kurzeme in general. Littorina Sea sediments can be divided into two layers – the deepest silty sand layer (now 41-20 m below sea level) has developed in underwater conditions. Above it, fine-grained and medium-grained sand with organic sediment inclusions has accumulated in the conditions of coastal zone.

In terms of total amount of accumulated sand during the Littorina stage, the north coast of Kurzeme peninsula is one of the largest in the southern and eastern Baltic Sea area (Ulsts, 1998) **(Fig. 1)**. The Littorina sands here form a 2 to 4 km wide accumulative terrace with several generations of dune ridges extending along the entire southern coast of the Irbe Strait, while the Cape of Kolka is located 10 km from the shoreline of the Baltic Ice Lake. Thanks to this, Irbe Strait coastal underwater slope has less gradient than elsewhere in the coast of Latvia.

Cape is formed on a Littorina Sea accretional landform – spit **(Fig. 2)**. Shape and location of the cape has been prone to changes during transgressions and regressions of Littorina Sea. During the last significant water level changing events approximately 2800 years ago, erosion and coastal retreat took place in cape area (Ulsts, 1998). After the stabilization of sea level in modern Baltic, intensity of coastal processes decreased remarkably over the all coastline of Latvia (Knaps, 1966). Consequently, the amount of sand reaching Kolka decreased as well. Thenceforth Cape Kolka is gradually changing its shape and position. It can be argued that nowadays and for the last few centuries, the Cape Kolka is dominated by coastline retreat, sometimes interrupted by brief and intense episodes of accumulation. From 1890 till 2005 coastline of the Irbe Strait close to the Cape has retreated for 120-160 meters, while coastline of the Gulf of Riga has retreated for more than 350 meters (Eberhards, 2003; Eberhards, Lapinskis, 2008).

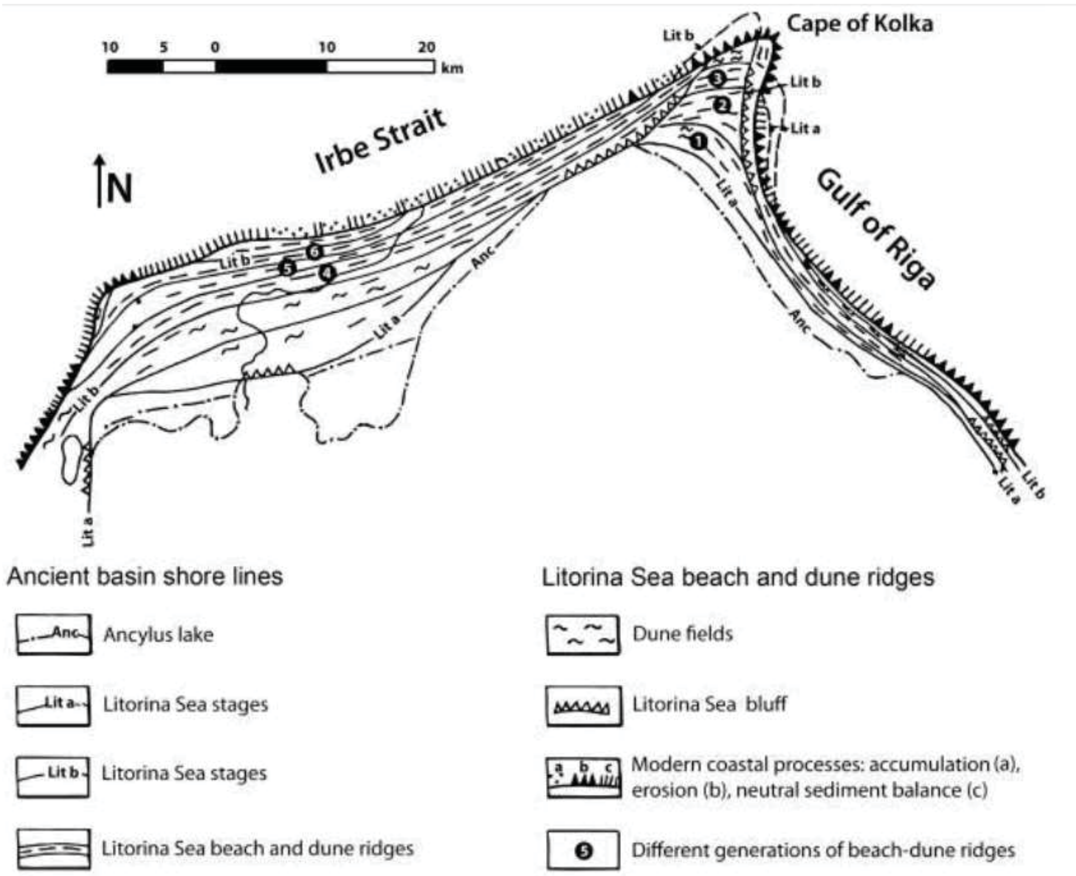

Fig. 1. Generalized palaeogeographical map of the Littorina Sea accumulation terraces and Cape Kolka (Ulsts, 1998).

The formation of the northern coast of Kurzeme peninsula and its farther point – the Cape Kolka, has been determined by the intense influx of fine-grained sediments supplied by longshore sediment drift. This regionally significant longshore sediment exchange system commonly is referred as the Eastern Baltic longshore sediment flow. Movement of sediments in this system is dominated by the northward component. It begins on the northern shore of Sambian Peninsula and ends at the Cape Kolka (Ulsts, 1998). According to the estimates of R. Knaps, the annual amount of sediment movement along most of Latvia and Lithuania exceeds $3x10^6$ m^3 per year, but on the coast near Ventspils even $10x10^6$ m^3. It was estimated that the Cape Kolka receives an average of $6x10^6 – 8x10^6$ m^3 of fine-grained sediment per year. Comparably, according to calculations made by T. Sommere (Sommere, Viška, 2014) the simulated intensity of bulk sediment transport on the western shoulder of Cape Kolka reaches up to 6×10^6 m^3/year.

Sandy material supplied by the sediment flow nowadays is deposited in large area of coastal underwater slope of western shoulder of the Cape. It is estimated that the accumulation intensity varies in a very wide range. In 1935 P. Revelis estimated that an area of a few square kilometers on average accumulates approximately $5x10^6$ m^3 of sand per year (Ulsts, 1998). Ulst's studies, on the other hand, have shown that sand is accumulated at depths of more than 10 m, but closer to coastline it is mostly erosion. A detailed study (Andersons, 2011) carried out in 2010 also showed that accumulation occurs only in a few areas and that the estimates of accumulation volume previously expressed are highly exaggerated.

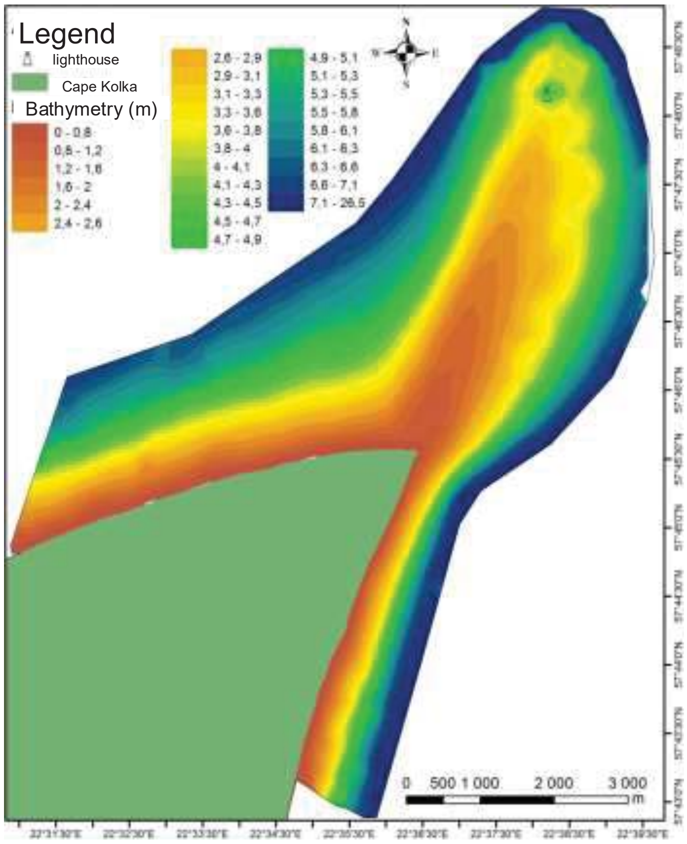

Fig. 2. Bathymetry of underwater part of Cape Kolka during the summer of 2010 (Andersons, 2011).

Recent changes in Cape Kolka coast (1992-2019)

During the severe storms of 1993, 1999, 2001 and 2005, Cape Kolka area was subjected to intense erosion due to particularly high surge level and high energy wave conditions. According to measurements, erosion rate reached its maximum in 200 m long coastal section directly to the south of Cape, where 10-30 m^3/m of fine grained sand was removed from beach and older forested dunes during each of the mentioned storm events **(Figs. 3, 4, 5)**. The biggest change in shoreline configuration and shore features elevation came from the storm of January 2005 **(Figs. 4, 5 top-left)**. In some short sections retreat of the sandy bluff face reached 30 m during this single event (Eberhards *et al.* 2006; Eberhards *et al.* 2009; Lapinskis 2010).

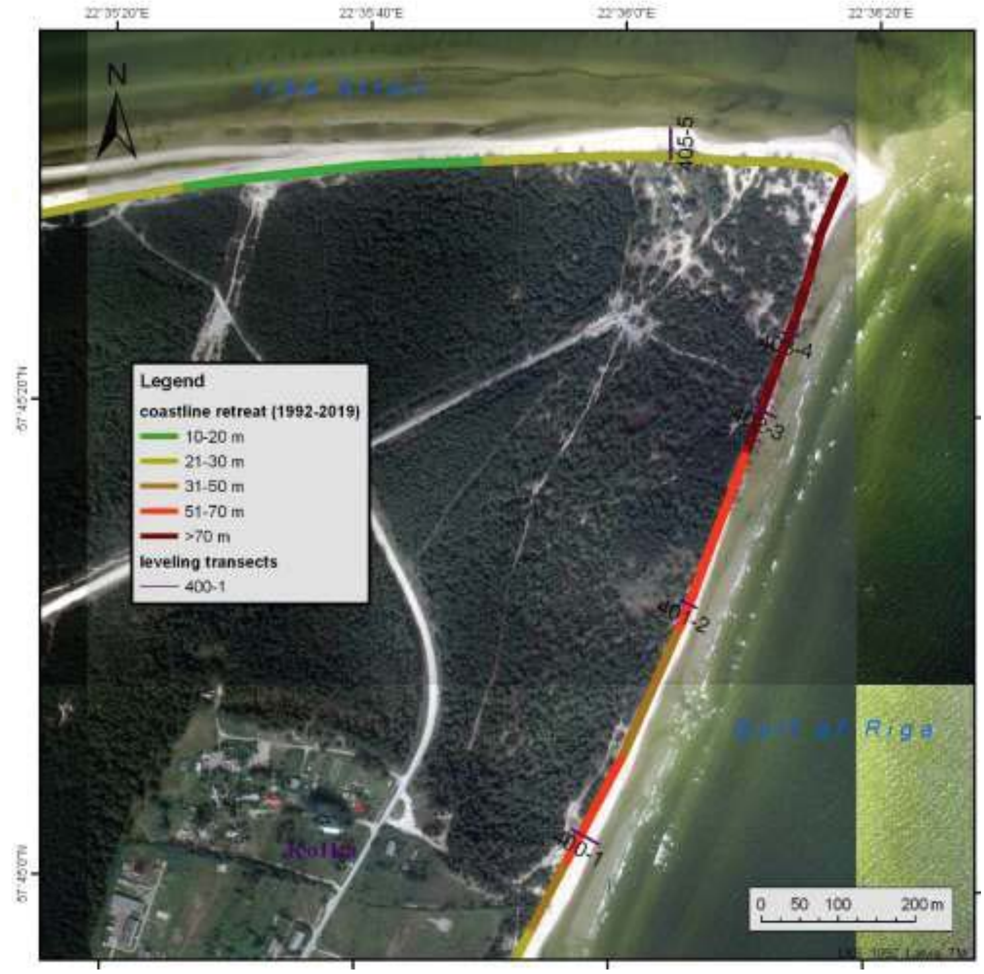

Fig. 3. Cape Kolka area, averaged coastal retreat since 1992 and location of stationary leveling transects.

According to stationary measurement data, coastline retreat and net loss of sediment from subaerial part of coastal slope is present in all Cape Kolka area. On the southern shoulder of the Cape, coastal retreat persists even during relatively "calm" weather, formation of primary dune does not take place at all, and volume of beach sediment remain very low (<5m^3/m) **(Fig. 4, 5)**. On the western shoulder of the Cape the so-called coastal post-storm recovery phenomena can be observed to some extent, but pre-1992 sediment volumes are never reached (Fig. 4). For the majority of Cape area, during the years without severe storm events (2008-2019), the volume of beach and primary dune sediments has fluctuated from year to year by less than 2.0 m^3/m.

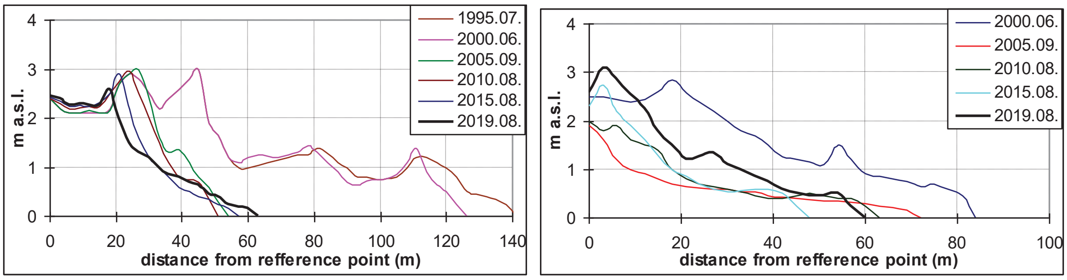

Fig. 4. *Left* – Coastal retreat and changes of coastal subaerial features as measured in stationary leveling transect Kolka 402-3; *Right* – stationary leveling transect Kolka 405-5.

Fig. 5. *Top-left* – Erosion of old forested dunes 800 m to the west from Cape Kolka during storm of January 2005; *Top-right* – Sandy beach and primary dune ridge at the stationary leveling transect Kolka 402-3 (300 m to the south from Cape Kolka) in 1999; *Low-left* – Erosion of the old forested dunes at the stationary leveling transect Kolka 402-3 in 2018; *Low-right* – Inefficient coastal protection attempt – 80 m long section of revetment installed in the1980s.

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Stop 4a. BALTĀ KĀPA SITE: ANCYLUS LAKE AND LITORINA SEA STAGES IN THE GULF OF RIGA, BALTIC SEA

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The Baltā Kāpa (Eng. the white dune) site situates ca 1 km inland from the recent western coast of the Gulf of Riga, eastern Baltic Sea, in a straight distance of 100 km NE of Riga, the capital city of Latvia, and only 20 km south of the Kolka Cape. This part of coast is NW-SE stretched and largely hidden from the Baltic proper born western winds, because of the shadowing effect of the Northern Kursa Upland. This is also why this part of the coast remains more-or-less stable and not entirely exposed to the coastal erosion and retreat even during extreme events (Eberhards *et al*., 2006).

The Baltā Kāpa site is one that reveals a coastal geological situation of western part of the Gulf of Riga and belongs to so called – the coastal plains – that fringe along the Latvian coast and reach as far up as few km inland. However, at the surroundings of the Baltā Kāpa these plains are rather reduced and not as wide as elsewhere, and thus border directly with the Northern Kursa Upland from SW. Plains consist of three rather clear units. The Baltic Ice Lake plain is the highest among them and most sea-distant, and lies at an altitude from 10.4 m to 12.3 m. Distinct dune ridge (old beach bar) with a relative height up to ca. 16 m occurs atop of this plain along with few smaller and less expressed bars. Towards the sea, the Litorina Sea Lagoon plain occurs with elevations between 6.4 m and 9.4 m a.s.l. with its highest point of 9.7 m a.s.l. that marks the highest Litorina (Lit a) coastline. Finally, nearly a 1 km long barrier spit borders with the recent coastline and represents a ridge-swale complex. This pattern is occasionally disturbed by a number of elongated or parabolic dunes. The Baltā Kāpa sites represents this latter with a maximum altitude of 18.1 m a.s.l. and is cut through by the Pilsupīte River. Within the Litorina Sea Lagoon plain at a current isoline of ca. 7.5 m a.s.l., the second Litorina Sea coastline (Lit b) is considered (Eberhards, 2003; Kalniņa, Eberhards, 2006). No Ancylus-related surficial features have been reported from this area.

