VILNIUS UNIVERSITY

NATURE RESEARCH CENTRE
INSTITUTE OF GEOLOGY AND GEOGRAPHY

DANGUOLĖ KARMAZIENĖ

THE MORPHOGENESIS AND SPATIAL SPREAD OF THE KAME TERRACES OF THE LATE NEMUNAS GLACIATION

Summary of Doctoral Dissertation
Physical sciences, Physical geography (06 P)

Vilnius, 2014

Doctoral disertation was prepared in 2007–2011 at the Nature Research Centre, Institute of Geology and Geography

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The dissertation is defended at the Vilnius University and Nature Research Centre Physical Geography Joint Council

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The official defense of the dissertation is due to be held at the public meeting of the Physical Science Council at the Nature Research Centre, Institute of Geology and Geography on May 15, 2014, at 15.00.
Address: Ševčenkos str. 13, LT-03223, Vilnius, Lithuania.

The summary of the dissertation was distributed on April 14, 2014.
The dissertation is available at the Libraries of Vilnius University and Nature Research Centre, Institute of Geology and Geography.

VILNIAUS UNIVERSITETAS

GAMTOS TYRIMŲ CENTRAS
GEOLOGIJOS IR GEOGRAFIJOS INSTITUTAS

DANGUOLĖ KARMAZIENĖ

VĖLYVOJO NEMUNO APLEDĖJIMO KEIMINIŲ TERASŲ MORFOGENEZĖ IR JŲ ERDVINĖ SKLAIDA

Daktaro disertacijos santrauka
Fiziniai mokslai, fizinė geografija (06 P)

Vilnius, 2014

Disertacija rengta 2007–2011 metais Gamtos tyrimų centro Geologijos ir geografijos institute

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Disertacija bus ginama viešame Fizinės geografijos mokslo krypties tarybos posėdyje 2014 m. gegužės mėn. 15 d. 15 val. Geologijos ir geografijos instituto salėje.
Adresas: T. Ševčenkos 13, LT-03223, Vilnius, Lietuva.

Disertacijos santrauka išsiuntinėta 2014 m. balandžio mėn. 14 d.
Disertaciją galima peržiūrėti Vilniaus universiteto ir Gamtos tyrimų centro Geologijos ir geografijos instituto bibliotekose.

INTRODUCTION

Kame terraces were formed by the decaying Upper Nemunas (Weichselian) glacier. They occupy an important place in the system of glacigenic landforms. Kame terraces in the territory of Lithuania are found in the relief generated by the Baltija glacier of Nemunas glaciation. Morphologically and morphometrically, they have much in common with the glacial glaciofluvial terraces.

Relevance of Research

In recent years, kame terraces have been distinguished within large-scale geological projects and small-scale mapping of the territory of Lithuania. Previously, the deposits of kame terraces had been identified as proglacial glaciofluvial deposits or glaciolacustrine sediments. The Lithuanian kame terraces occurring within the Upper Nemunas glaciation area are characterised by a highly varied morphology, genesis and structure. Analysis of previous research concerning the terraces in the areas subject to continental glaciation indicates that issues surrounding their formation, structuree and morphogenetic classification have received little attention to date within the scientific literature. Previous publications typically contain simple descriptions of the geomorphological location of the kame terraces along with descriptions of their morphological characteristics. The Lithuanian scientific literature only addresses the glaciolacustrine kame terraces bordering the distal slope of the glacier marginal formations of the Upper Nemunas (Weichselian) continental glaciation. Identify kame terraces mapping and restore their formation conditions, is very important kame terraces classification, which so far has not. In terms of their morphology and morphometry, kame terraces have much in common with proglacial glaciofluvial terraces. For this reason, the major features of kame terraces determined during the present research work are important not only from the point of view of scientific research but also for geological mapping.

Research Object

Kame terraces identified in different orographic macro-forms were chosen as the research objects. The kame terraces studied formed in the marginal Baltija Uplands and Žemaičiai insular Upland as well as within the ice marginal ridges.

Data Sources

The author of the dissertation data accumulated during field expeditions, through Lithuanian territory geological and geomorphological mapping. The author also made use of published literary sources and data stored within the Geological Database of the Lithuanian Geological Survey.

Main objective

The main objective of the present research was to investigate the spatial distribution, morphology, architecture, origin and location of kame terraces in the Upper Nemunas glaciation area.

Main tasks

- Analysis of morphology and structure of kame terraces.
- Reconstruction of the sedimentary environments associated with the deposition of the kame terraces.
- Examination of the variations in the particle-size characteristics of the sediments and deposits of kame terraces as exposed in horizontal and vertical sections.
- Reconstruction of the conditions under which the formation of kame terraces took place with particular reference to ice margin dynamics.
- Morphogenetic classification of kame terraces.

Novelty of Research

- The morphological and morphometric characteristics of the surface of kame terraces are described in detail for the first time.
- The data about the structure of terraces were collected and synthesised.
- The granulometric composition of the glaciolacustrine deposits composing the kame terraces was analysed in detail for the first time.
- The morphological differences between glaciofluvial and glaciolacustrine terraces was determined.
- Defined kame terraces formation mechanism during the Late Nemunas glaciation.
- The spatial distribution of kame terraces was clarified.

● The dissertation suggests the first morphogenetic classification of kame terraces in the territory of Lithuania.

Vantage points

● Kame terraces represent distinctive forms of glacial relief associated with ice-marginal formations.

● Kame terraces were deposited in supraglacial and terminoglacial sub-environments.

● The variability of terrace morphology, morphometry and structure of terraces as well as the structure and texture of composing deposits were predetermined by variability of sedimentary conditions.

● Variability in the glaciofluvial and glaciolacustrine conditions associated with the deposition of the kame terraces was determined by the location of a glacier and the margins of isolated ice blocks in respect to forms of relief as well as by glacier meltwater flow dynamics.

Practical Importance

The conducted research is of fundamental importance since the morphogenesis, architecture and palaeogeographical conditions of formation of different types of kames terraces, created by the decaying Upper Nemunas (Weichselian) glacier, can be used to clarify the formation of similar forms in other regions. The research also has practical value as the sediments and deposits composing kame terraces represent promising targets for the prospecting and exploitation of valuable minerals (gravel, clay, etc.). The obtained results can also be used for the reconstruction of palaeogeographical and palaeoglaciological conditions and can also be applied to territorial planning.

Approbation of the Obtained Results

The results were reported in 2 articles published in scientific periodicals included in the database with cited references (WEB of Knowledge Thomson Reuters) and 6 other refereed scientific papers. The obtained results also were reported at 8 international scientific conferences and field symposia and their associated published proceedings.

Extent and Structure

The present doctoral dissertation is composed of an Introduction, 5 sections, Conclusions, List of References, and List of Author's Publications. The dissertation is comprised of 167 pages including 88 illustrations and one table. The List of References has 173 entries.

Acknowledgments

The author is sincerely grateful to all who directly or otherwise helped to prepare the dissertation. The greatest thanks go to scientific supervisor Prof. Dr. Hab. Algimantas Česnulevičius for support and valuable advice. I also wish to express my thanks to Dr. Richard I. Waller for professional English.

1. OVERVIEW OF PREVIOUS INVESTIGATIONS

Initial interest in the kame terraces formed around the margins of glaciers in mountain regions arose at the end of the 19th century. British researcher T. F. Jamieson was the first to attempt to explain the origin of these terraces. He associated their formation with the activity of mountain glaciers (Jamieson, 1874). In 1893, there appeared in the scientific literature descriptions of mountain glacier deposits left by meltwater at the glacier edges. After glacier decay, accumulations of these deposits formed accumulative terraces (Russell, 1893). R. D. Salisbury named the formations of this kind "kame terraces" (Salisbury, 1894). At this time, the kame terraces occurring in areas of mountain glaciers were interpreted as stratified deposits left by meltwater streams flowing between the glacier and the mountain slope (Doll, 1970; Charlesworth, 1928; Klimaszewski, 1960; Szupryczynski, 1963 and others). After the glaciers decayed, these deposits formed accumulative terraces. In their shape and size, the resultant kame terraces do not differ from their initial form (Flint, 1957). The terraces are symmetrically distributed on both sides of valley slope and are slightly inclined in the direction of stream flow. R. F. Flint mentions series of kame terraces acknowledging that they can be positioned one below the other. In these cases, terraces record the changes of streams induced by the thinning glaciers (Flint, 1957). In his later work, the researcher emphasises that kame terraces differ from fluvial terraces in that they are rarer than recent river terraces (Flint, 1971).