Organic sediment horizon with wood was found in the bottom part on the banks of the Pilsupīte River at the height of 2-4 m a.s.l. (Eberhards, 2000), and further dated back to between 8895±65 (Grīnbergs *et al*., 1975) and 7600±80 uncalibrated ^{14}C years (Loze, 1998), and was initially correlated with the Ancylus Lake stage (Eberhards, 2000). However, uncalibrated age results correspond to 9982±219 and 8383±177 ^{14}C calibrated years BP, respectively following the OxCal 4.3 (Ramsey 2017), and represent the low water level phase in Baltic Sea basin before the Litorina transgression. In neighbouring Ģipka site this low water level phase is reflected by peat accumulation at the height of 3.0-2.8 m a.s.l. dated in between 9.2 and 8.3 cal ka BP. In an adjacent Pärnu Bay the water-levels below to zero have also been recorded in between 9.8 and 8.5 cal ka BP (Nirgi *et al*., 2019).

Fig. 1. A: An arrow points to the shell-rich horizon at the Baltā Kāpa site (June 2017). B: marine mollusc shell as found in the organic-rich horizon (photo: E. Kalińska).

Few centimetre-thick mollusc shell-rich horizon exists at a height of ca. 4-5 m a.s.l. **(Fig. 1A)**, and its ^{14}C dating gave a result of 6200±80 uncalibrated years BP (Meirons *et al*., 1993; 7082±191 cal. year BP if following the OxCal 4.3). This somehow corresponds with the Litorina Sea transgression between 8.5 ka BP and 7.3 ka BP (Nirgi *et al*. 2019) and similarly with a neighbouring Ģipka site, where the interlayer with Litorina transgressional sand interlayer was accumulated at ca. 7.3 ka. Typical sea mollusc shells as *Cardiun edule, Macoma Baltica*, *Mytilus edulis*, *Peringia ulvae* and *Ecrobia ventrosa* were found in the shell-rich horizon (Meirons *et al*., 1993, also identified by Mudīte Rudzīte, **(Fig. 1B)**), thus supporting the marine conditions. Later at ca. 5–6 cal years BP, a shallow lagoon in this area served as a settling of the Neolithic community (Loze, 2005), also in the religious context (Loze, 2008).

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Stop 4b. HOLOCENE RELATIVE SHORE-LEVEL CHANGES IN THE GULF OF RIGA: ĢIPKA SITE IN NORTHWESTERN LATVIA

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Sediment succession in the Ģipka outcrop, NW Latvia **(Fig. 1)**, demonstrate an interplay between the Glacial Isostatic Adjustment (GIA) and water-level changes in the slowly uplifting (in present day 1.5 mm per year) coast of the Gulf of Riga **(Fig. 2B)**. From the bottom to the top this 6-m-thick succession consists of: upwards coarsening sand complex (unit G1), lower fen peat (unit G2), transgressive sands (unit G3), clay gyttja and gyttja beds (unit G4) covered by the upper fen peat (unit G5) and organic rich silty-sandy deposits (unit G6) **(Fig. 3)**.

Fig. 1. The Gipka outcrop in NW Latvia (57^0 34’ 36’’; 22^0 37’ 31’’; photo: A. Rosentau).

Results of the diatom analyses, scanning electron microscope (SEM) analysis of sand grains, and GIS-based landscape modelling together with seven AMS and three OSL dates were used to interpret this sedimentary record. The luminescence date from the uppermost part of the high energetic sand complex of the unit G1 suggest deposition at about 9.3 ka during the Early Litorina Sea stage while the deposition of the whole regressive complex occurs at the time when retreating shoreline of the Ancylus Lake/Early Litorina Sea passed the Ģipka area. Thick-bedded sand of multiple reversed grading layers, a medium-bedded sand of multiple normal grading layers and mud rip-up clasts in sand matrix have been described in this sand complex suggesting storm surge wash-overs. Lower fen peat accumulation (unit G2) on top of the coastal sands suggests low water level (below 3 m a.s.l.) of the Early Litorina Sea since 9.2 cal. ka BP. At about 8.3 cal. ka BP peat accumulation is replaced with deposition of transgressive sands with organic laminas (unit G3) suggesting that Litorina Sea flooded the area. These sands contain mixture of fresh and brackish water diatoms deposited probably in the river mouth during the transgression of the Litorina Sea. Transition from sand to gyttja clay (unit G4) deposition and changes in diatom composition around 7.8 cal. ka BP falls within the period of fast relative sea level (RSL) rise. This event was first described from the Blekinge coast, southern Sweden (Yu *et al*., 2007) and was later documented in the Kattegat (Sander *et al.,* 2015), Gulf of Finland (Rosentau et al., 2013) and Gulf of Riga areas (Nirgi *et al.,* 2019). During the short period around 7.8–7.6 cal. ka BP, the RSL rose more than 1 m per century, being faster than the concurrent eustatic sea level rise calculated from

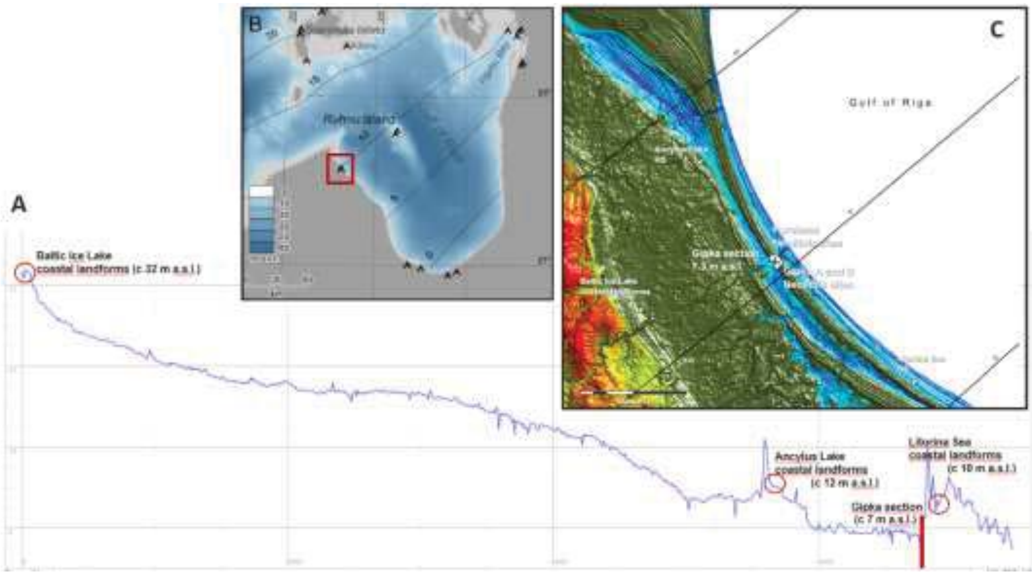

Fig. 2. A. SW-NE oriented airborne LiDAR-based geomorphologic profile from the central part of the study area (Fig. 1A) with indication of Baltic Ice Lake final shoreline, Ancylus Lake and Litorina Sea highest shorelines and their elevations. B. Palaeogeographic reconstruction of the Litorina Sea maximum in Gulf of Riga with RSL isobases at about 7.3 cal ka BP (after Muru *et al.*, 2017) C. Palaeogeographic reconstruction of the Vidales-Pūrciems lagoon at about 5.5 cal ka BP with indication of RSL isobases and Neolithic settlement sites.

the far-field sites. The calculated average RSL rise rate in Ģipka was around 0.6-0.7 m per century during the period from 8.3 to 7.3 cal. ka BP, thus somewhat less than the maximum values. However, as suggested from diatom data these rates may have been faster around 7.8-7.6 cal. ka BP. During the transgression a brackish water lagoon was developed and existed in the area for almost 3000 years. The highest salinity values were in between 7.2 and 5.7 cal. ka BP, thus somewhat later compared to the highest water-level in the lagoon. Changes in gyttja composition and disappearance of brackish water diatoms suggest that lagoon was isolated from the Gulf of Riga around 5.0-4.8 cal. ka BP. The lagoon was completely overgrown at about 4.8-4.6 cal. ka BP then upper fen peat (unit G5) started to accumulate in the area. Luminescence dating and SEM analyses of the overlying sand deposit (unit G6) show that since at about 4.0 ka the area of the former lagoon was affected by fluvial activity.

Palaeogeographic reconstruction **(Fig. 2C)** shows that an elongated shallow-water lagoon existed in the area and was used by Neolithic settlers in Pūrciems and Ģipka areas sometime in between 6 and 5 cal. ka BP (Loze, 2006). Reconstruction shows that some of the Neolithic settlements were located on the seaward side of the lagoon behind protective coastal landforms while some of the sites were placed along the dune belt. Salinity reconstructions show that during the occupation, the lagoon was a brackish water body with high productivity and calm waters and therefore probably well suitable for installation of (stationary) fishing constructions.

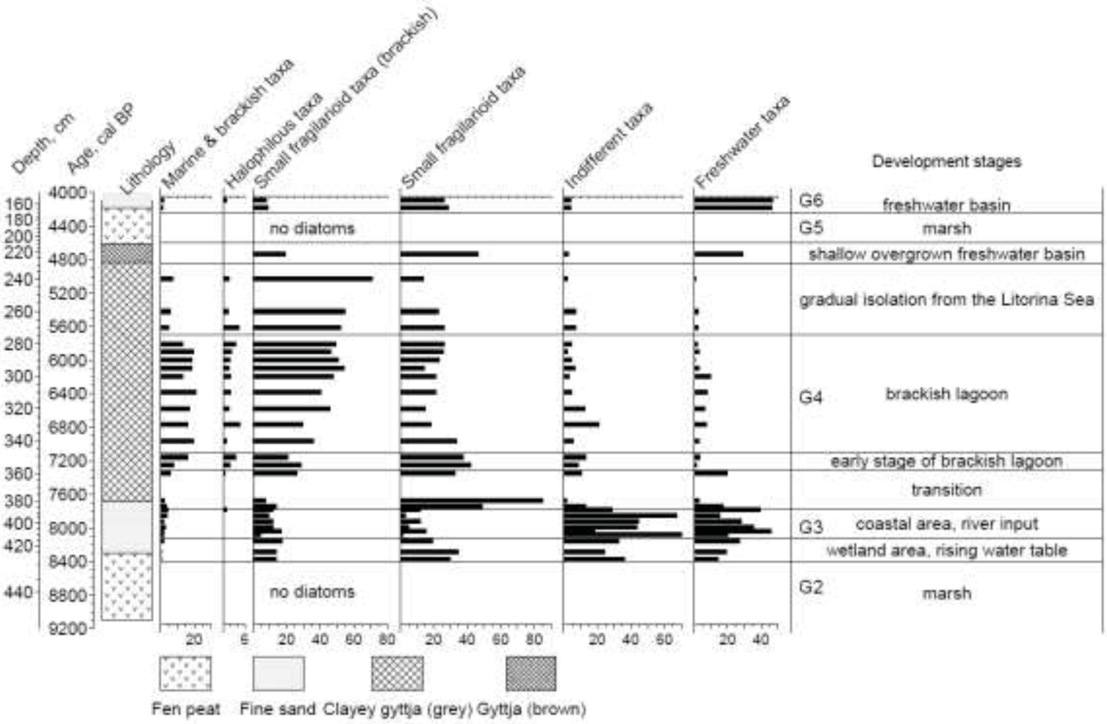

Fig. 3. Sediment stratigraphy, modelled chronology and summary diatom diagram of the Ģipka section (analysed by I. Grudzinska-Elsberga).

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Stop 5. LITORINA SEA AND ANCYLUS LAKE COASTLINES IN THE VICINITY OF VENTSPILS LAGOON

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The Late Glacial and post-glacial history of the Baltic Sea is mostly about several transgressive and regressive events that alternated during the last 16 ka (Andrén *et al.,* 2011; Björck, 1995), and further resulted in a number of landforms as ancient shorelines and lagoons. These landforms are traceable in the territory of Latvia, and an ancient lagoon in the area of the harbour Ventspils town, western Latvia is considered in this study **(Fig. 1)**.

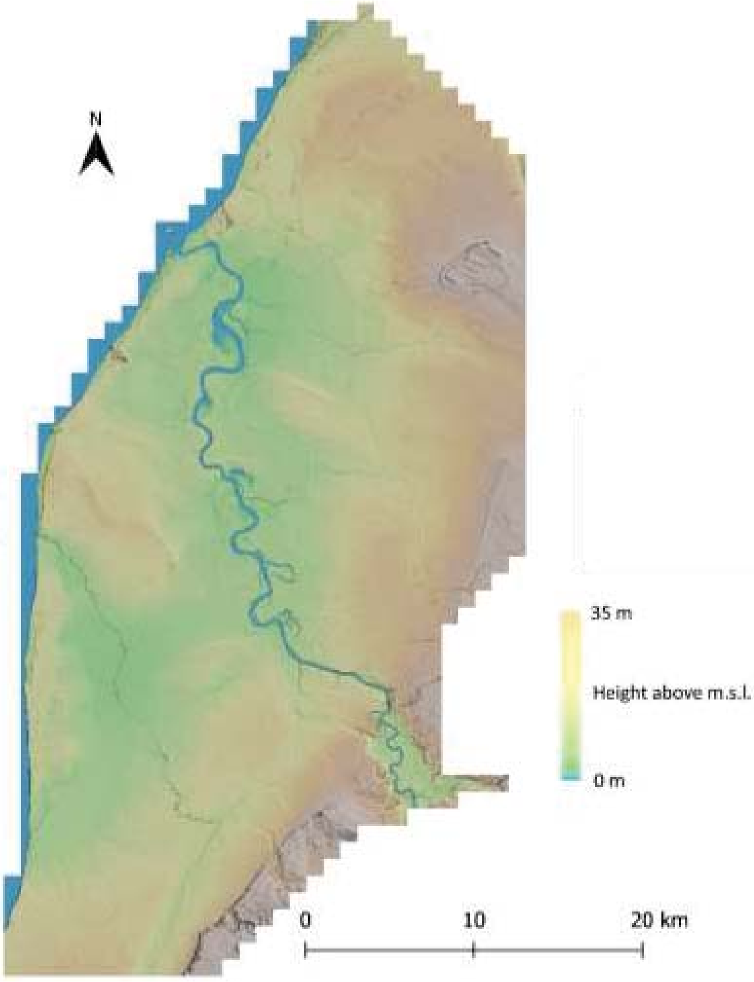

Fig. 1. Digital terrain model (DTM) of the location of the old Ventspils lagoon.

The lagoon itself had dimensions of ca. 40 km in length and ca. 15 km in width and served as a favourable setting for human settlements. That is why numerous Mesolithic-Neolithic evidences of human occupation have been found in this area (Bērziņš *et al.*, 2016). Here, periods with rising water level marked a lagoon development were followed by sea regression that left the lagoon deeper inland, and therefore, series of ancient shorelines are primary expected few kilometres inland south and east of Ventspils.

To trace these shorelines, an automated LiDAR data-processing method was implemented to build up a high-detail terrain model (Breijers, 2019), which served as the main data source for a statistical approach of decrypting the old shorelines. The statistical analysis of the terrain was carried out in three steps. Firstly, the most prominent edges, the ones that could potentially be parts of the old shorelines, were detected using a QGIS programme's *WhiteBoxTools 1.1.0* plugin's tool *DownslopeIndex* (*Vertical drop: 1.5*; *Output type: distance*), which outputs the distance from any given cell in order to achieve a relative drop of 1.5 meters. Secondly, elevation data from the DTM was assigned and normalised using SAGA GIS plugin's tool *Raster normalisation* for those raster cells with the *DownslopeIndex* distance below 300 meters. Finally, another raster map was created, which represented distance data along the glacioisostatic uplift axis (335°; Rečs, Krievāns, 2013) or the distance to a line (65°-245°) outside the study area thus allowing to add distance values (also normalised using the *Raster normalisation* tool) to the aforementioned raster cells. After multiplying the normalised height and distance rasters, *K-means clustering for grids* (SAGA GIS tool) was carried out to get 30 clusters in order to negate any noise values that might have affected further analysis. After manual verification, 9 out of 30 clusters were chosen for modelling the ancient water levels **(Fig. 2)**. The surface trend analysis of each given cluster was carried out twice using *WhiteBoxTools 1.1.0* plugin's tool *TrendSurface* (*Polynomial order: 2*): first, to detect any outlying raster cells (±0.4 m) and, second, to get the final trend surfaces, which were used to represent the ancient water levels and, subsequently, the ancient shorelines.

The ancient water levels were modelled in this study and their respective shoreline displacements show a weak compatibility with previous research in the region. For example, the highest theorized lagoonal Ancylus shoreline in the NNW part of the lagoon was set at about 15-17 m above the current sea level (Гринбергс, 1957; Veinbergs, 1996). The particularity of the modelled water level surfaces, shown in **Fig. 3**, stimulate a hypothesis, that several of the modelled surfaces might either belong to various beach forms of a single stable stage or the statistical method has picked up coastal landforms that have formed during severe storms.

Apart of LiDAR-wise methods, an optically stimulated luminescence (OSL) dating method was used to determine a depositional age of the sediments. To obtain this, 21 OSL samples were taken from 8 sites located along the ancient lagoonal shoreline during the summer fieldworks in 2019, and previous model-based methods helped in distinguishing the localities where the Ancylus and Litorina sediments correspond **(Fig. 4)**. Preliminary results as obtained from the Lund Luminescence Laboratory, Lund, Sweden clearly show that large part of samples reveals feldspar contamination as also apparent from previous studies in the region (i.e. Kalińska, 2019).

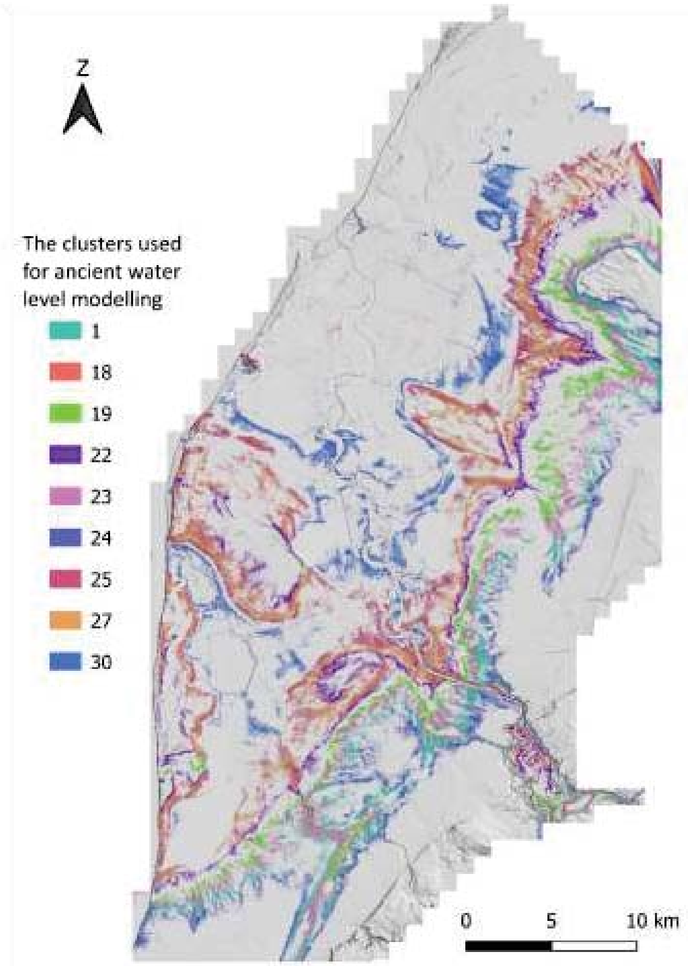

Fig. 2. The clusters used for ancient water level modelling.

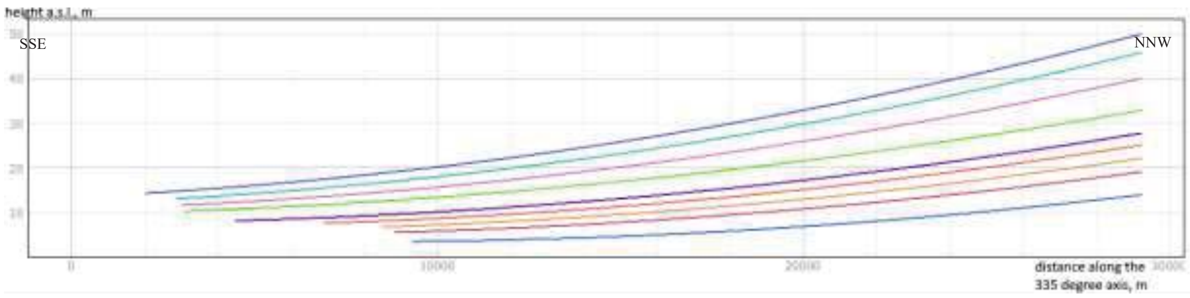

Fig. 3. Modelled ancient water level trend surface profile lines along the 335° axis.

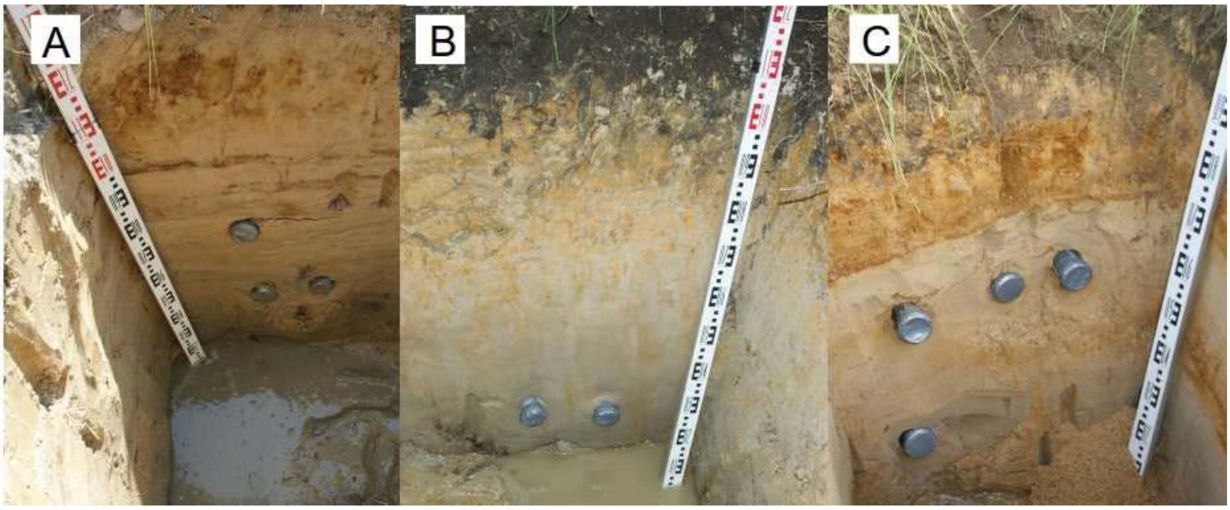

Fig. 4. Luminescence sampling strategy at selected sites as (A) Imantas 2, (B) Jaunpikas 2 and (3) Kanes.

Acknowledgments

This study is supported by the lzp-2018/1-0171 project "People in a dynamic landscape: tracing the biography of Latvia's sandy coastal belt".

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Stop 6a. WEICHSELIAN SOFT-SEDIMENT DEFORMATION STRUCTURES INDUCED BY UNEVEN LOADING AND GLACIGENIC EARTHQUAKES (BALTMUIŽA SITE, W LATVIA)

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The Baltmuiža site is located at the Baltic Sea bluff in the western Latvia **(Fig. 1A)**. The 70-metres thick Quaternary sediments lies directly on Devonian rocks (Kalniņa *et al*., 2000). In the lowermost part of Quaternary succession is a thin till layer, probably of Saalian (MIS 6) age (Saks *et al*., 2012a), while the remaining part of the succession contains sands, silty sands and silts of Jūrkalne 1, Jūrkalne 2 and Jūrkalne 3 Members **(Fig. 1B)**. Moreover, a residuum of the MIS 4 till (i.e. pebbles, cobbles and boulders), between Jūrkalne 2 and Jūrkalne 3, is distinguished (Juškevics *et al*., 1998; Kalniņa *et al*., 2000; Saks *et al*., 2012a). The top part of the sedimentary succession consists of Late Weichselian till and Baltic Ice Lake sediments above. The study sediments of Jūrkalne 3, up to 40 m thick (Kalniņa *et al*., 2000), are composed mainly of fine- to medium-grained sandy layers interbedded by silts. Ripple cross-lamination, horizontal lamination and through cross-stratification in Jūrkalne 3 (Kalniņa *et al*., 2000; Saks *et al*., 2012a) were deposited by low-energy currents, interrupted by the higher energy dune sedimentation attributed to wave processes in a shallow basin (Kalniņa *et al.*, 2000; Saks *et al*., 2012a). According to the results of OSL dating (Saks *et al*., 2012a, Woźniak *et al.*, 2021) the Jūrkalne 3 was deposited during MIS 3 – early MIS 2, i.e. in front of the advancing Late Weichselian ice sheet (cf., Hughes *et al*., 2016; Larsen *et al*., 2016).

The study area was covered by the ice sheet during the Late Weichselian. At the end of glaciation, the older sediments have underwent a heavy diapirization because of local ice advance of so-called Apriki glacial tongue (Saks *et al*., 2012b). Between Late Weichselian till and sands of Jūrkalne 3 patches (up to 2 metres thick at Baltmuiža) of glacially redeposited clayey silt occur. The clayey silt reveals massive structure, but in its lower parts thin (few-millimetres-thick) sandy shear planes are recognised. Additionally, thin shearing layer (tectonic lamination) is present at contact zone between clayey silt and sands of Jūrkalne 3. After the deglaciation, the Late Weichselian till was partly eroded by wave action during different stages of the Baltic Ice Lake. As a result, a boulder pavement with sandy cover above it are visible in the uppermost part of the bluff.

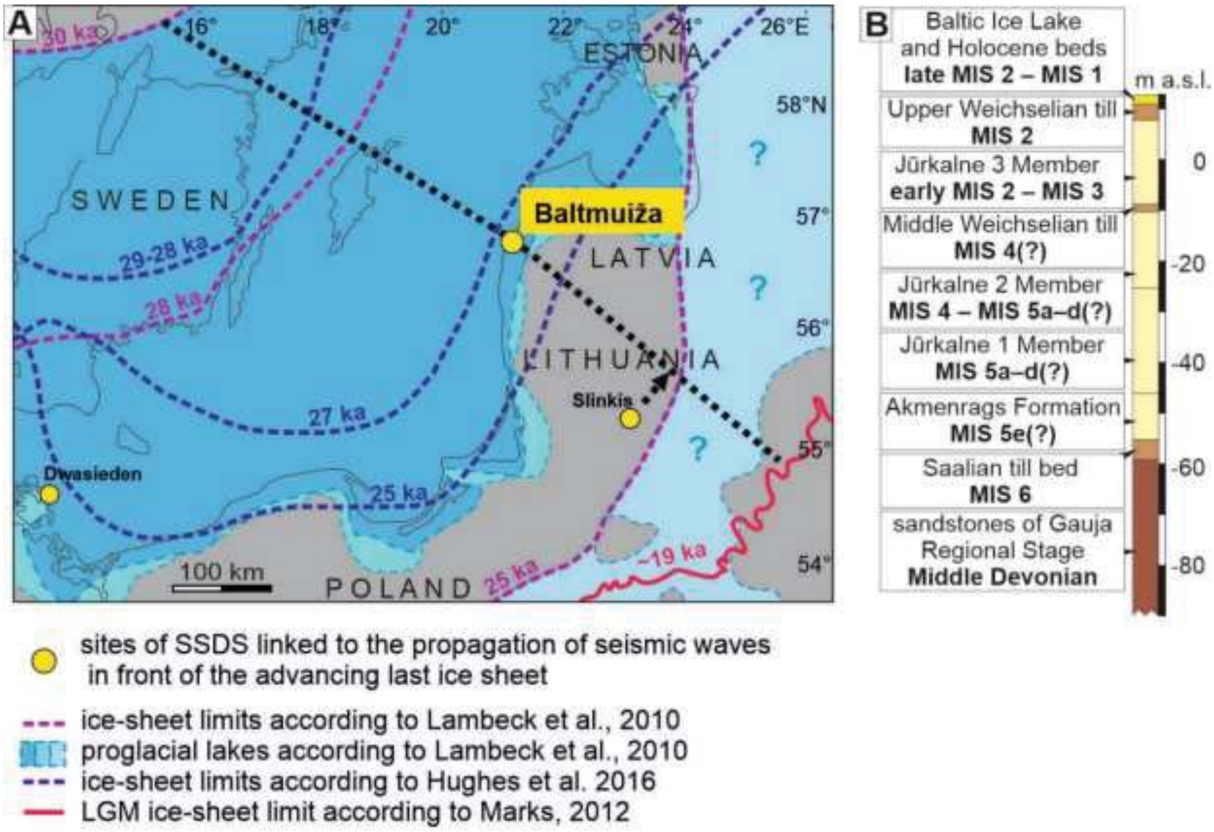

Fig. 1. Location of the study site (Woźniak et al., 2021, with minor changes). A: Limits of the ice sheet and extensive proglacial basin during the early and middle MIS 2 in the SE Baltic area. B: Synthetic Quaternary sequence with its basement (Saks et al., 2012b, with minor changes).

At Baltmuiža site, sediments of Jūrkalne 3 reveal a non-diapirized nature but contain smaller scale soft-sediment deformation structures (SSDS) 'trapped' within sandy and sandy / silty layers (Belzyt *et al*., 2018; Woźniak *et al*., 2021). Seven internally deformed layers were recognised. Their visible lateral extent is limited by talus deposits covering the bluff, and it reaches from a few metres to 12 m. Layers SSDS-1, -2 and -3 are stacked on top of each other, but undeformed sandy sediments can be seen between layers SSDS-3, -4, -5, -6 and -7 **(Fig. 2A)**.

Detailed sedimentological analyses of these deformed layers indicate that liquefaction and re-liquefaction were responsible for the development of SSDS. Liquefaction caused the reorganization of grains in sediments resulting in the development of SSDS within the layers. The most indicative evidence of initial liquefaction are injection structures, load casts and seudonodules which occur frequently in each layer with SSDS in the study site (Fig. 2B–E).

Traces of a unique findings of both initial liquefaction and re-liquefaction were recognised within at least four of the seven layers with SSDS. Repeated liquefaction of sediments is uncommon due to the increase of sediment compaction resulting in the reduction of liquefaction

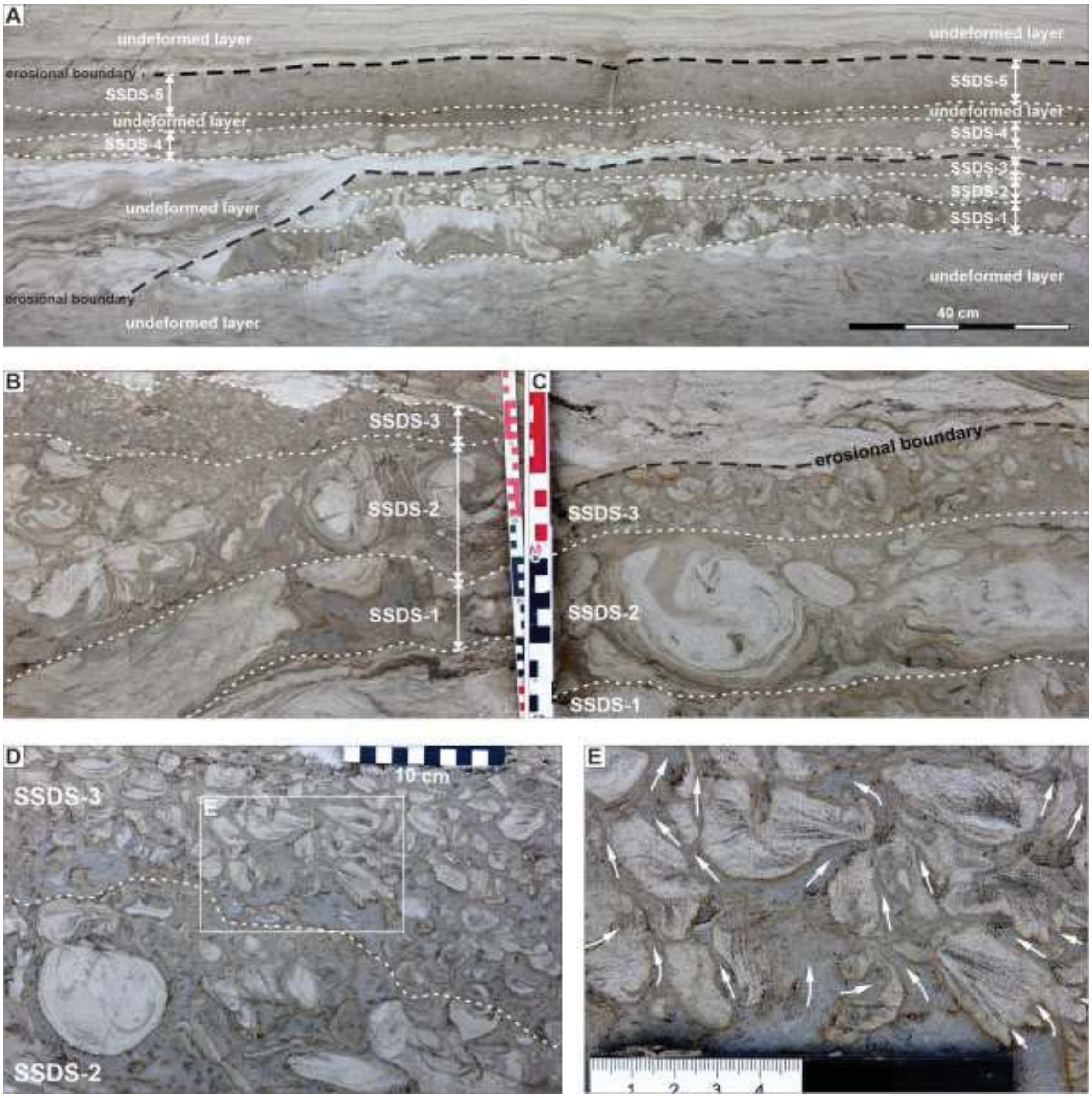

Fig. 2. Selected features of layers SSDS (Woźniak *et al*., 2021, with minor changes). A–B: Lateral view along a set of five layers with SSDS. B: Lateral view along the set of three SSDS layers (1-3); note the eroded top boundary of the layer SSDS-1 in the left part of the photo. C: Silty sand pseudonodules of different size in the layers SSDS-2 and -3; not the eroded top boundary of the layer SSDS-3. D–E: Silty sand pseudonodules and sandy silt injection structures in the top part of the layer SSDS-3.

potential after solidification (e.g., Youd, 1973, 2003; Obermeier, 2009). It is difficult to re-liquefy sediment affected by previous liquefaction due to the increased packing of grains and decreased hydration after initial liquefaction. The effects of re-liquefaction phenomena are: (1) two different generations of pseudonodules – one generation with preserved internal lamination and relatively regular distribution, and another with deformed internal lamination and a chaotic-distribution of pseudonodules, (2) two generations of injection structures, (3) clastic injection pipes that incorporate sediments deformed by the initial liquefaction, and (4) disrupted load casts.