The first scientific publications about kame terraces in the areas of continental glaciation appeared in the 60^{th}–70^{th} of the twentieth century. During the Pleistocene glaciations of the European continent, kame terraces formed in the zones of the old Žemaitija (Saalian), Medininkai (Warthian) and the last Nemunas (Weichselian) glaciations. During the last glaciation, terraces formed in the British Isles (Sissons, 1958; McCann, 1961; 1966; Peacock, 1970; 1971; John, 1972; Gray, 1975; Firth, 1984; Thorp, 1986; Gordon, 1993; Gray, 1993; 1995; Brazier *et al.*, 1998; Gray, 1991; Hall, 2002), the Jutland Peninsula and surrounding islands (Schou, 1949; Schwan, Van Loon, 1979; Schwan *et al.*, 1980), and in the territory of Germany (Stephan, Ehlers, 1983). Many studies of kame terraces have been conducted by Polish scientists (Slowański, 1971; Kotowski, Kraiński, 1998a; 1998b; 1998c; Olszewski, 2000; Lisicki, 2001; Gontaszewska, Kraiński, 2007; Falkowska, 2008; 2009). Kame terraces also are found in the northern part of Belarus (Комаровский, 2009; Матвеев, 1988). In the territory of Latvia, terraces are found at the slope bottoms of Vidzeme, Aluksne and Latgala uplands (Аболтыньш, 1971; Мейронс, 1975; Аболтыньш *и др.*, 1976; Страуме, 1979; Daukšans *et al.*, 2011). They have been identified in the northern part of Estonia (Ряхни, 1965; Раукас *и др.*, 1971; Раукас, 1978; Raukas *et al.*, 2010). The kame terraces of Valdai Hills are associated with meltwater stream channels (Саммет, 1961; Бискэ, 1963; Баканова *и др.*, 1969; Малаховский *и др.*, 1969; Фаустова, Чеботарева, 1969; Чеботарева, Фаустова, 1969; Баканова, Малаховский, 1972; Фаустова, 1972; Чеботарева, 1972; Знаменская, 1978; Малаховский, 1979).

Studies of kame terraces in Lithuania. In Lithuania, investigations of kame terraces are scant. The earliest information was obtained during the Lithuanian geological survey undertaken at a scale 1:200 000. Collection of data for the first geological survey in the Alytus region was focused on clay deposits (Pakuckas, 1940). The Viečiūnai clay composing a kame terrace was described as suitable for production of bricks. The origin and age of the clay deposit were not determined. The author confined himself to a practical interpretation of the clay. In the Inventory of Mineral Resources of the Lithuanian SSR, the known mineral resources were ascribed to genetic types and subtypes. A sub-type of kame terraces was distinguished to which the Alaušas clay deposit was ascribed (Vonsavičius, 1959).

During the exploration of the sediments of the Mūša proglacial glaciolacustrine basin, it was observed that the deposited material occurred on two – upper and lower – levels (Mikaila, 1962). The deposits of Linkuva kame terrace were interpreted as having accumulated on the upper level of the Mūša proglacial basin.

During the investigation of the clay deposits in the south-eastern part of Lithuania, some of them were ascribed to kame-terrace sub-type (Mikaila, 1966). In the author's opinion, the Žūklijai clay deposit situated on the second terrace of the Vilkokšnis Lake belongs to the kame-terrace sub-type. He points out that the clay of this sub-type is thick and distinctively striped. The thickness of the exploitable layer often reaches 10 m.

The article about the Viečiūnai kame terrace (north-west of Daugai), found in the Dzūkai Upland in the zone of marginal formations of Baltija glacier, was the first scientific publication (Гайгалас *и др*., 1978).

A genetic classification of glaciofluvial deposits appeared in 1984 (Юргайтис, 1984). In this classification, the meltwater deposits of kame terraces are assigned to a separate genetic type. It was pointed out that the deposits of kame terraces are less widespread than the deposits of glaciofluvial terraces.

Based on lithological investigations of glacial deposits in Lithuania, their genetic classification was developed where kame terrace deposits were included in the genetic group of glaciofluvial deposits (Юргайтис, 1984; Jurgaitis, Juozapavičius, 1989; Гайгалас, Ярцев, 1992; Šinkūnas, Jurgaitis, 1998).

More explicit data about glaciolacustrine kame terraces identified along the North Lithuanian, Middle Lithuanian and Pajūris marginal ridges were published in a scientific article (*Bitinas et al*., 2004). The article was devoted to the structure of the terraces and a reconstruction of conditions responsible for their formation.

This survey of the previous investigations of kame terraces leads to the following conclusions:

1 – The formation of kame terraces in the zone of mountain valley type glaciers has been well researched.

2 – The existing literary sources are mainly restricted to descriptions of the geomorphological setting and morphological features of kame terraces.
3 – More or less explicit investigations of kame terraces formed under the conditions similar to the ones in the territory of Lithuania were carried out in Poland. In Germany, where the Upper Nemunas glacial relief occupies the northern part of the country, very few terraces were identified as kame terraces. On the other hand, the attribution of some forms of relief to kame terraces seems doubtful.
4 – All the described kame terraces are analysed in the context of kame relief.
5 – Kame terraces are often ascribed to other distinct forms of glacial relief, e.g. terraced hills with flat summits.
6 – The dating of terraces using optically stimulated luminescence (OSL) methods has failed to produce reliable ages due to an insufficient number of samples. The obtained dates are consequently scattered over a wide range of ages.
7 – Investigations of the conditions and mechanisms of formation of kame terraces were initiated by Lithuanian researchers at the end of the 20th century.

2. METHODS

An attempt was made to collect possibly the most exhaustive geomorphological and geological material that could serve as a basis for pursuing the main objective of the present dissertation: to investigate the spatial distribution, morphology, structure, origin and dislocation of kame terraces in the Upper Nemunas glaciation area.

The data for the present research has been collected by the author since 2002–2006 within the geological mapping of Quaternary deposits at a scale 1:50 000. Supplementary field works were conducted in 2007–2010. The research is also based on the available Quaternary geomorphological and geological maps at different scales (Геоморфологическая..., 1980; Lietuvos..., 2000; Guobytė, 2002). The cartographic method was chosen as the main research method: decoding of aerophotographs, analysis of topographic and factual material of different years, core samples from boreholes, and geological and geomorphological maps and schemes of Quaternary deposits at a scale 1:10 000 including not only the kame terraces but the surrounding areas as well. The available data allowed a more objective evaluation of the conditions associated with the genesis of the kame terraces.

A total of 23 kame terraces were investigated. Sixteen terraces were investigated more thoroughly. The terraces were chosen with consideration of their prevalence in different orographic areas. The investigated kame terraces formed in the marginal Baltija Uplands and Žemaičiai insular Upland and within the ice-marginal ridges. The Kuktiškės, Rubikiai, Vaitkūnai, Viečiūnai and Alaušas kame terraces of the marginal Baltija Uplands and Kurtuvėnai, Užventis, Skaudviliai, Kaltinėnai and Survilai terraces of the Žemaičiai insular Upland were investigated in detail. The investigated Lapės, Kulautuva, Jonava and Molupiai terraces formed at the Middle Lithuanian marginal ridge. The Linkuva kame terrace occurred along the marginal ridge of North Lithuanian stage and the Margininkai kame terrace near the marginal ridge of the Pajūris stage.

Applied aerophotomethods. Stereoscopic decoding of aerial photographs using the field and borehole data provided the primary basis for investigation of surface geomorphology and geology. The relief in the aerial photographs under the stereoscope was analysed using a stereo model. Therefore, firstly, the relief forms resembling terraces were identified according to the typical forms and sizes characteristic of terraces. The morphological and genetic types of terraces were established based on the field and borehole data. Many geomorphological objects were easily decoded in the stereo model according to the surface location or photon contrast. Black and white aerial photographs at a different scale (1:6 000, 1:10 000, 1:14 000, 1:15 000, 1:17 000, 1:18 000, 1:19 000 1:20 000 and 1:25 000) and from different years (1951, 1952, 1955, 1958, 1964, 1966, 1967, 1969, 1975 and 1998) were decoded. It should be noted that the photographs of different years were of different decodability grades. The aerial photographs of 1952–1958 were the most geologically and geomorphologically informative as until these years, the surface of the territory of Lithuania had been little affected by anthropogenic activity. Using all available factual data, the decoding results were interpreted and a scheme of the distribution of kame terraces was compiled (Fig. 1.).

During associated ***field work***, the kame terraces identified in the aerial photographs were investigated *in situ*, the preliminary maps were controlled, complementary material for completion and geomorphological description of the maps was collected, the textural composition of kame terraces was established and their distribution was specified.

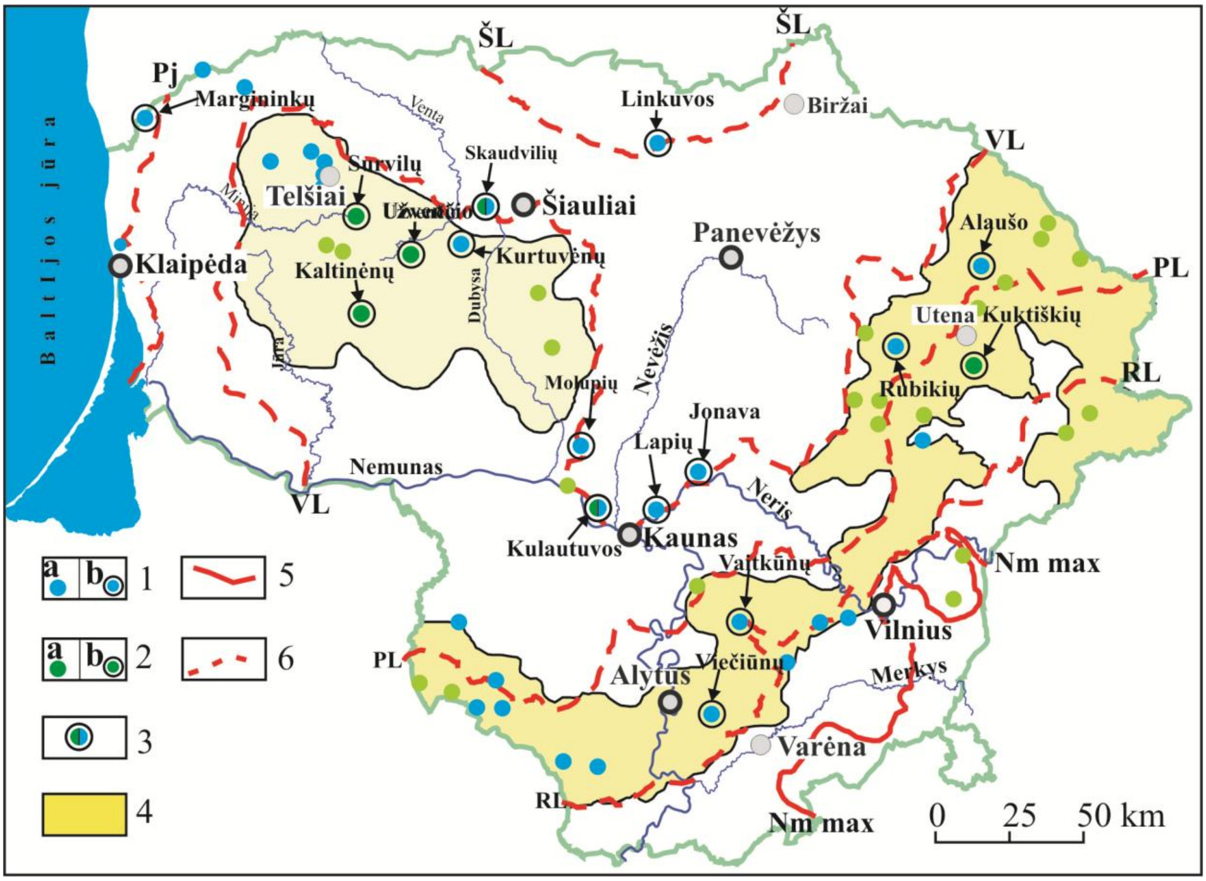


Fig. 1. Distribution scheme of kame terraces:

1 –glaciolacustrine kame terraces (out of scale): a – widespread, b – investigated in detail; 2 – glaciofluvial kame terraces (out of scale): a – widespread, b – investigated in detail; 3 – complex (glacioaquatic) kame terraces (out of scale, investigated in detail); 4 – large elevations of the Last Glacial; 5 – the maximal expansion boundary of the Last Glacial; 6 – the Upper Nemunas (Late Weichselian) marginal morainic ridges: RL – East Lithuanian, PL – South Lithuanian, VL – Middle Lithuanian, ŠL – North Lithuanian. The maximal expansion boundary of the Last Glacial and the marginal morainic ridges of the Last Glacial (according to R. Guobytė).

Field work was conducted on all the kame terraces identified by the decoding of aerial photographs in order to check, specify and supplement the data about geological and geomorphological objects distinguished by decoding. During field work, 1.2 m deep test pits at the observation points were dug out or boreholes were drilled using spiral hand drills. The lithological composition of surface deposits was recorded and the geomorphological setting of the locality described. In total, 800 observation points were described. The spacing of observation points was uneven. In the areas where the contours of geological-geomorphological objects were clearly visible in the aerial photographs the network of observation points was scarcer. In other places, the distribution of observation points was denser. Geomorphological profiles of the forms of relief were described.

In order to determine the structure of the deposits and sediments forming the kame terraces, boreholes of different depths were drilled. The drilling works were carried out in terraces that had no quarries, trenches or outcrops. The core samples were described and samples were taken *in situ*. To determine the texture of clayey deposits of glaciolacustrine terraces, a few boreholes were drilled using vibrodrill. The material of individual observations was supplemented with abundant geological information obtained from analysis of sections of boreholes drilled in kame terraces.

Investigation of outcrops and quarries. During the field work, 6 quarries and 58 test pits were investigated in detail (described, photographed, measured and sampled). The outcrop deposits and sediments were defined according to their structural and textural features: lithology, type of stratification, and orientation of composing micro-layers.

Investigation of granulometric composition. Samples for granulometric analysis were taken from borehole, quarries and outcrops. Sampling was performed taking into account the structure and texture of deposits and sediments and thickness of layers. The total of collected samples amounted to 230. Using screens and the pipette method, 13 fractions were distinguished: >10, 10–5, 5–2, 2–1, 1–0.5, 0.5–0.25, 0.25–0.1, 0.1–0.05, 0.05–0.01, 0.01–0.005, 0.005–0.002, 0.002–0.001, <0.001 mm. Granulometric analysis was performed by the Lithuanian Geological Survey and laboratories of the Institute of Geology and Geography of NRC. The deposits and sediments were grouped using Last's classification (Last, 2001). The obtained results allowed precise determination of the lithology of analysed deposits and sediments.

Analysis of geochemical composition. To allow comparisons of geochemical composition, samples of clays were taken from the kame terrace and glaciolacustrine basins that used to be at the base of the terrace. 172 clay samples were taken from the two boreholes in the Linkuva glaciolacustrine kame terrace and 89 clay samples were taken from the two boreholes in the Mūša glaciolacustrine basin. They were used for analysis of geochemical composition of deposits. The total amounts of aluminium and 22 trace elements – Ag, B, Ba, Co, Cr, Cu, Ga, La, Li, Mn, Mo, Nb, Ni, P, Pb, Sc, Sn, Sr, Ti, V, Yb, and Zn – in the samples were determined at the laboratory of the Institute of Geology and Geography of NRC using atomic emission spectrophotometric analysis (AOES) (spectrometer DFS-13). The same method was used to determine the concentrations of Al, Zr and Y. The total amount of Rb was determined by the method of fluorescent analysis (x-ray spectrometer ARF-6). Also the total amounts of other trace elements – Fe, Ca and Mg – were determined. To facilitate comparisons of the geochemical composition of clay samples from the kame terrace and glaciolacustrine basin, a dendrogram of cluster analysis was compiled. For this purpose the Ward method was applied calculating the Euclidean distances between samples according to standardised concentrations of 23 chemical elements (Al, Ag, B, Ba, Co, Cr, Cu, Ga, La, Li, Mn, Mo, Nb, Ni, P, Pb, Sc, Sn, Sr, Ti, V, Yb, and Zn) that were identified in the samples.