Liquefaction was responsible for the injection, loading, pseudoloading and non-uniform loading of the sediments. The results show that despite compaction after liquefaction, sediment re-liquefaction caused by an allogenic trigger is still possible under favourable conditions, i.e., sediment anisotropy, cyclic loading, and preserved high water saturation.

All layers with SSDS are characterised by eroded tops (e.g., Fig. 2A–C), which indicate that deformation took place when these layers were close to the surface of sedimentation. The initial liquefaction was triggered by autogenic and allogenic factors, i.e., uneven loading and seismic wave propagation, while the re-liquefaction could be related to a single, allogenic trigger of mid-Late Weichselian glacigenic earthquakes at the front of the advancing last Fennoscandian Ice Sheet (Woźniak *et al*., 2021). Seismic waves were induced at the front of the advancingice sheet, estimated to be ca. 100–200 km from the study site; this was likely to have occurred by the stick-slip motion of ice above structural scarps (klints) which occur in the eastern Baltic (Woźniak *et al*., 2021). The study shows that glacigenic earthquakes, similar to these reported from modern glaciers, could be a widespread phenomenon in areas glaciated during the Pleistocene.

Acknowledgments

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Stop 6b. LARGE-SCALE GLACIOTECTONICALLY DEFORMED PLEISTOCENE SEDIMENTS: BALTMUIŽA SITE

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Baltmuiža site **(Fig. 1)** is located 7 km NE from town Pāvilosta in western Latvia. It is the central part of Baltic Sea cliffs stretching between Strante and Ulmale. The height of cliffs is up to 15 m and the modern topography comprises so called Piemare Plain of the Baltic Ice Lake covered by aeolian sands.

The bedrock in this part of western Latvia consists of Devonian sandstone, dolomitic marl, clay, dolomite and gypsum and is several tens of meters below the present sea level, and inclined in WNW direction. It is covered by a thin layer of reddish brown, possibly Saalian till (Saks *et al*., 2012b) which is underlain by sand and gravel in places. Previously this till unit was attributed to the Elsterian glaciation (Danilāns, 1973; Seglins, 1987; Kalniņa *et al*., 2000). Up to 30-m-thick marine clayey, silty and silty sand sediments of possibly Eemian to Early Weichselian age occur above the lower till unit. This is followed by the middle till unit (dark grey) which is largely eroded and sporadically distributed up to the thickness of only 1 m. It is mainly located below sea level and could be possibly of Middle Weichselian age coinciding with the ice advance during the Middle Weichselian (so called Talsi stadial after Zelčs *et al*., (2011). The middle till is covered by nowadays visible sequence of Pleistocene sediments consisting mainly of silty clay, silty and fine sand (described previously as the Jūrkalne 3 Member by various authors and referred as intertill unit further), which in turn is overlain by a discontinuous cover and variable thickness (generally up to 2 – 3 m) of the Late Weichselian till and/or Late glacial and Holocene marine and aeolian sand and gravel. The Middle Weichselian sandy sediments are protruded by dark grey clayey silt diapirs throughout the all cliff sections near Baltmuiža, which are the most prominent features of this kind in Latvia.

The upper till cover is very defragmented and usually has an appearance of lens-like bodies which are generally bent upwards but the opposite occur as well. It appears only in the upper part of the inter-diapir spaces **(Fig. 2A)**. Till sediments seems to be occasionally re-washed by the waters of the Baltic Ice Lake with the only remains of boulder pavement. Besides aforementioned, at least 10-m-thick beds of the upper till are visible in places. It has a generally massive structure and well-developed fissility and lot of subglacial clasts suggesting the development in a subglacial traction zone. Although sometimes the upper till unit macroscopically appears as one, distinct layers can be distinguished in places by varying internal structure, granulometric composition, colour and compactness attesting complex development and deformation history.

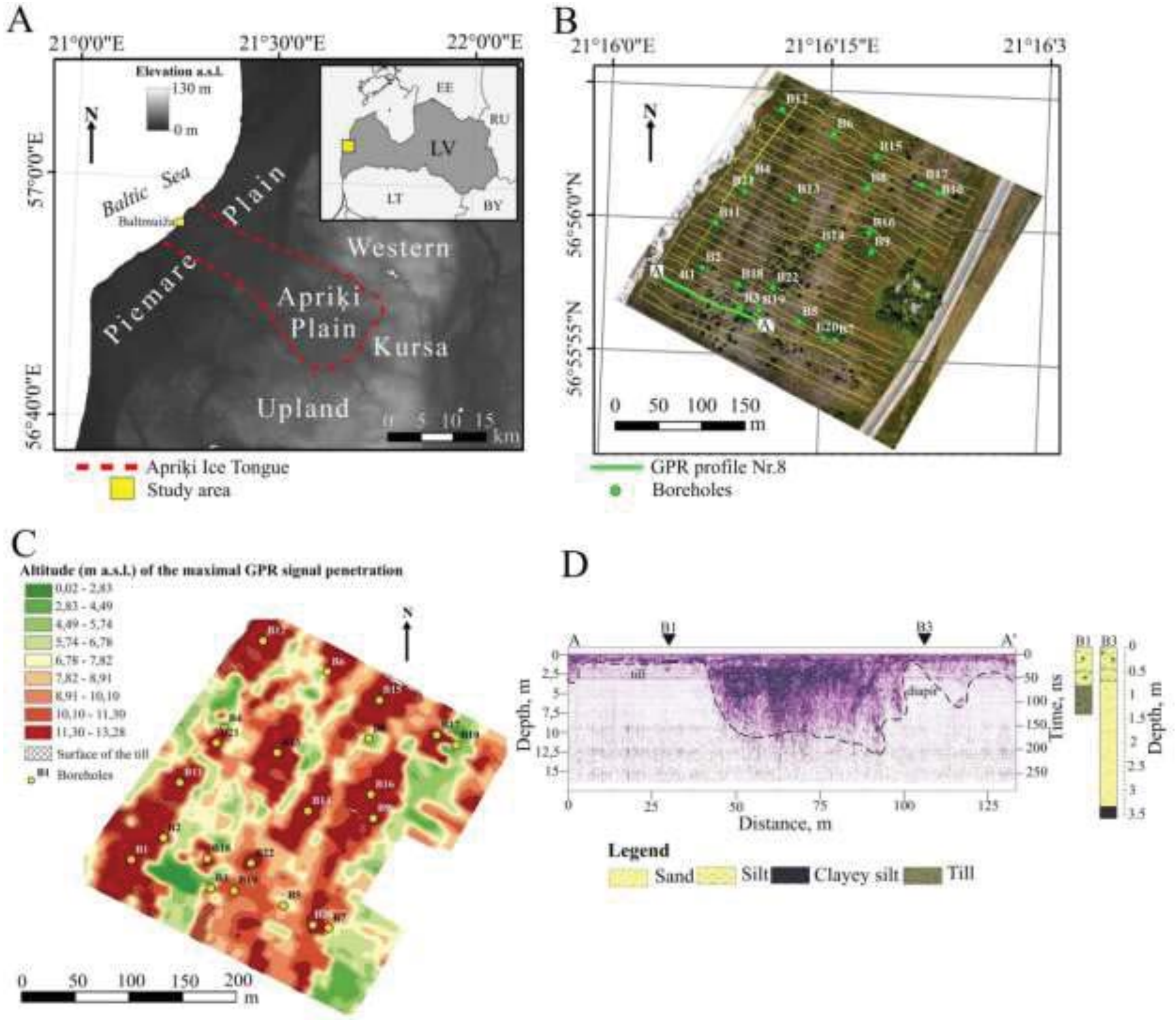

Fig. 1. A) The location of the Baltmuiža site. B) Study area of the geophysical investigations near Baltmuiža including locations of GPR profiles and boreholes. C) A map with the interpolated GPR maximum signal penetration altitude. Note that metres are above sea level. Red areas are possible distribution of the upper till patches interpreted form radargrams and verified by boreholes. D) Characteristic radargram and logs of boreholes showing the various sediments (till, sandy sediments and clayey silt representing diapir).

The base of till is characterised by shear zones, where till sediments are protruded by sandy sediment stringers and intraclasts. The upper till usually have a pebble orientation maxima dipping towards WNW which coincides with the ice flow direction of the Apriki ice tongue. The other measurements of directional elements of glaciotectonic structures have varying orientations as also shown by previous investigations (Dreimanis *et al*., 2004, Kalvāns *et al*., 2004; Saks *et al*., 2012). The thickness of total Pleistocene deposits near Baltmuiža is ~60 m (Juškevičs *et al*., 1998).

Baltic Sea cliffs of western Latvia have been studied by various scientists, and firstly by Dreimanis (1936), who concentrated his effort on the granulometrical and lithological composition of two greyish till beds. Later the main attention has been paid to the intertill sediments between Ulmale and Jūrkalne by Konshin *et al.* (1970) and Veinbergs and Savvaitov (1970) attributing those to marine sediments (coastal and lagoonal). Danilāns (1973) studied pollens and diatoms and of section North of Ulmale which corresponded to both marine and freshwater diatoms. He correlated these sediments to late Holsteinian or Early Saalian that were supported by palynological investigations of Kalniņa *et al.* (2000). Seglins (1987) reported freshwater diatoms from the intertill sediments. Since 1999 mainly stratigraphical issues have been addressed by researchers and presented in several field trips (Dreimanis, 1999; Dreimanis *et al*., 2004; Kalvāns *et al.,* 2004; Saks *et al*., 2012b). New studies of stratigraphy and glaciotectonic deformations were presented at the Peribaltic group International Field Symposium in Western Latvia in 2004. Stratigraphy of intertill sediments were revised by Saks *et al.* (2012) based on the new OSL dating. Previous Early Saalian shallow water silty and sandy sediments were proved to be of Middle Weichselian age ranging from 25 to 52 ka. Upper dark grey till was attributed to Late Weichselian instead of Saalian (*ibid*.). The sample from Baltmuiža site was collected from the shallow water plane-parallel laminated fine-grained sand bed at the depth of 3 m from the ground surface and the obtained OSL date is the youngest one – 26 ± 2.6 ka (ibid.). This age which is almost identical to the ages of nearby bluffs at Ulmale (26 ± 4.1 and 28 ±4.6 ka) characterize still ice-free conditions and gives a possible time of onset of the Late Weichselian glaciation in this region that occurred after 26 ka. The existing reconstructions of Middle Weichselian sea level attest that the sea level was considerably lower than today at the end of MIS 3 suggesting the Middle Weichselian sediment deposition well above the global sea level in the freshwater lake which existed in the Baltic depression at least during 52 to 25 ka according to Saks *et a*l. (2012).

At the time of the Weichselian glaciations, the study site and all western part of Latvia was covered by Baltic Ice Stream (BIS) of the Scandinavian Ice Sheet (Zelčs, Markots; 2004; Zelčs *et al*., 2011; Saks *et al*, 2012a). During the course of deglaciation, the Baltic Ice Stream (flow direction was generally from north) divided into the Usmas and Kurshian ice lobes, and the Kurshian lobe was split into several local ice tongues. One of them was the Apriķi ice tongue (AIT) which advanced from WNW (as demonstrated by the orientation of drumlins in the Apriķi Plain, see Saks *et al*., 2012a) during the North Lithuanian (Linkuva) phase (Zelčs, Markots, 2004; Zelčs *et al*., 2011).

The Late Weichselian glacial history and the formation of glaciotectonic structures of the study site have been addressed by previous researchers, one of the latest studies can be found in the publication by Saks *et al*. (2012a) who emphasises the changes in subglacial pore-water pressure as the main driver to AIT dynamics and the formation of diapirs. After Saks *et al*. (*ibid*) it can be summarized as follows: (1) the BIS stagnated in the area prior to the advance of the AIT leaving the dead ice fields; (2) the active ice masses of the AIT advanced against inactive ice, which led to a build-up of ice thickness; (3) when the critical shear stress was reached, the ice started to flow rapidly leading to a lowering of the ice surface and dropping of the subglacial pore-water pressure in sandy sediments; (4) pore-water pressure in silty/clayey low-permeability sediments remained high triggering diapir formation; (5) shearing of the diapir tops or sediments above diapirs and the deposition of till in the space between them further facilitated the rise of the diapirs. As noted by Saks *et al*. (2012a) such a situation can occur if the gradual pore-water pressure build-up under stable or slowly thickening warm-based ice is followed by a rapid ice thickness reduction in a surge event, which would rapidly lower pore-water pressure in upper sandy sediments.

New studies have been conducted during the recent years mainly focusing on the geophysical investigations combined with geological drilling and investigation of glaciotectonic deformation structures at the Baltic Sea bluffs (Lamsters *et al*., 2019). These results will be presented during the field excursion. The newest research comprises the study of the distribution and morphology of diapir structures, as well as complicated and disintegrated Late Pleistocene sedimentary sequence using ground penetrating radar (GPR) Zond 12-e with 300 MHz antenna and electrical resistivity sounding (ERS) system SYSCAL Pro Switch 72. GPR profiles (32) with a total length of ~10 km were recorded in the 300 x 200 m area. Interval between parallel profile lines was approximately 10 m. ERS were performed in the Wenner array recording two profiles with the two meter spacing between electrodes. To correlate the GPR and ERS data with actual sediment sequence in the study area, 22 boreholes were drilled. Main task was to reach the surface of till or clayey silt that comprises diapirs. The depth of boreholes was ~1 – 1.5 m if the till was reached and ~3.5 m if no clayey sediments were encountered.

The results of GPR survey show that it is possible to distinguish a strong reflection of surface of the till and strong reflection of the top of the clayey silt material (diapir). Weaker reflections are identified from undisturbed or deformed layering of sandy sediments as well. It is possible to detect the surface of the upper till unit or clayey silt diapirs, as well as sandy sediment sequence up to 13 m below ground surface. The maximum penetration depth of GPR signal was used to visualise the possible distribution of the defragmented Pleistocene sediments taking into account that shallow penetration depth (few meters) should coincide with the areas where clayey sediments are distributed. Created map **(Fig. 1C)** allowed distinguishing generally elongated spots which are parallel to the shore line (NNE – SSW) where strong GPR reflections are very closely to the ground surface (up to 1.5 m). Using the data obtained from the boreholes, we can conclude that shallow reflections comes mainly from the top of the till sediments which strongly limits the GPR penetration depth **(**see **Fig. 1D)**. These till patches are up to 150 m long but only up to 50 m wide, usually narrower **(Fig. 1C)**. The identified longitudinal patches of till are of particular interest because they do not agree with the conceptual model of Saks et al. (2012a), where the tops of diapirs became eroded and pile up in the ice flow direction behind diapirs. The dimensions of till patches are many times larger than diapirs themselves and from our point of view their genesis requires more complex explanation. Their very elongated distribution and orientation in mainly one direction requires particular further attention which cannot be solved form the existing data. Furthermore, it is still not clear, why the upper till unit is usually 2-m-thick but in places its 10 m or even more.

Where the penetration depth is little bit deeper (2 – 3 m), possible diapir structures could be identified. On radargrams these structures usually appears as zones free of reflections bordered by steep zones with stronger reflections **(Fig. 1D)**. Two diapirs can be clearly identified in GPR data and they are confirmed by borehole data as well. Unfortunately, due to the technical restrictions, it is not possible to reconstruct precise morphology of diapirs from the GPR data. Where the deepest penetration depth of the GPR signal comes from ~10 m below the ground surface, it possibly could represent the surface of the deformed clayey silt layer which are not risen as a larger diapir but it is not clear due to the penetration depth which is close to the lower limit of possibly obtainable GPR reflections with the particular antennas in sandy sediments.