Morphological profiles. Large-scale (1:10 000) maps and instrumental measurements were used to construct morphological profiles of the kame terraces. The profile lines were chosen so as to strike across the investigated forms of relief at an angle close to the perpendicular. The morphological profiles across the kame terraces clearly showed the specific morphographic and morphometric features of both individual terraces and the broader complex in which they occurred. The profiles revealed the character of relief elements: slope shape, length, and symmetry or asymmetry. This allowed the determination of the ratio between the surfaces of positive and negative forms of terrace relief. The latter is very important as according to the negative elements of kame terrace relief it is possible to determine the causes that predetermined their morphology and size.

Analysis of hypsometric location of kame terraces. General analysis of the hypsometric location of morphological profile and evaluation of its separate elements revealed the distribution sequence of the forms of terrace relief. The general character – lowering, elevating or on the same level – of morphological profile also contains certain genetic information.

Analysis of morphological profiles of kame terraces supplied data about the variety of distribution sequence of elongated mesoforms. Morphological analysis of the distribution sequence supplied geomorphological information about the boundary between the kame terrace and adjacent reliefs.

Analysis of spatial model of the surface. For orographic information, scanning LiDAR of the earth surface has recently been carried out. This comparatively new technology for the collection of topographic data has enabled the high resolution modelling of earth surface features. It helps to obtain explicit three-dimensional point information about the distribution of the forms of the earth surface. Analysis of the spatial model of the surface based on the laser scanning data clearly reveals the location of kame terraces. Analysis of the spatial model of the surface was applied to all terraces investigated in detail.

3. RECENT RELIEF OF KAME TERRACES IN LITHUANIA, THEIR STRUCTURE AND MATERIAL COMPOSITION

Kame terraces occurring in the Late Nemunas glaciation area of Lithuania's territory are characterised by their diversity of morphology, genesis and architecture. The internal architecture of terraces was directly affected by factors associated with their formation. According to whether the terrace deposits or sediments accumulated in still or flowing meltwater, glaciofluvial and glaciolacustrine kame terraces can be distinguished. A combination of still water conditions and flowing streams during terrace formation generated complex (glacioaquatic) kame terraces. Below the most widespread of Late Nemunas glaciation area at different types of kame terraces description.

3.1. Glaciolacustrine kame terraces

There is a glaciolacustrine kame terrace on the distal slope of the North Lithuanian ice marginal ridge. This terrace is located on the distal slope of the central part of the North Lithuanian ice marginal ridge in the Judiškiai–Megučioniai–Linkuva–Vienžindžiai area (Fig 2.).

Kame terrace is 22 km long and 0.5–1.0 km wide. In earlier studies, the clay occurring in the kame terrace was treated as sediment formed in the upper northern part of the Mūša glaciolacustrine basin (Gudelis, Mikaila 1960). Its surface is slightly inclined southward and reaches up to 65–70 m a.s.l. The northern edge of the terrace is bound by the marginal ridge, which rises to more than 80 m a.s.l.

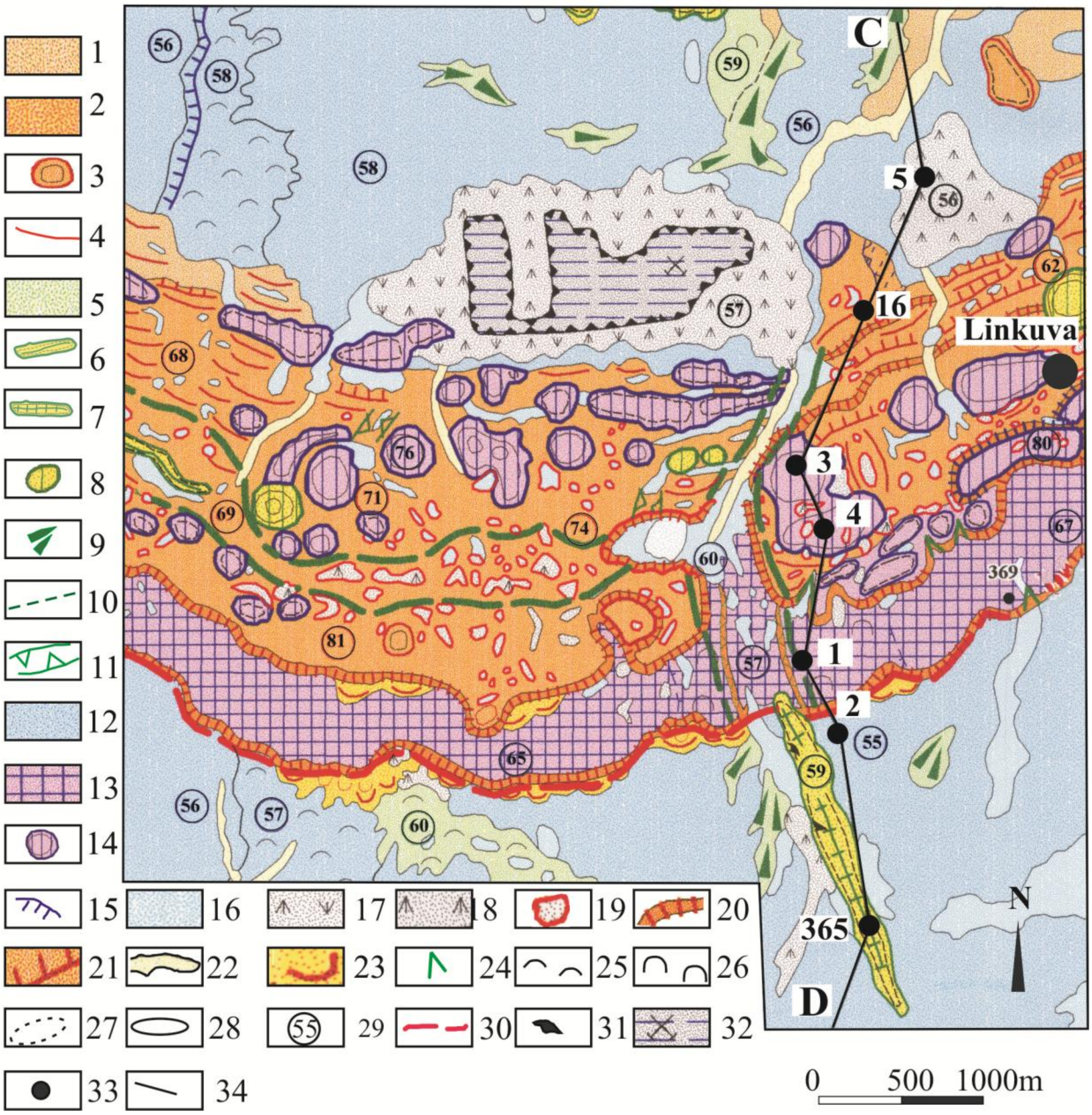


Fig. 2. Detailed geomorphological map of North Lithuanian ice marginal ridge fragment in the vicinity of Linkuva:

1 – till plain; 2 – ice marginal formations; 3 – morainic hill; 4 – morainic ramparts; 5 – outwash plain; 6 – crevasse fillings forms; 7 – esker; 8 – glaciofluvial kame; 9 – glaciofluvial delta; 10 – meltwater drainage channel; 11 – flow meltwater channel; 12 – glaciolacustrine plain; 13 – glaciolacustrine kame terrace; 14 – glaciolacustrine kame; 15 – levels of glaciolacustrine plain; 16 – lacustrine plain; 17 – combined type moor plain; 18 – low moor plain; 19 – glaciokarst kettle; 20 – steep slope; 21 – accumulative levels of glacigenic landforms; 22 – floodplain river valley; 23 – solifluction sheet; 24 – gully; 25 – slightly undulating plain (up to 1–2 m); 26 – undulating plain (up to 2–3 m); 27 – very low hill (up to 1–3 m); 28 – low hill (up to 3–5 m); 29 – prevailing altitude of land surface, in metres; 30 – limit of North Lithuanian phase; 31 – gravel pit; 32 – abandoned quarry; 33 – borehole site and its number; 34 – line of the profile (see Fig. 4).

The surface of the kame terrace is 10–15 m above the glaciolacustrine plain of the ice-dammed lake that is located south of the terrace (Fig. 3.).

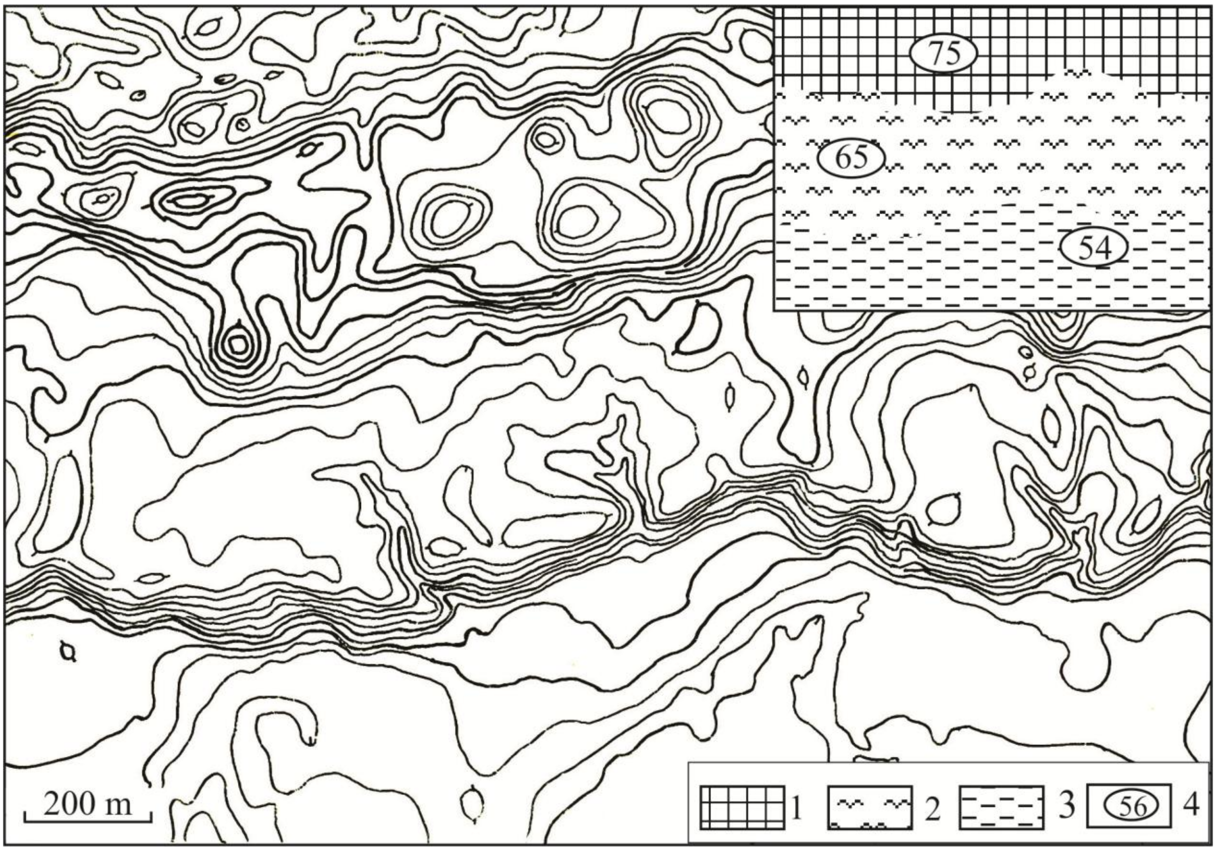


Fig. 3. Surface of kame terrace at Linkuva. Isohypses are drawn every 1.0 m: 1 – ice marginal formations; 2 – glaciolacustrine kame terrace; 3 – glaciolacustrine plain; 4 – prevailing altitude of land surface, in metres.

Gullies intersect the slope of the kame terrace. In general, the kame terrace consists of glaciolacustrine sediments with a maximum thickness of 15.2 m (Fig. 4.). These sediments comprise brown clay (or silty clay) with a generally massive structure, although in some places it contains small lenses (up to 1–2 cm thick) of fine-grained sand.

The rhythmic structure of the clayey sediments was determined in only a few places. Clay particles (fraction <0.005 mm) compose about 70–75% of sediments. The remaining sandy fraction amounts to 10% of sediments. The content of gravel and calcareous concretions (up to 10 mm in diameter) in clay is up to 3–5%. The massive clay of this lithofacies is a result of suspension settling.

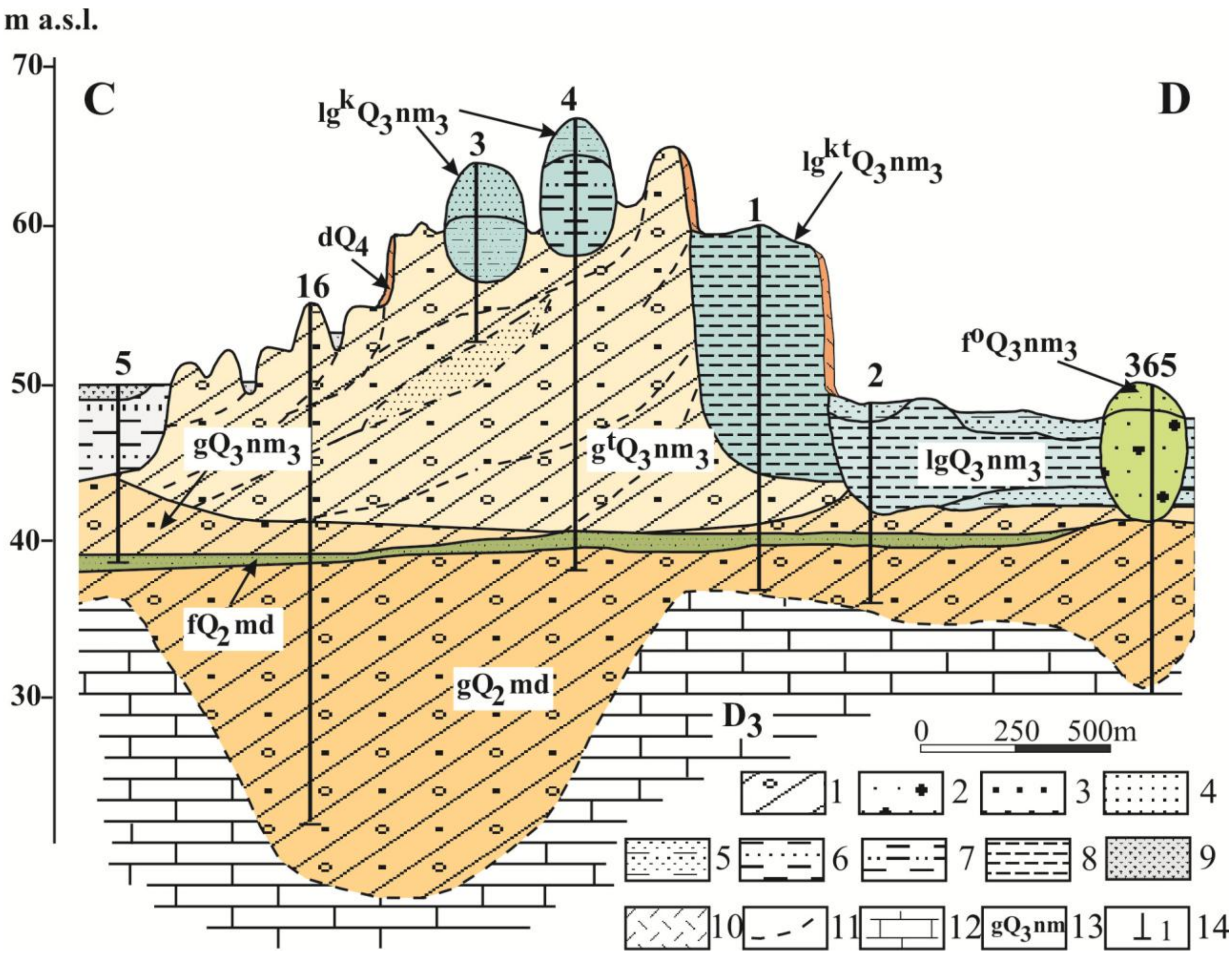


Fig. 4. Geological structure of the North Lithuanian ice marginal ridge in the vicinities of Linkuva:

1 – till; 2 – sand with gravel and cobble; 3 – various sand; 4 – fine-grained sand; 5 – silty sand; 6 – sandy silt; 7 – sandy silty clay; 8 – clay; 9 – peat; 10 – clayey sand with gravel; 11 – shear planes; 12 – dolostone (D_3); 13 – genetic and stratigraphic index of deposits: *Middle Pleistocene Žeimena formation Medininkai sub-formation*: gQ_2md – till; fQ_2md – glaciofluvial; *Upper Pleistocene Upper Nemunas formation*: gQ_3nm_3 – lodgement till; $g^tQ_3nm_3$ – deformation till; $lg^{kt}Q_3nm_3$ – glaciolacustrine kame terrace; $f^kQ_3nm_3$ – glaciofluvial kame; $f^oQ_3nm_3$ – glaciofluvial esker; lgQ_3nm_3 – glaciolacustrine; lQ_4 – lacustrine sediments; dQ_4 – deluvium; 14 – borehole site and its number. For location of the geological cross–section line see Fig. 2.

The homogeneous character indicates that clay particles could settle equally all over the lake. It should be emphasized here that the massive clay is unusually thick when related to the dimensions of the lake. Such thick massive clayey sediments are well known from glaciomarine deposits, where they are formed by prolonged settling of large amounts of fine-grained suspended sediments (Miall 1983).

3.2. Glaciofluvial kame terraces

The Upper Nemunas glaciofluvial kame terraces in the territory of Lithuania occur at the slopes of elevations formed at different stages of deglaciation and terraces within lake basins in elevated areas.

The Užventis terrace at the slope bottom of Middle Žemaičiai Uplands is ascribed to this type of glaciofluvial terrace (Fig. 5.).

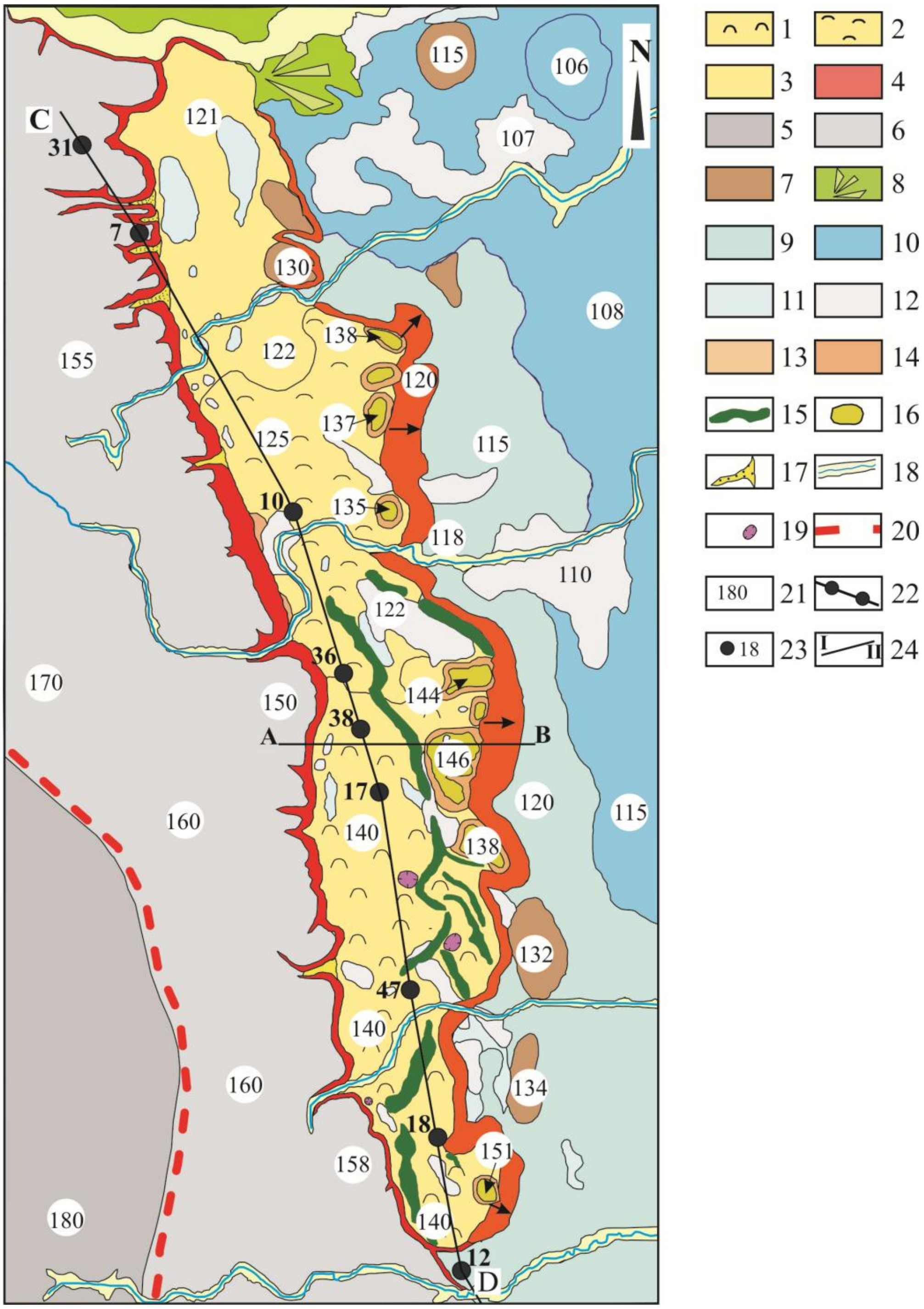


Fig. 5. Glaciomorphological scheme of the Užventis kame terrace:

1–3 – surface levels of kame terrace: 1 – high, 2 – medium, 3 – low; 4 – slope: a – of the elevation, b – of ice margin; 5 – ice marginal formations of the East Lithuanian phase; 6 – ice marginal formations of the South Lithuanian phase; 7 – fragments of lodgement till plain; 8 – delta; 9 – high level of glaciolacustrine plain surface; 10 – low level of glaciolacustrine plain surface; 11 – lacustrine plain; 12 – bog plain; 13 – kame slope; 14 – solifluction cover; 15 – esker; 16 – kame; 17 – alluvial fan; 18 – flood plain; 19 – glaciokarst pit; 20 – boundary of South Lithuanian Baltija phase; 21 – prevailing altitude of land surface, in metres; 22 – line of the profile; 23 – borehole site and its number; 24 – relief profile.

An elongated kame terrace extends in an almost meridian direction from Užventis across Želviai, Naikmiškė and Junkilai till Gedvilai. The terrace is 8 km long; its average width is 1.2 km. The surface of the Užventis kame terrace loops in a northerly direction ranging in altitude from 121 m up to 140 m. The terrace is separated from the adjacent uplands by a 10–15 m high straight slope (Fig. 6.).