We have shown that it is possible to distinguish the areas covered by upper till from the GPR data. The possible locations of diapirs can be drawn as well but this always needs clarification using geological drilling. Results from ERS greatly coincide with GPR results. Unlike GPR, ERS method allows detecting the thickness of the upper till unit and provides a lot deeper look on the possible under-till structures.

Combining GPR observations with investigations at the outcrops, we found that diapirs show a great variety of their height, width, and symmetry **(Fig. 2)**. The most remarkable are diapirs, which reach the topmost part of the cliffs and are ~13 m in height **(Fig. 2C)**. Usually, the tops of diapirs do not reach the upper part of cliffs and is overlain by Middle Weichselian sands. Some of them are inclined in the direction of ice flow suggesting moving ice during their formation. Only slightly concaved sandy sediments between diapirs suggest the frozen state during the injection of diapir structures and the narrow dyke-like structures in the upper part of some diapirs point at hydrofracturing process **(Fig. 2E)**. Such upward inclined clastic dykes consist of the same sediments as diapirs but in the most upper part they continue only as fractures in sandy sediments suggesting only highly pressurised excess water flow. The contacts between clayey silt material (diapir) and sandy sediments are very sharp **(Fig. 2B, D)** and only in places are characterized by thin shear zones, where sandy sediments are deformed by intraclasts/inclusions or thin layers of clayey silt. In zones, where clayey silt material has not been exposed to the diapirism processes, the primary bedding is observable as clayey silt layers interbedded with silty clay layers. The sedimentary bedding in diapirs has been deformed and is largely homogenized but secondary structures are visible in places, for example, upward flow-like structures. In places, the internal structure of diapirs is brecciated consisting of mainly clayey silt material with centimetres-size silty clay intraclasts **(Fig. 2D)**. This is can be particularly well visible near outer margins of diapirs.

Fig. 2. The examples of variable diapir structures near Baltmuiža. A) Low laying diapir and the lens of the upper till in inter-diapir space. B) A part of narrow diapir revealing a sharp contact between clayey silt and sandy sediments. C) Two prominent diapirs located closely to each other and reaching almost the top of the cliff. D) Sharp contact zone of diapir and sandy sediments with very well visible internal brecciated structure of diapir. E) A small diapir with long upward dyke.

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Stop 7. OLANDO KEPURĖ CLIFF: A KEY-SECTION OF WEICHSELIAN DEPOSITS

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The Olando Kepurė cliff (Dutch Cap) is located about 7 km to north from Klaipeda port breakwater and exposes the significant half of Quaternary thickness of the Lithuanian Maritime Region. The Quaternary deposits in this region occur on the rocks of the Lower Cretaceous, Upper Jurassic, Lower Triassic and Upper Permian. Pre-Quaternary surface is rich in dense palaeoincisions with an average depth of 30-40 m, sometimes reaching even 90-95 m. The average thickness of the Quaternary makes up 50-65 m, or 130-135 m in the deepest palaeoincisions. Lithologically, the Quaternary thickness is composed mainly of till (morainic sandy loam and loam). The inter-till deposits (gravel, sand, silt, clay, gyttja, etc.) are less distributed; their thicknesses don't exceed 15-20 m, as a rule. Larger thicknesses (to 40-50 m) are found only in the palaeoincisions.

Fig. 1. Olando Kepurė cliff in the Baltic Sea coast near Klaipėda city (photo: A. Bitinas).

The name of cliff – Olando Kepurė (Dutch Cap) – is quite unusual. According to V. Gudelis (1998), who was interested in the origin of this toponym, the name Dutch Cap could have come from noticing its similarity to the Dutch fisherman's cap, looking from the sea towards the coast. For many centuries, this cliff served as a landmark for local fishermen and ships sailing to the port of Klaipėda. Finally, in 1818, the name Olando Kepurė was legitimized on maps, thanks to the care of the state advisor engineer C. Wutzke. Until the end of the Second World War the cliff was protected as a coastal landmark for maritime shipping (Gudelis, 1998).

The Olando Kepurė cliff is the highest point on the whole Lithuanian Baltic Sea coast. Forested coast rises up to 22-24 meters above the sea level, whereas the erosion scarp height reaches approximately 16 meters **(Fig. 1)**. The most intensive coastal erosion is going in this part

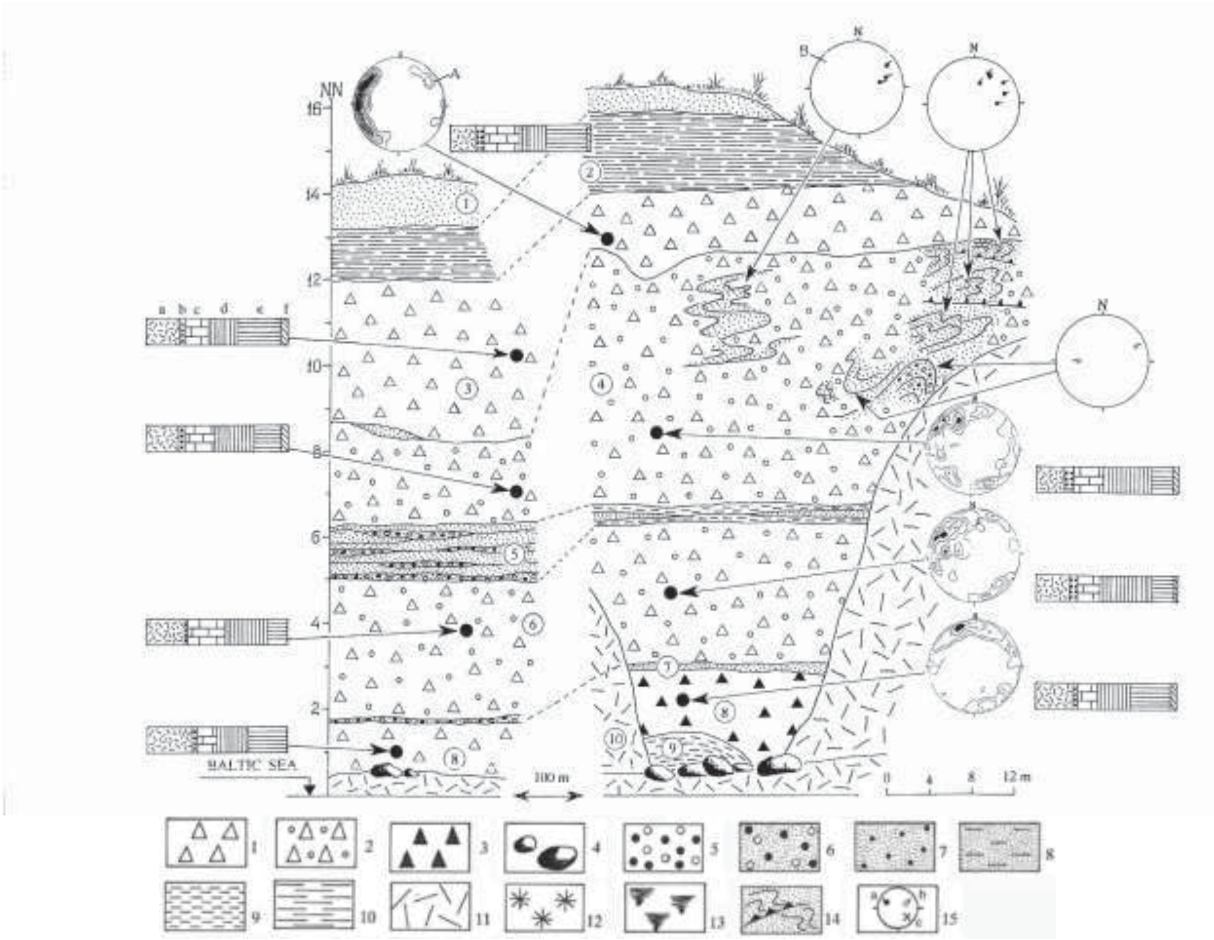

Fig. 2. Geological structure of Olando Kepurė cliff (after Bitinas, 2011).

1 – yellowish brown and brown till (moraine); 2 – grey-brown or brown-grey till; 3 – grey till; 4 – boulders; 5 – gravel; 6 – sand with gravel; 7 – sand (various granular composition); 8 – silty sand; 9 – silt; 10 – clay; 11 – slope deposits; 12 – limonite; 13 – buried soil; 14 – glaciodislocations; 15 – results of measurements of glaciodislocated structures (projection to the lower hemisphere): fold axis orientation – measured directly (a) and calculated according to indirect measurements (b), pole to bedding of layer (c). Results of till gravel fabric analysis are presented in the circle diagrams. Petrographic composition (%) of gravel part (Ø 5–10 mm) of till (in liner diagrams; after M. Melešytė): a – crystalline rocks; b – sandstone, aleurolite; c – dolomite; d – Silurian limestone; e – “other” limestone; f – other rocks. Stratigraphic and genetic interpretation of layers outcropping in the cliff (numbers in the circles): 1 – Holocene aeolian deposits; Late Weichselian (MIS 2) deposits: 2 – glaciolacustrine, 3,4,6 – glacial, with glaciodislocated floes of sand and gravel, 5 – aqua-glacial; 7 – glaciofluvial inter-till layer between Late Weichselian (MIS 2) and Middle Weichselian (MIS 4) glacial deposits; 8 – Middle Weichselian (MIS 4) glacial deposits; 9 – Ealy Weichselian (MIS 5a-d) lacustrine deposits; 10 – recent slope deposits.

of the Baltic Sea coast: the edge of the scarp recedes from the sea by approximately 0.4-0.5 meters per year. The well expressed Litorina Sea terrace with ancient cliff-like coast extends to the south from the cliff. The Olando Kepurė cliff with its scenic viewpoints is one of the most attractive and visitable places of the Seaside Regional Park. The geological structure of deposits outcropping in this cliff is represented in **Fig. 2**.

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Stop 8. GEOLOGY OF THE CURONIAN SPIT AND KLAIPĖDA STRAIT

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The spit of Kuršių Nerija (Curonian Spit) is 98 km long and 0.4-4.0 km width sandy barrier in the South –Eastern Baltic separating the lagoon of Kuršių Marios (Curonian Lagoon) from the Baltic Sea. The area of Curonian Lagoon is 1584 km^2 with 413 km^2 belonging to Lithuania. The largest depth is 5.8 m in the southern part of lagoon, the average depth – 3.8 m. Administratively the northern half of the Curonian Spit (50 km) belongs to Republic of Lithuania, the southern one (48 km) – to the Kaliningrad region of Russian Federation. In both parts of the Spit were established the National Parks; the whole Curonian Spit in 2002 was included in the UNESCO World Heritage List as object of cultural landscape with many natural and cultural heritage valuables.

Curonian Spit being a unique natural heritage area represents:

– natural geomorphological (physiographic) features of the great dune ridge: diversity of dune forms at different stages of formation; separate dune peaks, diversity of blown sand plain, capes and small bays, which are valuable from both aesthetic and scientific point of view;

– sandy beaches, the Baltic Sea coastal dune ridge, and great dune ridge provide for natural and seminatural habitats to threatened species of animals and plants; the old forests habitats are of outstanding universal value from the scientific and conservational points of view;

– precisely delineated by the Baltic Sea Curonian Lagoon area of outstanding universal value from the point of view of science, conservation and natural beauty.

Curonian Spit landscape being created not only by natural processes but even by human activities represents the combined work of nature and that of man. It illustrates evolution of fisherman society and settlements over time, under the influence of the physical constrains and opportunities presented by their natural environment on one hand, and further development of natural areas caused by human. Cultural properties in Curonian Spit represent:

– sites (fishermen settlements): where works of man and nature are of outstanding universal value from the ethnocultural, historic and aesthetic value;

– monuments: architectural works, which are of outstanding universal value from the point of view of history, art and science.

The geology and geomorphology of the Curonian Spit, Curonian Lagoon and adjacent region had been studied by numerous researchers: J. Schumann, G. Berendt, A. Tornquist, H. von Wichdorff and others. Detailed investigations of the Curonian Spit and Curonian Lagoon origin and development during Lateglacial and Holocene started only in the second half of 20th century. Pollen and diatom methods and radiocarbon (^{14}C) dating were carried out by V. Gudelis, M. Kabailienė, A. Gaigalas, V. Klimavičienė, N. Savulynienė, and many others. Currently the investigations continue a new generation of scientists using the modern research methods.

In the northern, Lithuanian part of the Spit, deposits of the Last Glaciation (Late Weichselian) are presented by till and glaciolacustrine clay occurring at altitudes from -25 to -30 meters, while in the southern part the till deposits are at the depth from -2 to -4 meters, and in the vicinity of Rasytė (Rybachyj) they are a few meters above the present sea level. Most probably, the formation of the Curonian Spit started during the transgression of Ancylus Lake, when the water level was a dozen meters lower than present, also continued during the Litorina and Post-Litorina Sea stages. Thus, the Curonian Spit is sandy bar composed generally by marine sand. Eroded coasts of the Semba Peninsula served as a source area for the marine sand. Later the major part of the Curonian Spit surface was occupied by an aeolian sand plain called here *palvė*. Along the western margin of the Spit (marine beach) there is a protective dune ridge, commonly of 6-12 m high and mainly human-made. A long range of high dunes – the Great Dune Ridge – is stretching along the eastern margin of the Spit.

The dunes are typical landform for the entire Lithuanian coast, but only in the Curonian Spit dunes clearly dominate on the surface. Since the early beginning of the Spit existence, the aeolian processes play a very important role for its development. They formed the largest and the highest dune formations in North Europe. The dune tops rise up to 60–70 m; the official highest point in Lithuanian part of the Spit – Vicekrugo Hill – is 67.2 m high (forested dune). The other similar dune (alive, moving) named Sklandytojų (Glider Flyers) also reaches 67-68 m height. The average height of the dunes is about 40 m. Great Dune Ridge consists of dunes of a few generations: ancient parabolic dunes covered by ancient soils; and new very high, migrating, longitudinal dunes streaching above the first ones. The Juodkrantė parabolic dunes remained since the end of the Litorina Sea time, i.e., Atlantic period. Now they are overgrown by forest. Very interesting and distinctive dunes are situated between Juodkrantė and Pervalka, where they were not affected by human activity. At present this area is the Grey (Dead) Dunes Nature Reserve. There are several soil horizons and tree remains buried by the sand. Dunes in this part of the Spit are practically stable, whereas the area close to Nida with the Parnidis Dune is an excellent example of moving dunes. The eastern shoreline of the Spit is very uneven: there are numerous sand peninsulas called by Lithuanians *ragas* (horn).

The Klaipėda Strait, what links the Curonian Lagoon (Kuršių Marios) with the Baltic Sea and separates the Curonian Spit from the mainland, is the best investigated area from geological point of view. In its most narrow place the Strait is 385 m wide, whereas, in the widest it reaches 1500 m. At present the depth of aquatory, after artificial regular dredging, varies from 8 to 15.5 metres. The only seaport of Lithuania is built in the Strait. According to data of a few tens of boreholes (Figs 1 and 3), drilled during engineering geological mapping at a scale of 1:5 000, the Quaternary sequence in the Strait and surroundings is represented by Pleistocene and Holocene deposits of different genesis: glacial, glaciofluvial, glaciolacustrine, lacustrine, marine, aeolian. The uppermost part of deposit thickness is composed of Late Glacial and Holocene deposits originating from different stages of the Baltic Sea development. The frequent layering of till (glacial sandy or clayey loam) and inter-till (sand, silt, somewhere – sandy gyttja) deposits formed during a few (?) cycles of glaciations is characteristic feature of Pleistocene thickness. The infrared optically stimulated luminescence (IR-OSL) dating of lacustrine inter-till sandy sediments shows that they age fall within the range of marine isotope stages (MIS) 5d-5a. The subsequent more detailed examination of geological setting of Quaternary sequence has led to the assumption that the sampled inter-till deposits occur not *in situ* (Fig. 2), i.e., they are found as blocks (rafts) in the thick till beds that have been formed by the ice advance during the Weichselian early pleniglacial maximum (MIS 4). This conclusion does not support the former standpoint that the till beds beneath the bottom of the Klaipėda Strait were formed during the Warthanian (Medininkai, MIS 6) glaciation.

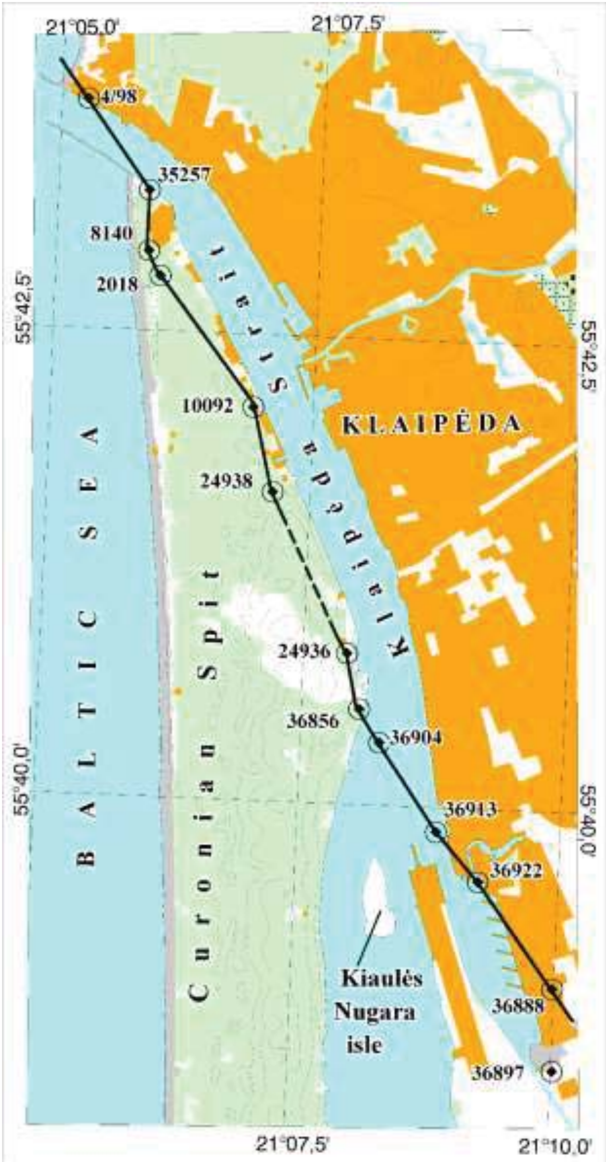

Fig. 1. Location of geological cross-section.

Fig. 2. Core of borehole from Klaipėda Strait: glaciodislocated inter-till micro-layers of clay, silt and silty sand (photo: A. Damušytė).

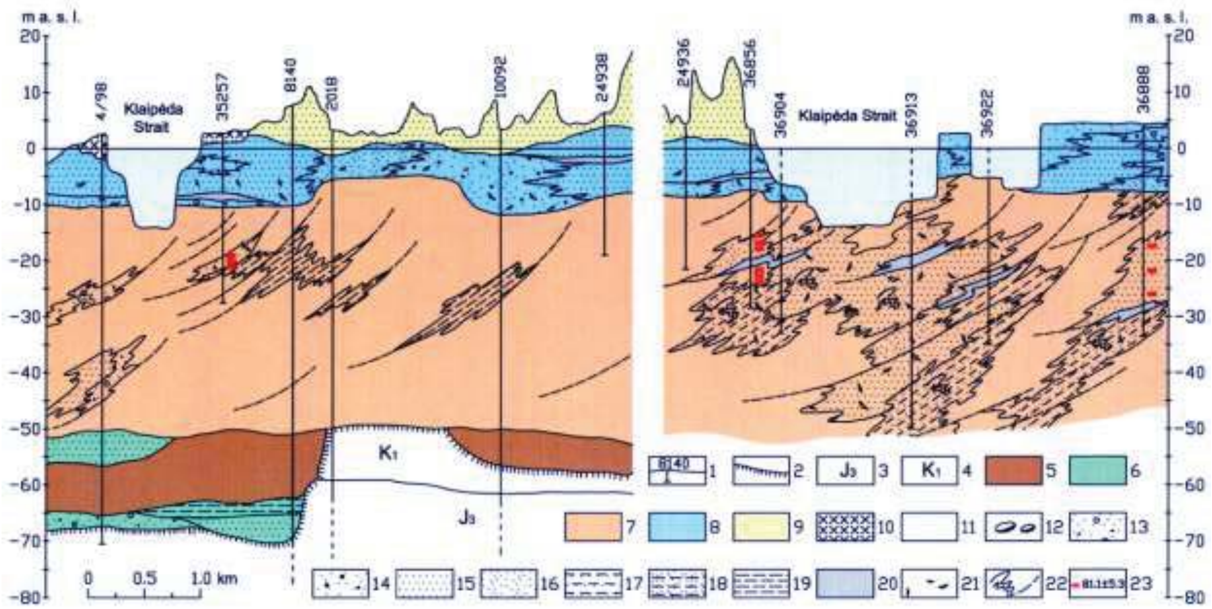

Fig. 3. Geological cross-section along the Klaipėda Strait.

1 – borehole and its number; *2* – surface of pre-Quaternary deposits; *3* – upper Jurassic deposits; *4* – lower Cretaceous deposits; *5* – middle Pleistocene glaciogenic deposits; *6* – middle Pleistocene glaciofluvial and glaciolacustrine deposits; *7* – upper Pleistocene glaciogenic deposits with glaciotectonized blocks of inter-till limnic deposits; *8* – Late Glacial and Holocene marine and lagoonal deposits; *9* – Holocene aeolian deposits; *10* – anthropogenic deposits. Lithology of deposits: *11* – till; *12* – boulders; *13* – sand with gravel; *14* – various-grained sand; *15* – fine-grained sand; *16* – very fine-grained sand; *17* – silty sand; *18* – sandy silt; *19* – clay; *20* – gyttja, peat; *21* – fine dispersal remnants of organic matter; *22* – glaciotectonic features (folds, thrust faults); *23* – sampling point for infrared optically stimulated luminescence dating (IR-OSL): number indicates the luminescence age of deposits (in ka) (after Bitinas *et al*., 2011).

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Stop 9. AMBER BAY IN THE CURONIAN SPIT: 19TH CENTURY AMBER MINING

In 1855, during canalizing the waterway in the Curonian Lagoon near Juodkrantė, the workers discovered amber in the lagoon bottom deposits. Shortly thereafter, various businessmen expressed their interest in this discovery. The first person to start the works of organized excavation for amber search was former miller, owner of ships, later Klaipėda innkeeper Vilhelm Stantien. When merchants from Dancig joined him and a company of amber excavation „*V. Stantien and M. Becker*“ was founded. The government also contributed to the company's activity. In order to attract cheap labor the company encouraged the residents of Juodkrantė to join amber excavation. Having the volumes of trade increased, spacious bunkhouses were constructed to the north of Juodkrante, ship repair workshop was opened, port quay and workshops for production of the divers' clothes were equipped. Gradually, Juodkrantė became an industrial town. The works of amber excavation were performed only in the summertime – around 30 weeks per year by three shifts. The amber excavated from the Lagoon's bottom had to be cleaned and separated from admixtures. The excavated "empty" sediments were used for the expansion of land area. From 1860 till 1890, approximately 75 thousand kilograms of amber on the average per year were excavated. Having the amber mining declined, in 1890, the excavation works contract was not renewed, therefore, the excavation works in Juodkrante were terminated.

During the amber digging a collection of amber ware of the Middle Neolithic was discovered on the Lagoon's bottom sediments. Later the amber collection was entitled as the Amber Treasure. Professor of the Königsberg University Richard Klebs deserved the most for preserving the collection, therefore, quite often the treasure is named after him. Having organized exhibitions in various cities of the world, this treasure became known and famous in the whole world. After the World War II, only 5 findings were left. Along with other remained exhibits of the treasure, they are kept in Museum of Geology and Palaeontology of Göttingen University. According to descriptions and drawings from the book of R. Klebs, the artist B. Kunkulienė made two sets of amber moulages, which currently are exhibited in Palanga Amber Museum and in Mizgiriai Amber Gallery in Nida.

During the whole summer season, the Amber Bay is decorated with sculptures which are created by artists from Lithuania and Latvia (photo below).

Source of information: http://www.krastogidas.lt/en/objects/596-amber-bay
https://visitneringa.com/lt/ka-pamatyti/gintaro-ilanka-juodkrante

Stop 10. GREY (DEAD) DUNES: PALEOSOLS AND HUMAN IMPACT TO THE DUNE'S EVOLUTION

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The unique monument of the Curonian Spit development – a few buried soil horizons – has been found in the Great Dune Ridge, extending between Rasytė (Rybachyj) and Juodkrantė. German naturalist J. Schumann (1859) was the first who has mentioned this fact. G. Berendt, H. von Wichdorff and others Prussian scientists had prolonged investigations of the ancient soil horizons (paleosols). Significantly more data about the development of the dunes was given only in the second half of XX century by scientists of Lithuanian Academy of Sciences: academician V. Gudelis was an initiator of the investigations **(Fig. 1)**. Numerous articles in various publications examined this phenomenon (Gudelis 1976, 1989–1990, 1986; Gudelis *et al*. 1976, 1993; Gaigalas *et al*. 2008, 1991, and others).

Currently a major part of the Great Dune Ridge is overgrown by grass and forest and only a few places with open sand afford an opportunity for investigations of the buried soil horizons (paleosols) **(Fig. 2)**. These horizons are found northwards from Pervalka between Agila Hill and Vingis Dune on the windward (western) slopes of the dune ridge. Only one soil horizon has been mentioned by H. von Wichdorff (1919), but later up to 7 layers of paleosols have been found. The Great Dune Ridge in the Curonian Spit is composed of two aeolian sand complexes. The lower dunes complex had been formed as parabolic, the so-called "ancient buried parabolic dunes," and the upper one had been formed generally during 16–19th centuries. Paleosols overlay the surface of the ancient buried parabolic dunes. Since the beginning of the Subboreal period, the plant cover in the Curonian Spit has been destroyed several times. After the vanishing of vegetation cover above the parabolic dunes, an aeolian processes were activated and sand started to move forming the new dunes above the paleosols. The high amount of charcoal in the paleosols confirmed the presumption that big fires had caused the decrease of vegetation. The ancient soil layers are composed of the forest litter of various thickness, podzol horizon, which is composed of grey fine sand, and illuvial horizon which is of reddish or brownish colour due to high content of iron and manganese. Even stumps and trunks of huge trees have been found in some places. An origin of the ancient forest fires as well as a scale of dune advances after the fires were under discussion for a long time.

The earliest traces of humans have been detected in Juodkrantė and Nida, and were attributed to the Middle Neolithic (Rimantienė, 1989). The entire Curonian Spit was populated only during the Late Neolithic, the period of Corded Ware Culture.

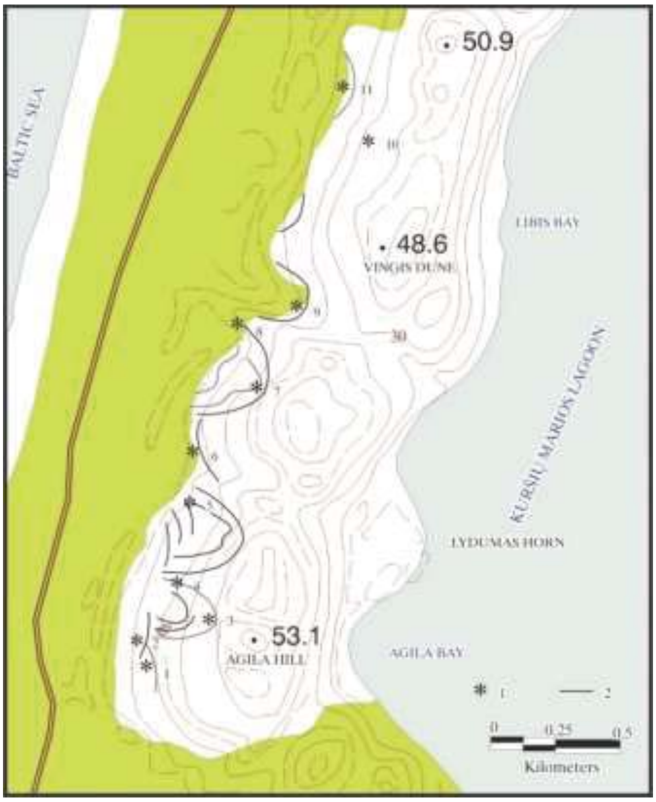

Fig. 1. A sketch map of paleosols exposures (marked by asterisks) and their spatial distribution (black lines) in the Curonian Spit, southern part of the Grey (Dead) Dunes near Pervalka (after Gudelis, Savukynienė, 1995).

Fig. 2. A view of paleosols in the Grey (Dead) Dunes (photo: A. Bitinas).

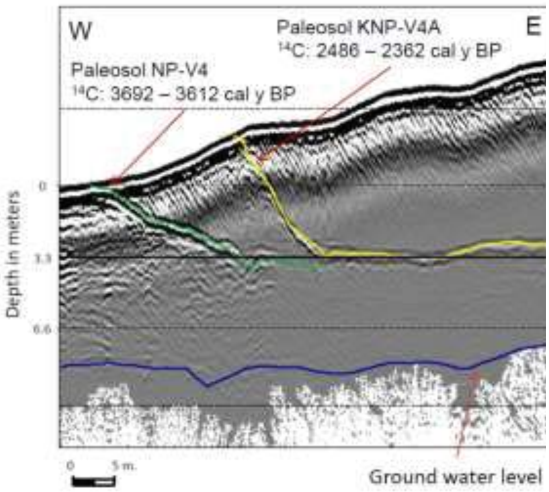

Fig. 3. Paleosols of different age in the GPR profile (after Dobrotin, 2013).

Since the 15th century, forests were devastated by man. The wood-cutting in 16-17th centuries caused the catastrophic consequences, when 14 villages have been covered by wind-driven sand. To stop the movement of dunes, the afforestation was initiated in 19th century. G. D. Kuvertas, a head of the post office in Nida, has initiated the afforestation that was finished in 1902.

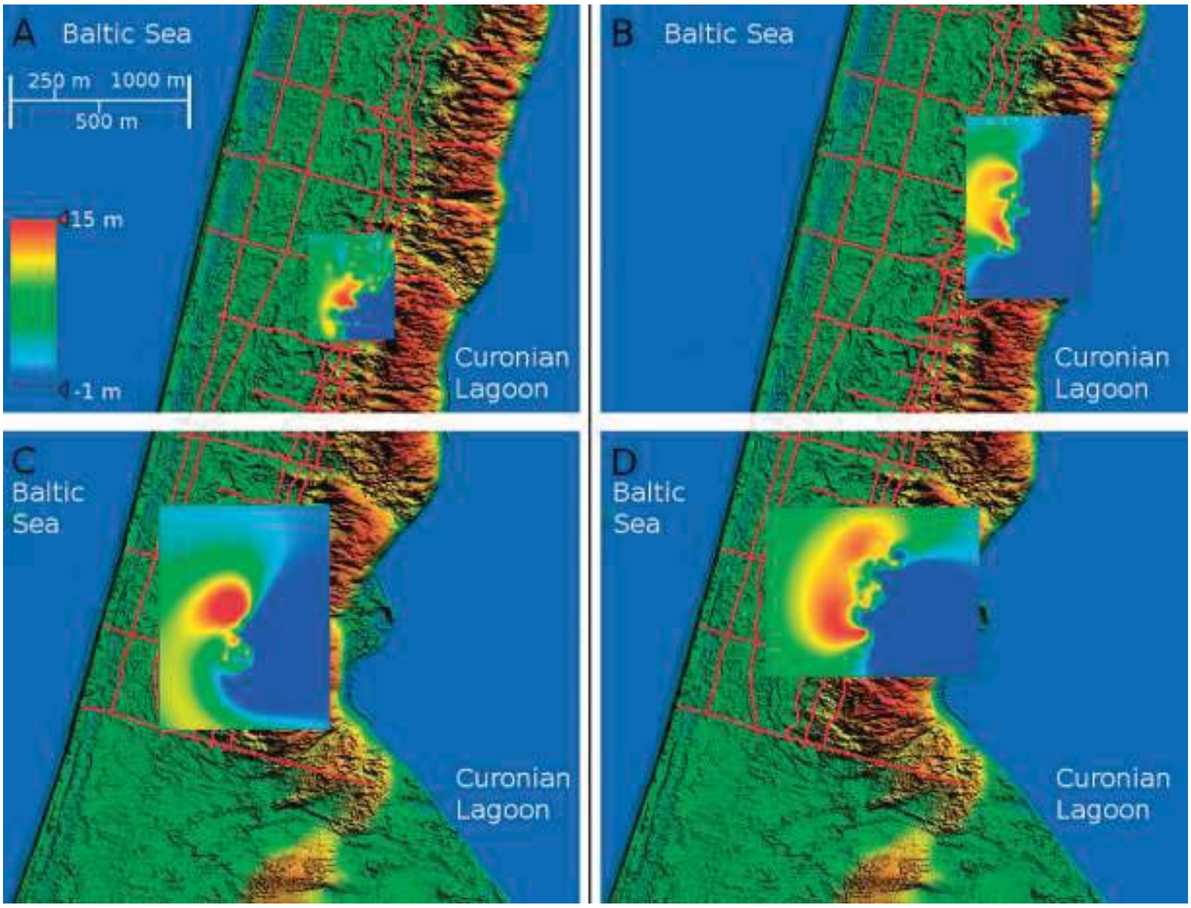

Fig. 4. Paleogeographic reconstructions of the Dead (Grey) Dunes massif for different points in time: A, C – about 3800–3500, B – about 430, and D – about 1000 calendar years BP. The reconstructed fragments are shown as inserted rectangles; the remaining parts on the figures are filled in by LIDAR topography with georadar survey grid. Colour height scale is valid for reconstructed paleorelief only (after Dobrotin *et al*., 2013).