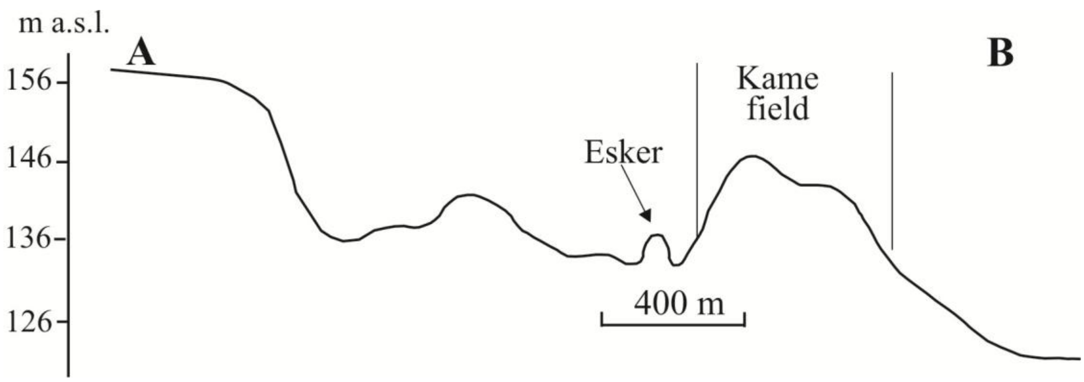


Fig. 6. Cross profiles of the Užventis kame terrace. Location of profiles A–B are shown in Fig. 5. and Fig. 7.

Junction canals and hollows extend along the terrace slope. Most of them are boggy. The slope is dissected by numerous ravines and gullies. The kame terrace is separated from the lower glaciolacustrine plain by an ice-marginal slope. The contour line of the slope is uneven and serrated. The slope of the terrace was abraded by glaciolacustrine basin waters. The terrace relief is complex in character due to the negative and positive forms of relief that includes numerous eskers and kames. A chain of eight kames occurs at the terrace step between Želviai and Junkilai.

Chains of eskers extend from the middle of the terrace (Gedruikiai) to its southern edge. The kames are typically 6–8 m in height although they do reach up to 12 m. They vary in width from 200 m to 350 m and are typically around 500 m in length. Their slopes are steep.

The esker crests display meandering plan forms. The crest line is uneven and undulating. The eskers are typically 3–5 m in height although some reach up to 10 m in height. The average length of the eskers is 500 m; the shorter eskers are 300 m long whereas the longer ones extend for up to 1.5 km. The width at the slope bottom varies from 30–50 m to 100 m. The esker deposits dip towards the deposits of the kame terraces. Eskers of this type are called “eskers with roots”.

Glaciokarst depressions and pits occur on the terrace surface. The hollows are large – up to 800 m in length and 100–200 in width – and extend along the terrace surface. The pits are funnel shaped, concentric and display steep sides. They are 50 m in diameter and up to 7 m deep.

According to morphographic and morphometric analyses, three types of relief were distinguished in the kame terraces: flat, slightly undulating and undulating plains. The undulating plain relief is dominant. Three terrace levels were distinguished: low, medium and high. Their surfaces are characterised by different types of relief (Fig. 7.).

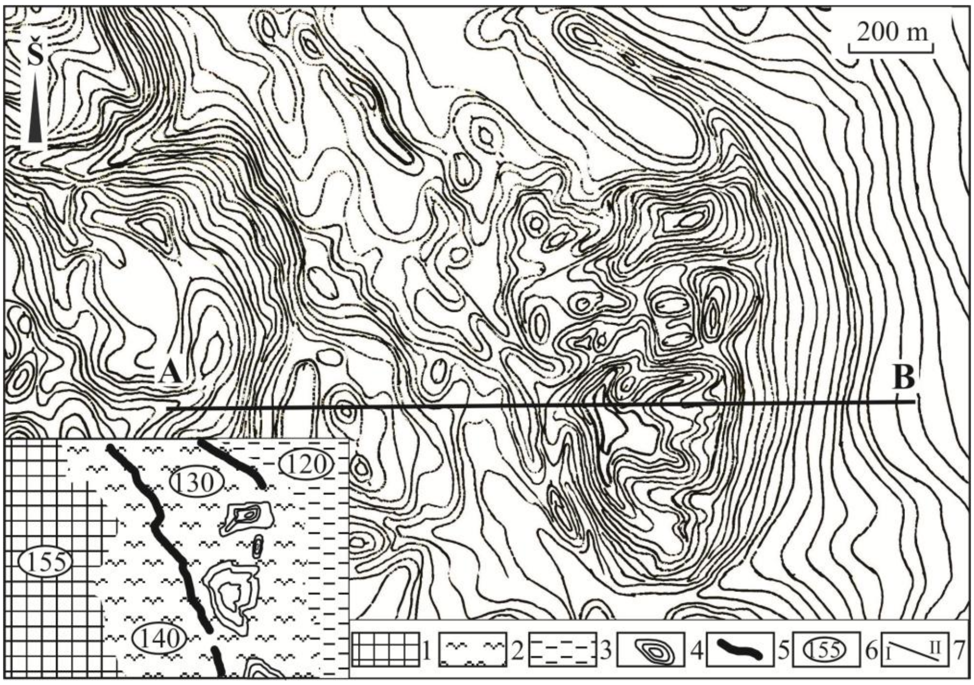


Fig. 7. The surface of high-level kame terraces. Isohypses are drawn every 1.0 m. A–B – the cross section of the terrace relief is shown in Fig. 6. The location of the profile is shown in Fig. 5.

1 – Middle Žemaičiai hill terrain; 2 – kame terrace; 3 – glaciolacustrine plain; 4 – kame; 5 – esker; 6 – prevailing altitude of land surface, in metres; 7 – location of the relief profile.

The Užventis kame terrace borders the eastern slope of Middle Žemaičiai hill terrain. It is classified as a glaciofluvial kame terrace formed by glacial meltwater streams. The meltwater streams fell into an 8 km long and 1.2 km wide depression south of Užventis and infilled it with glaciofluvial deposits. The average thickness of glaciofluvial deposits of the Užventis kame terrace is 20–22 m. The maximal thickness is 38.2 m, the minimal thickness is 7.5 m. The thickest deposits accumulated along the slope bottom (Fig. 8.).

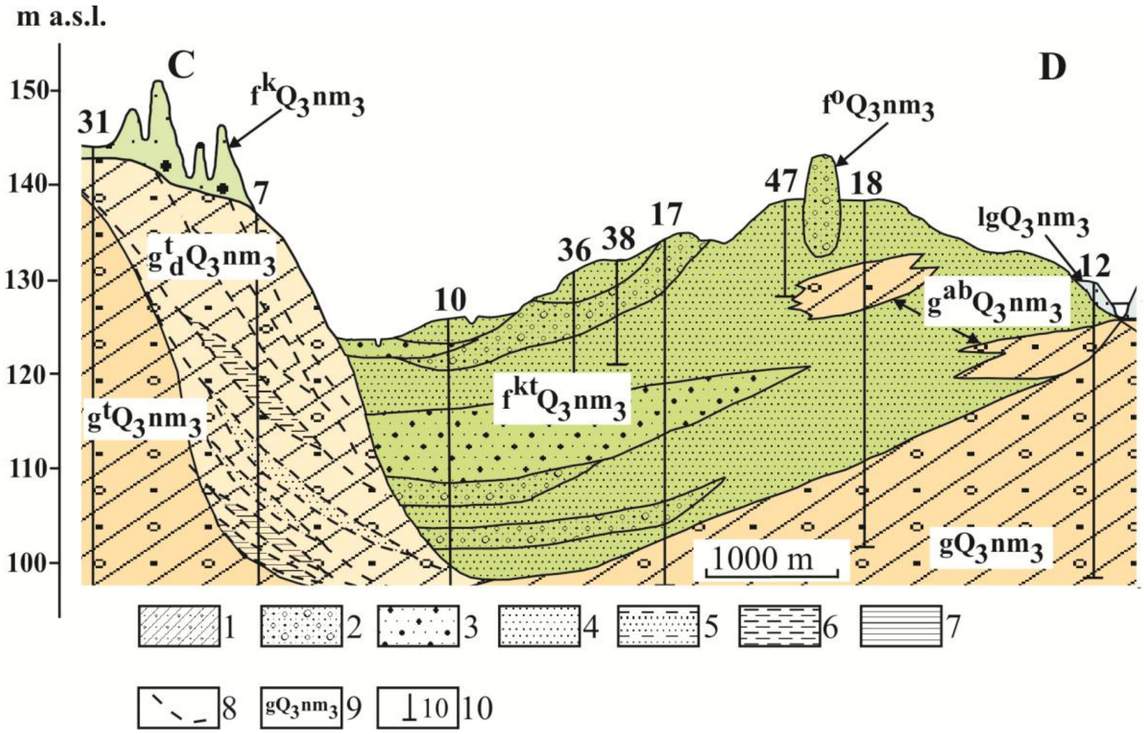


Fig. 8. Profile and deposits along the Užventis kame terrace. The location of the profile is shown in Fig. 5.:

1 – till; 2 – gravel and sand; 3 – various sand; 4 – fine-grained sand; 5 – silty sand; 6 – silt; 7 – clay; 8 – shear planes; 9 – genetic and stratigraphic index of deposits: *Upper Pleistocene Upper Nemunas formation*: glacial deposits: gQ_3nm_3 – lodgement till; $g^t_dQ_3nm_3$ – deformation till; $g^tQ_3nm_3$ – deposits of ice marginal formations; $g^{ab}Q_3nm_3$ – ablation till; glaciofluvial deposits: $f^0Q_3nm_3$ – esker; $f^kQ_3nm_3$ – kame; $f^{kt}Q_3nm_3$ – kame terraces; lgQ_3nm_3 – glaciolacustrine sediments; 10 – borehole site and its number.