During the last decade with the help of modern geophysical and geochronological techniques – ground-penetrating radar (GPR) surveys, LIDAR data, radiocarbon (^{14}C) and optically stimulated lumininiscence (OSL) dating, computer modelling – the detailed investigations of paleosols were carried out in the Dead (Grey) Dunes massif located between Juodkrantė and Pervalka **(Fig. 3)**. The paleosols representing past soil-forming generations in the Dead (Grey) Dune massif survived fragmentarily, mainly in the southern part of the massif along the western slope of the Great Dune Ridge. According to the results of radiocarbon (^{14}C) dating it is possible to distinguish four soil-forming generations (age in calendar years BP): 5800–4500, 3900–3100, 2600–2400, and 1900 – modern. The latest generation contains several paleosols of different age, but the more detailed subdivision of this pedogenic phase is not currently feasible due to methodological problems of sediment dating. The reliable paleogeographic reconstruction of paleodunes morphology and ancient coastlines of the Curonian Lagoon in the present Grey (Dead) Dune massif is available only fragmentarily, in the very limited areas where the paleosols survived, i.e., in the southern part of the massif **(Fig. 4)**.

During all the soil-forming phases the ancient coastline of the Curonian Lagoon was, apart the minor shifts, approximately at the same position – close to the central part of the present Curonian Spit, i.e., along the western slope of the Great Dune Ridge. The ancient dune massifs (parabolic dunes currently remained unchanged only in the vicinity of Juodkrantė) evenly covered the entire area of the Curonian Spit. The Great Dune Ridge has been formed only starting from the XVI century due to extremely high aeolian activity influenced by destructive human practices. The ancient forest fires stimulated only local re-activation of aeolian processes and, in contrary to the opinion of previous investigators, did not triggered significant migration of the main dune massifs.

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Stop 11. PROTECTIVE DUNE IN THE CURONIAN SPIT – A "COMMON PROJECT" OF HUMANS AND NATURE

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The Protective Dune Ridge (Lithuanian abbreviation – APK) of the Curonian Spit reveals the human and wind's creative power. It was designed to prevent sand invasion from the seashore to the inner part of the Spit; the project was initiated by dune supervisory inspector Søren Bjørn (1744–1819). A 98 km-long man-made ridge formation started in 1802 and continued, with particular brakes, until 1903.

Western, wind-proof Protective Dune Ridge's slope is constantly destroyed by wind which drifts the sand at the foot of the ridge and blows out various erosive (deflation) forms: caves, moulds, ravines, etc. The width of the APK is from 30–40 meters (southern part of Smiltynė) to 220 meters (northern part of Pervalka). Height varies from 7–8 up to 10–11 meters, at Smiltynė it rises up to 14–15 meters above sea level. The waves at the beach emit coarse sand, in places – with gravel and pebble (near Juodkrantė, Pervalka) and form steeper beach. The sand brought by the sea currents and waves occurs under the APK everywhere, while fine and silty lagoon sand with admixture of organic matter is found only in the southern part of Nida.

Information stand for the visitors of the Curonian Spit National Park about geological structure of the Protective Dune Ridge.

A view of Protective Dune Ridge (photo: A. Bitinas).

Stop 12. PHENOMENON OF "DUNE TECTONICS": EXTRUSIONS OF LAGOON MARL FROM UNDER THE DUNES

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Southwards from Nida where the Great Dune Ridge descending into the Curonian Lagoon, at the foot of the Parnidis Dune, the most famous outcrop of the lagoon marl was exposed for many years **(Fig. 1)**. The second and biggest exposure of the lagoon marl is located farther to the south, close to the Lithuanian-Russian state border **(Fig. 2)**. The length of this formation reaches up to 700 m, height is 3.5 m, and width is 50–60 m. There are a few belts of lagoon marl outcrops (ridges) extending parallel to the Great Dune Ridge. These deposits since 19th century the Prussian researchers used to call as *haffmergel*. Analogically, the Lithuanian scientist named it as *marių mergelis*, which means "lagoon marl". This is a general name for the mentioned deposits because they are not homogenous – lithological composition varies according to the proportion of organic matter, carbonates and clay particles: gyttja, clayey gyttja, gyttja clay and, in places, clay with organic matter.

Geological investigations show that lagoon marl is widespread below the significant part of the northern, Lithuanian, half of the Curonian Spit, and also outcropping on the Baltic Sea bottom (nearshore) close to Šarkuva (Lesnoe), i.e., in the southern part of the Spit which belongs to Russian Federation.

Fig. 1. Small exposure of lagoon marl at a foot of Parnidis dune occurred during 2007-2008 winter season; currently totally destroyed by wave and ice abrasion (photo: A. Damušytė).

Fig. 2. Exposure of lagoon marl close to the Lithuanian-Russian state border (photo: Lithuanian State Department of Tourism).

According to the lithological data of boreholes, as well as results of investigations by ground-penetrating radar (GPR), in the vicinity of Nida the top of the lagoon marl layer occurring *in situ* is fixed at a depth from -6.8 to -8.9 m NN. It is overlain by barrier sands up to 7–10 m thick. The bottom of the lagoon marl dips down to -14.5 meters below the sea level, i.e., the thickness of theses sediments varies from 5.4 to 9.0 m. The complex investigation (pollen, diatom, and molluscs analyses, ^{14}C dating) shows that the lagoon marl beneath the present-day Curonian Spit was deposited in a freshwater lagoon.

The detailed investigations of the Baltic Sea bottom along the southern half of the Curonian Spit using side-scan sonar, a multibeam echosounder, seismic imaging, sediment sampling and video observations allowed identification and mapping of an underwater landscape formed by extensive outcrops of laminated and folded lagoon marl at water depths of 5–15 m. The combined onshore–offshore data indicates that relict lagoon marl was deformed, compacted and dehydrated by a massive dune-covered coastal barrier migrating landward (retrograding) over these sediments during the Littorina Sea transgression in a processes termed "dune tectonics" **(Fig. 3)**.

"Dune tectonics" model comments:

A. During marine transgression a nearshore sand bar was formed. The bar was located seaward of the present-day Curonian Spit. The sand was transported alongshore to the northeast by prevailing currents from its source along the eroded coast of the Sambia Peninsula.

B. Development of the nearshore sand bar and its transformation to the coastal barrier raised above the sea level could happen due to glacial isostatic adjustment of the region: the uplift prevailed against the sea level rise. As a result, a freshwater lagoon was separated from the Baltic Sea basin, where were favorable conditions for calm sedimentation and formation of the lagoon marl layer. Along the crest of the barrier, aeolian processes resulted formation of sandy dunes. Subsequently, probably due to shoaling of the lagoon and circulation of longshore currents, the lagoon marl was covered by sand.

C. During the subsequent marine transgression, the sea coast was exposed to wave erosion and retreated landward. At the same time, as a result of erosion intensification along the Sambia Peninsula, the spit increased in volume and retreated due to continued aeolian activity and dune expansion. As a result, lagoon marl was gradually buried by aeolian sand due to advance of sand dunes. The great mass of the dunes and persistent pressure due to their loading weight caused plastic deformation of the lagoon marl layers and their extrusion to the surface, above the lagoon water level. As is evident in the vicinity of Nida and beneath Parnidis Dune, the 7–8 m thick sand layer above the lagoon marl is too thin to initiate marl deformation, whereas an additional weight of 30–35 m high dunes could have served as a trigger for marl deformation and ultimate extrusion.

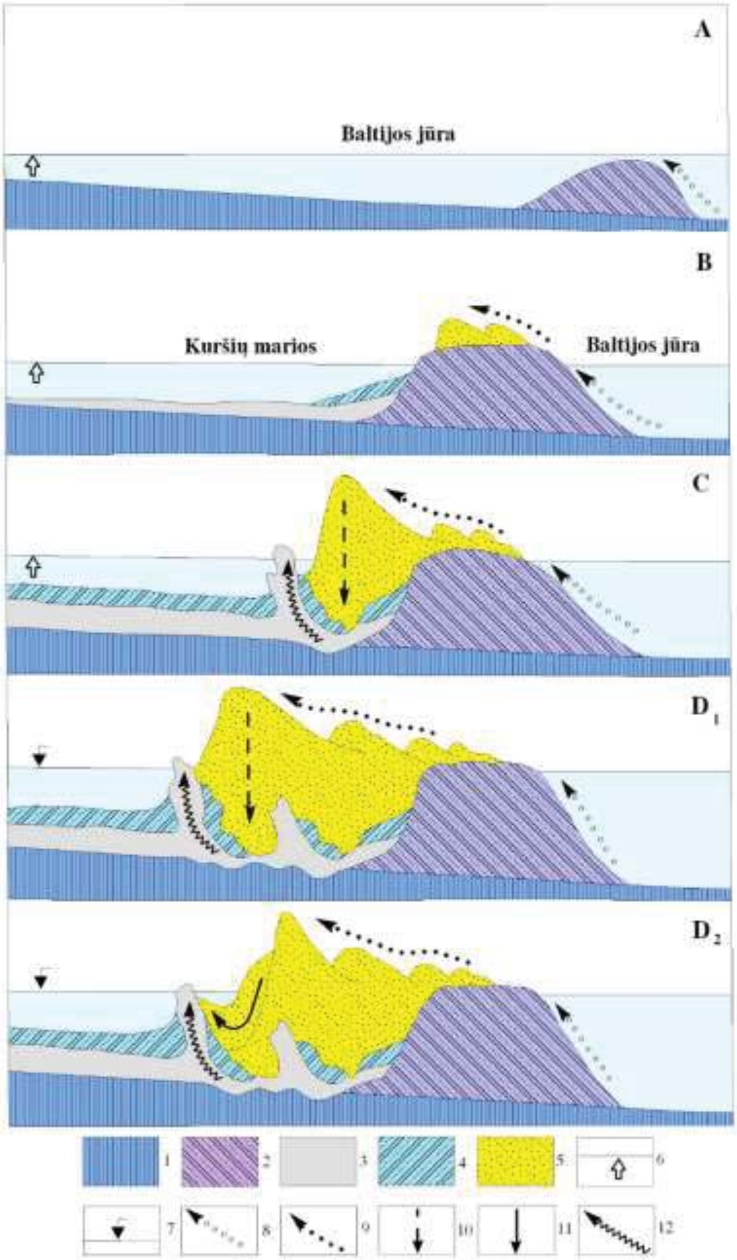

Fig. 3. Conceptual model of “dune tectonics”

Deposits: 1 – substrate of palaeo-basin bottom (unidentified deposits); 2 – barrier sand; 3 – lagoon marl; 4 – lagoon sand sheet; 5 – aeolian sand. Processes: 6 – water level rise; 7 – stabile water level; 8 – marine sand transport and accumulation; 9 – sand blowout and accumulation; 10 – gravitational subsidence; 11 – avalanching; 12 – plastic extrusion of lagoon marl.

Two modes of lagoon marl extrusion from under the sand dunes are working:

D1. The first mode involves lagoon marl outcropping linked with slow extraction (squeezing) of lagoon marl (diapirism) due to a gradually increasing load of aeolian sand. Such a process has been progressing through time due to continuing eastward movement of large dunes. This scenario is confirmed by the emergence (new outcrop formation) during the winter of 2007–2008. A high amount of moisture in the dune due to heavy rains or melting snow may have increased the weight of the dune and triggered the extrusion. As a result of dune migration, progressively new portions of lagoon marl are extruded, and later buried by sand in the inner part of the spit.

D2. The second mode represents very rapid lagoon marl extrusion (e.g. thrust-fault type) to the surface due to a catastrophic collapse of sand dunes into the lagoon (sand avalanching). Such a case is described in the literature based on eyewitness accounts – the fishermen present at the lagoon during such event. The last collapse of an active dune slipface happened on 4th July 1922, about 4.5 km to the south of Juodkrantė (Šimoliūnas 1939). The arc-shaped ridge of lagoon marl was formed abruptly as a result of this event. It was up to 4 m in height (above lagoon water level) and occurred at a distance of a few hundred meters from the lagoon shore (location of the collapsed dune).

Examples of so-called “dune tectonics” are quite rare in the coastal or inland dunefield areas and are governed by the interaction of two main factors: 1) presence of plastic deposit layers (in our case – lagoon marl) beneath the groundwater table; and 2) active development of aeolian processes, i.e., migration of massive sand dunes. But at present this geological process is becoming less intensive in the Curonian Spit: the dune height and the rate of migration are decreasing due to lack of sand caused by insufficient sand supply from the seaward sources. The reason is that during the last two centuries the massifs of active dunes and the sea coast were separated by the artificially planted forest along the entire length of the Curonian Spit.

In 1964 the outcrop of lagoon marl at a foot of Parnidis Dune, representing this rare geological-geomorphological process, was declared as Lithuanian geological monument protected by law.

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Stop 13. AUKŠTUMALA PEATBOG: THE WORLDWIDE FAMOUS HIGHMORE

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Aukštumala wetland ecosystem with lake complexes, typical biocenoses, protected species of fauna and flora is s situated in W Lithuania, within the northern part of the Nemunas Delta **(Fig. 1)**. The total area of the Aukštumala complex reaches 3018 ha, of which 98% are described as raised bogs, 1% - transitional bogs and remaining 1% are identified as a marsh (Grigaravičienė et al., 1995). Peat mining was carried out in Aukštumala for over 100 years, with negative ecological impact on the site. In order to preserve and restore this unique ecosystem the Aukštumala Telmological Reserve has been established in the western part of the wetland at the 1995. In our days 5 types of habitats of European importance can be found in Aukštumala Thelmological Reserve: active raised bogs, degraded raised bogs, bog woodlands, natural dystrophic lakes, depressions on peat substrates of the *Rhynchosporion*. In 1902 the scientific monograph describing the development, structure and etc. of the Aukštumala highmoor was published (Weber, 1902). Today we define this study as the and was the first scientific monography of this type in the world.

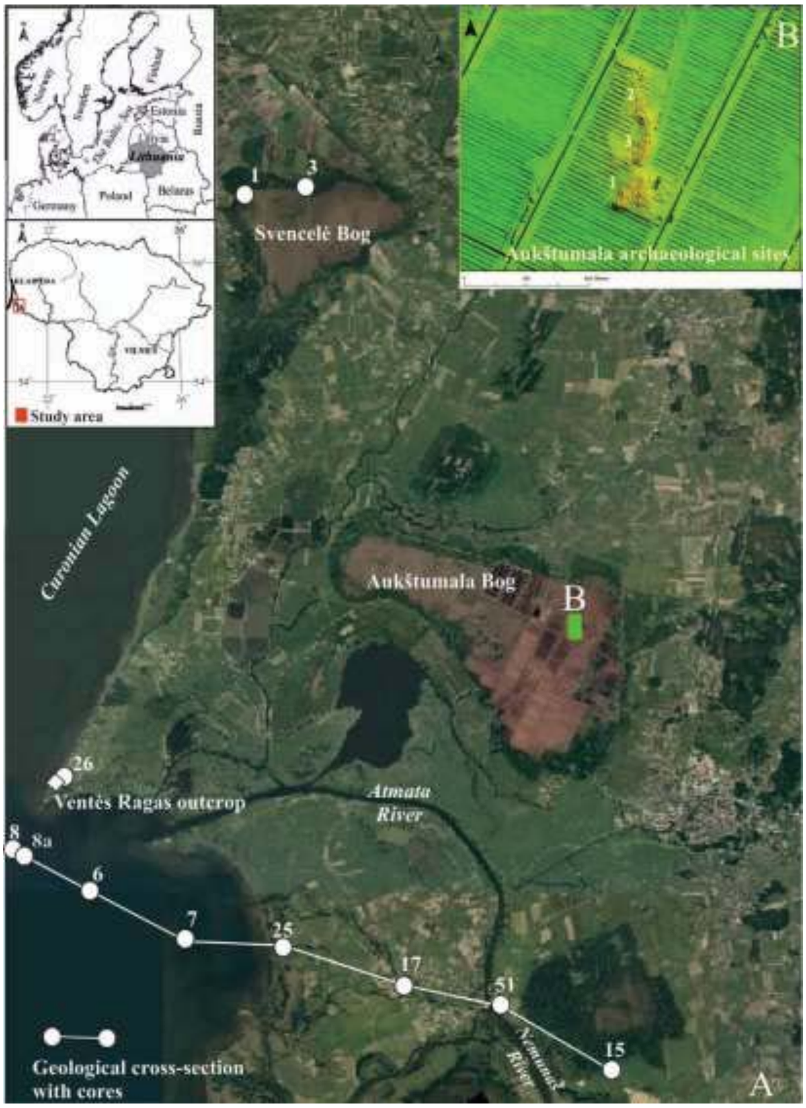

Fig. 1. Northern part of the Nemunas River delta with location of the Aukštumala peatbog, geological cores and archaeological sites (Damušytė et al., 2021).

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Stop 14. VILKYŠKIAI END-MORAINIC RIDGE (RAMBYNAS HILL): EVOLUTION OF NEMUNAS RIVER DURING THE LATE GLACIAL AND HOLOCENE

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Rambynas hill is located in the western edge of the Vilkyškiai end-morainic ridge which have been formed during one of the last Scandinavian Ice Sheet oscillations at the end of Late Weichselian (Late Nemunas – according to Lithuanian Quaternary stratigraphic scheme) glaciation **(Fig. 1)**.

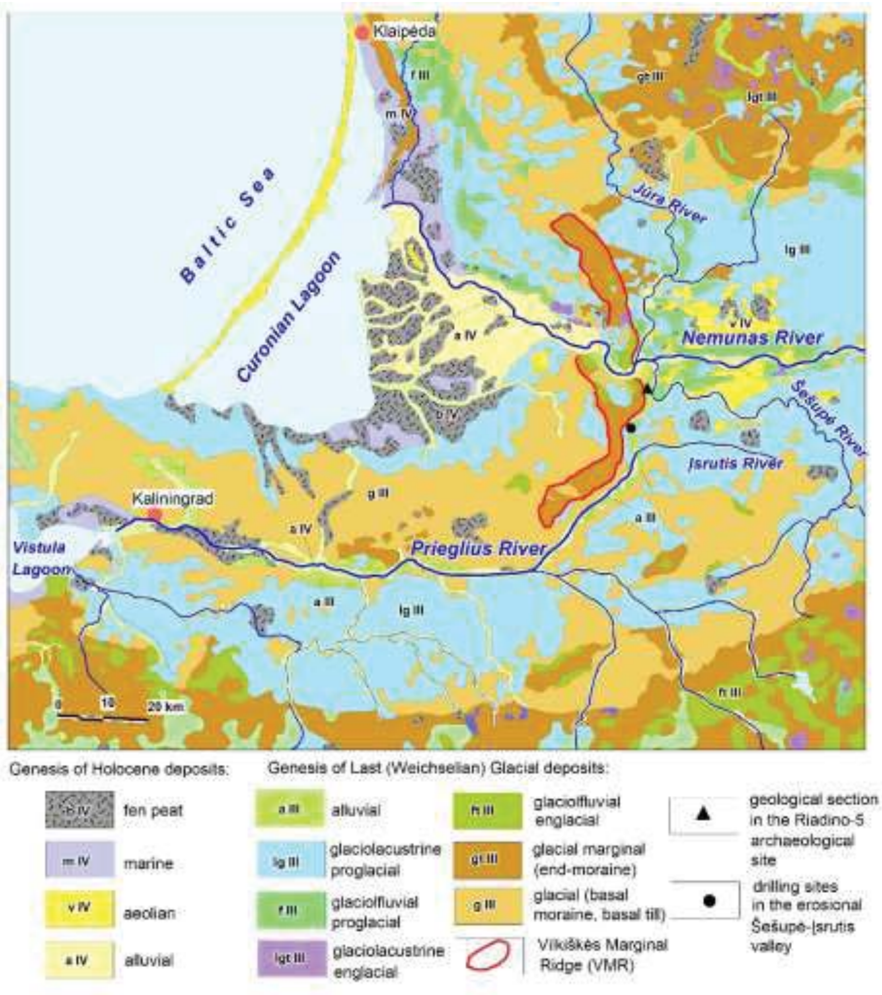

Fig. 1. Geological map of the Vilkyškiai end-morainic ridge and the surrounding region (after R. Guobytė).

The Vilkyškiai end-moraine ridge has more complicated geological and geomorphological structure than the typical marginal ridge **(Fig. 2)**. The highest hill Rambynas is 40 m above the level of the Nemunas River. Its summit is 45.8 m a.s.l. The Rambynas Regional Park occupies the central part of ridge located to north from the Nemunas River valley.

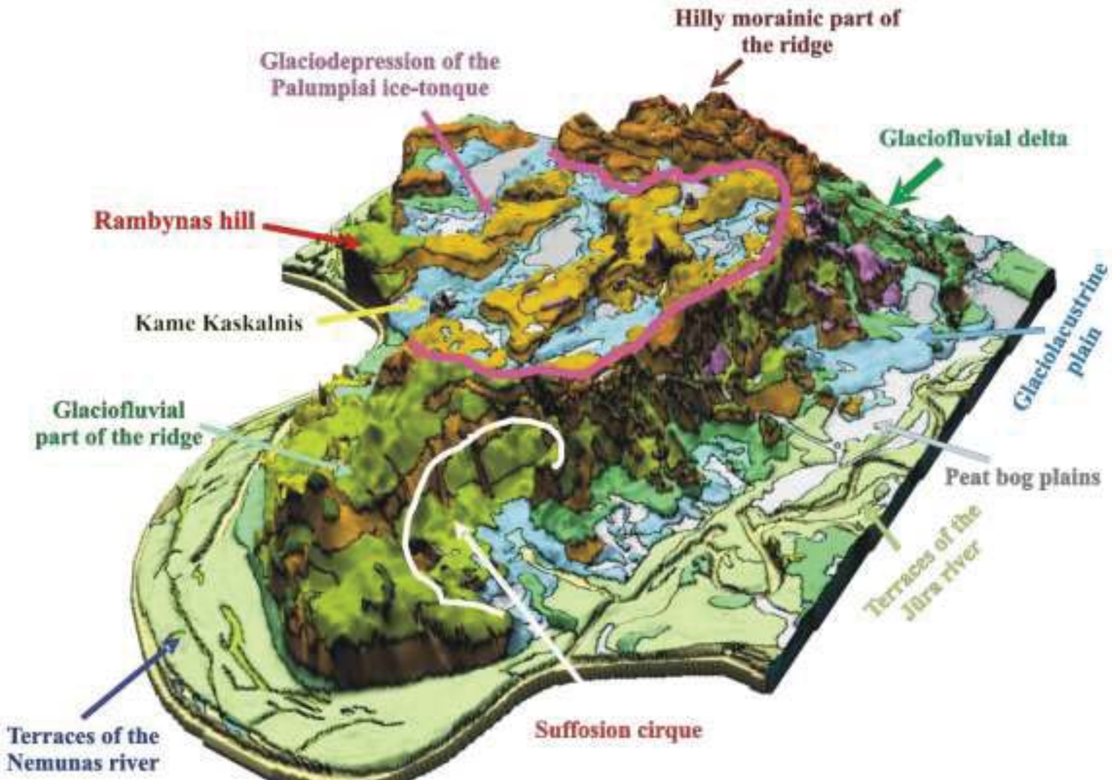

Fig. 2. Geomorphological map of the Vilkyškiai end-moraine ridge to north from the Nemunas River valley (after A. Jusienė).

The E-W trending geological profile trough the Vilkyškiai end-moraine ridge (including Rambynas hill) compiled on the basis of boreholes revealed that the ridge is composed of fine and very fine-grained sand, which thickness reaches 50 m in places **(Fig. 3)**. The upper part of the sandy sequence (up to 28 m deep) belongs to the glaciofluvial deposits of the Late Weichselian (Late Nemunas) glaciation (f III nm_3), while the lower part is presented by glaciolacustrine deposits of the Saalian (Medininkai) glaciation (lg II md). Some boreholes have even reached the Saalian (Medininkai) till (g II md). The ridge overlaying till of the Late Weichselian (Late Nemunas) glaciation is only 2–3 m thick. Thus, it can be concluded that the central part of the Vilkyškiai end-moraine ridge isn't a typical end-moraine ridge (composed, as a rule, by thrust-folded layers of till and other deposits), but is a big kame massif.

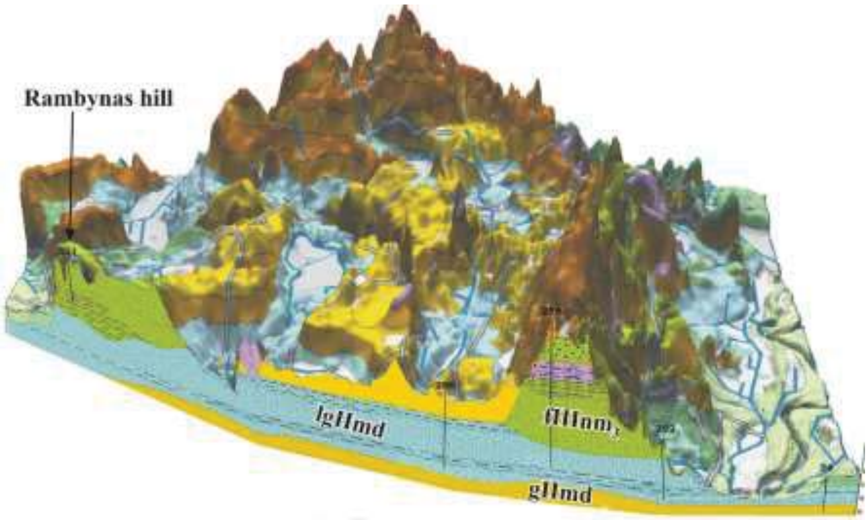

Fig. 3. The E–W trending geological profile trough the Vilkiškiai end-moraine ridge (after Guobytė, Jusienė 2007).

The Vilkyškiai end-moraine ridge is cut through by Nemunas River – the 1.5-2.5 km wide breakout through the ridge (or so-called Ragainė Channel). Administratively, this is the Russian-Lithuanian cross-border area. This area around the Nemunas and Šešupė rivers confluence is a key-area for solving important palaeogeographic issues actual for this region: when the Vilkyškiai end-moraine ridge was crossed by river; when the Nemunas Delta started to form; why the essential change of hydrographic network occurs, etc. After the final deglaciation of the region, in the beginning of Holocene (about 12-11 ka BP), a network of rivers was finally developed – they started to modify their valleys, and to meander. At that time the Nemunas River flowed westward, but the Vilkyškiai end-moraine ridge, as an obstacle, blocked its further flow to the west. As a result, the Nemunas River turned to the south and flowed via the recent lower riches of the Šešupė River, also used the significant length of the Prieglius River valley. It is possible to assume, that during the Yoldia Sea stage the Nemunas River flowed into the sea somewhere westward to the current Vistula Lagoon. The results of conventional radiocarbon (^{14}C) dating and pollen analysis in the recent dry valley between the Šešupė River and the Įsrutis River, as well as results of the previous studies in the archaeological site Riadino-5, enable to conclude that the Nemunas River has gnawed through the Vilkyškiai end-moraine ridge approximately 9.5 ka before present. A set of palaeogeographic reconstructions of the investigated area for different periods of the very end of Late Weichselian and beginning of the Holocene illustrates the Nemunas River evolution **(Fig. 4)**.

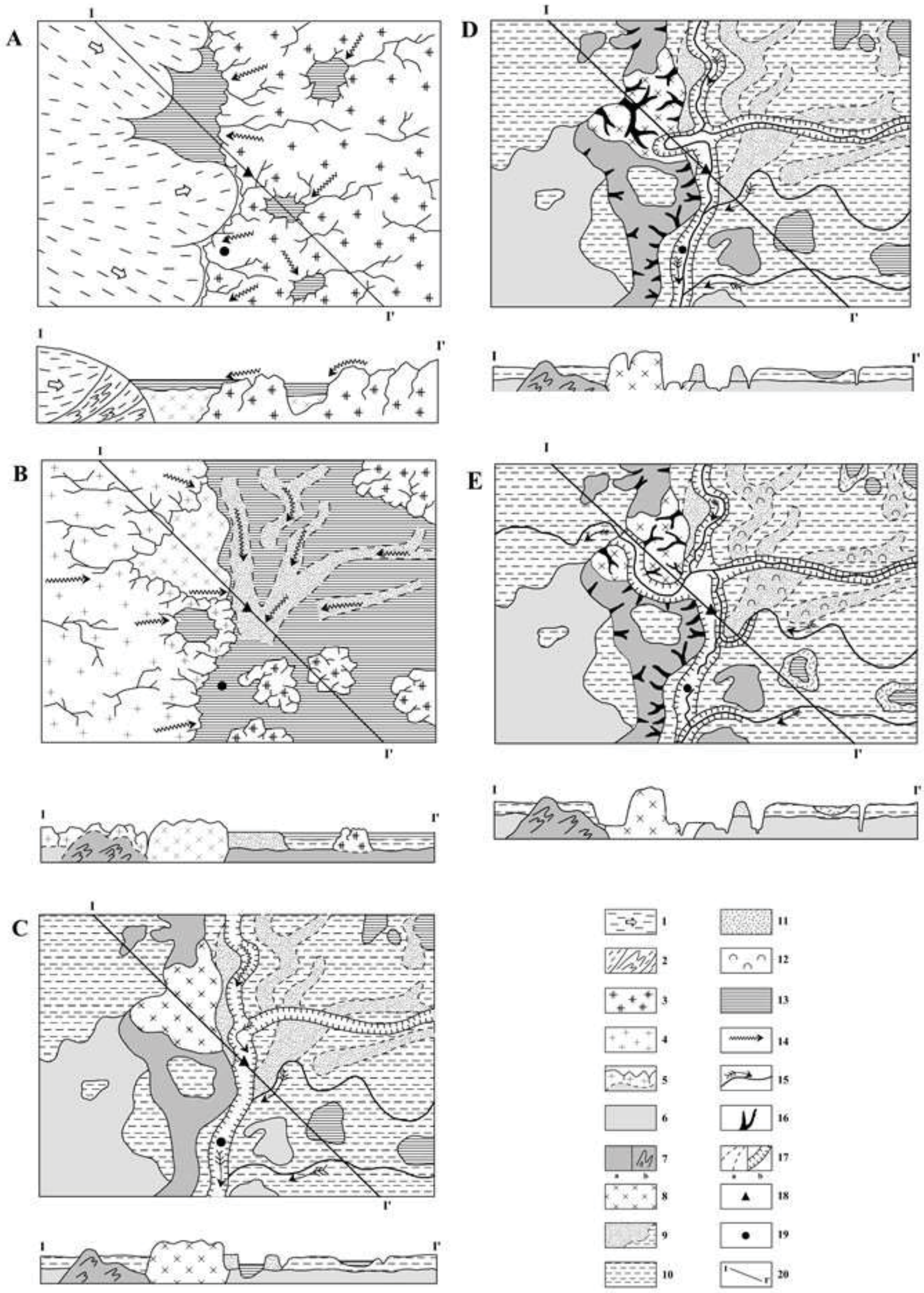

Fig. 4. The schematic model of palaeogeographic situation changes in the Nemunas and Šešupė rivers confluence region at the very end of Late Weichselian and beginning of the Holocene; below each scheme the palaeogeological cross-section is presented (after A. Bitinas). Palaeogeographic schemes are carried out approximately for these periods: A – 15.0-14.5 ka BP; B – 14.0 ka BP; C – 13.5-13.0 ka BP; D – 11.0 ka BP; F – 9.5 ka BP.

1 – active ice: arrow shows ice flow direction; 2 – thrust-fold structure of ice lobe at its margin. Dead ice: 3 – older glacial advance, 4 – younger glacial advance (surge, oscillation). 5 – dead ice and till: dashed line means unclear stratification between melting ice and till; 6 – basal till; 7 – marginal (deformational) till: a – in plane, b – in geological cross-section; 8 – kame massif (sand); 9 – glaciofluvial sediments (various sand, sand with gravel): dashed line means not clear expressed lithological-genetical boundary between glaciofluvial and glaciolacustrine sediments; 10 – glaciolacustrine sediments (fine-grained sand, silt, clay); 11 – peat; 12 – aeolian dunes; 13 – meltwater basin;14 – direction of meltwater flow; 15 – river and its flow direction; 16 – ravine; 17 – meltwater valley formed by: a – irregular braided stream (shallow), b – oriented stream (erosional, deep); 18 – Riadino-5 archaeological site; 19 – drilling sites in the dray erosional Šešupė-Įsrutis valley; 20 – line of palaeogeological cross-section.

Thus, since approximately 9.5 ka BP the Nemunas River flowed directly to the west from the Vilkyškiai end-moraine ridge, possibly into the Ancylus Lake occurring somewhere westward from the current Curonian Lagoon. Later, after the Litorina Sea transgression, the current Nemunas Delta formation started. The hydrographic basins of the Nemunas and Prieglius rivers were separated by new divide formed between the Šešupė and Įsrutis rivers.

In addition to all this, the palaeogeographic reconstructions of the Nemunas and Šešupė rivers confluence region could be useful for identification of migration ways of people during the Palaeolithic period as well as distribution of settlements during this archaeological epoch.

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