Fine-grained sand occurs on the terrace surface between its middle part and the edge (from Užventis till Želviai). Gravely sand is dominant between Želviai and the southern periphery of the terrace. As glaciofluvial sediments were transported into the depression from all sides, the lithological composition of the deposits is varied, comprising gravel-sand deposits, various sand, and fine-grained sand. These lithological varieties often are silty and sometimes clay-rich. The vertical distribution of deposits shows no regular pattern. In some places fine-grained silty sand occurs in the upper part of the layer whereas gravelly-sand or various sand occurs in the lower. In other places, fine-grained silty sand occurs in the lower or middle parts of the layer. The portion of gravel in gravely-sand deposits accounts for 41 % of the total. In the sections of the southern part of the terrace, the sequence contains intercalated layers of ablation till up to 5 m thick.

The terrace deposits overlie grey compact till with gravel – 7–10%.

The 10 m high kame is composed of gravel and gravely-sand deposits with gravel fraction (5–70 mm) accounting for 35% (dominant fraction 10–20 cm).

Eskers meandering on the kame surface have "roots". The sections of esker deposits usually are distinguished for alternation of various sand and gravely-sand and slanting stratification.

3.3 Complex (glacioaquatic) kame terraces

Kame terraces of this type are found at the slopes of elevations formed at different stages of deglaciation, along the distal slope of marginal ridges, in glacier crevices, melting and other cavities and by the slopes of tunnel-valleys.

At the slopes of the tunnel-valley that occurred on the ice margins, sediment accumulated that after deglaciation was deposited on the land surface as kame terraces. The **Skaudviliai kame terrace** located in the Kurtuvėnai hill terrain along the Venta–Dubysa tunnel-valley belongs to this type of terrace. The northern part of the Kurtuvėnai massif is traversed by a tunnel-valley connecting the Venta and Dubysa rivers. In one of the publications (Нечипоренко, 1989) devoted to the distribution of palaeoincisions and tunnel-valleys, which are an analogue of recent palaeoincisions, the author emphasises their close correlation with tectonic, in particular neotectonically active faults. The depth of the Venta–Dubysa tunnel-valley is 50 m, the length 15 km and the width 1.5 km. It is wider in its peripheral parts: in the eastern part it is 2.5 km wide and in the western part it widens to 4 km. In the eastern part, the tunnel-valley terminates with a small outwash fan. The available data show that the bottom of the tunnel-valley is filled with a 20 m thick layer of sandy deposits composed of interstratified layers of fine-grained, medium-grained and various sands (two 24 m deep boreholes were drilled in the tunnel-valley). A basal layer of gravel and pebbles in the tunnel-valley bottom overlies till deposits. In the Holocene, a 1–2 m thick layer of lacustrine sediments accumulated on top of glaciofluvial deposits (filling the tunnel-valley) and there were subsequently buried by biogenic deposits – peat. In some places, the thickness of the peat layer exceeds 4 m. Based on the available data and bearing in mind that palaeoincisions and tunnel-valleys in the recent surface reoccur in the same places, it can be assumed that the real depth of the complex may even reach 100 m. The Skaudviliai kame terrace formed at the slope of Venta–Dubysa tunnel-valley (Fig. 9.).

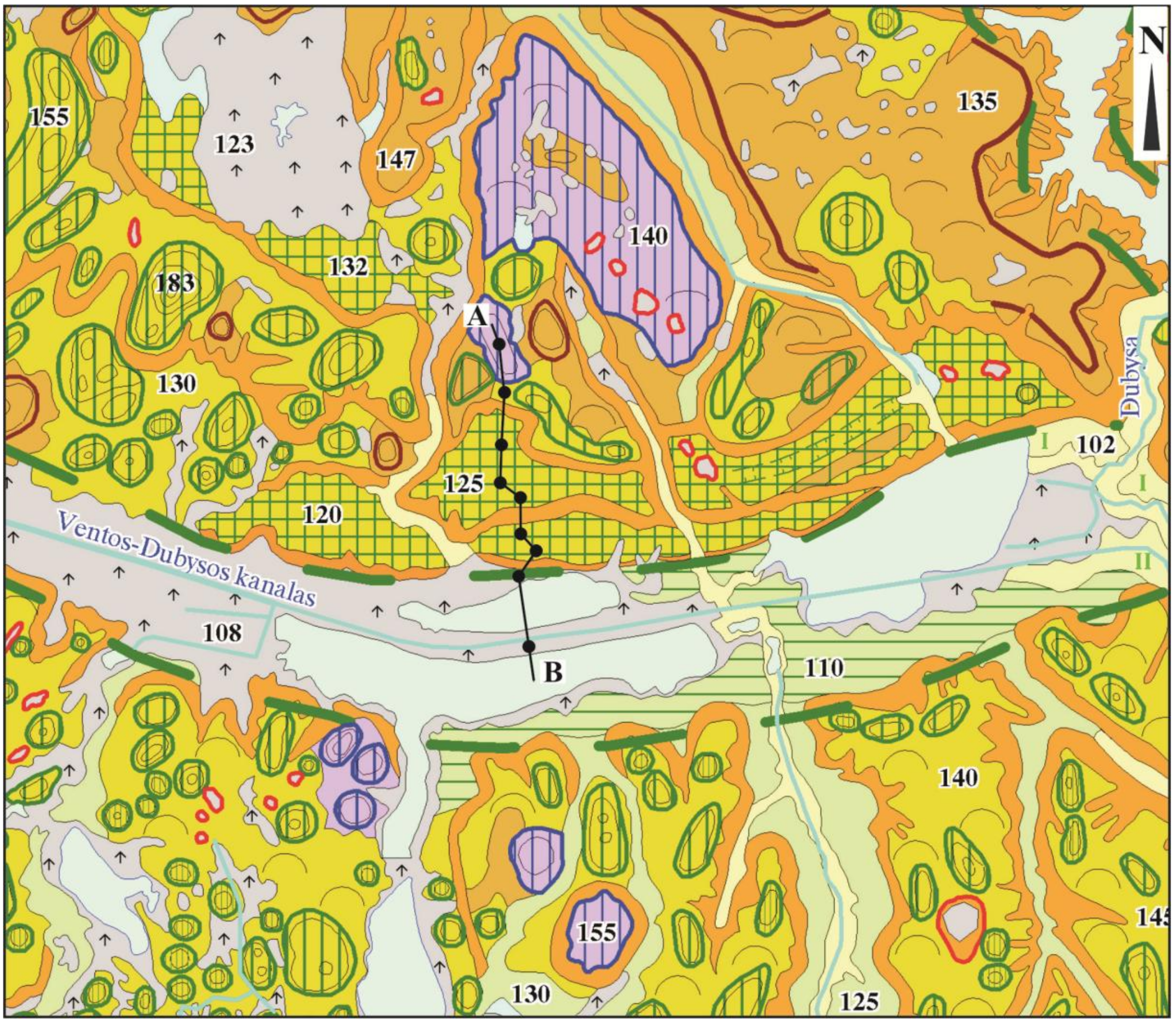
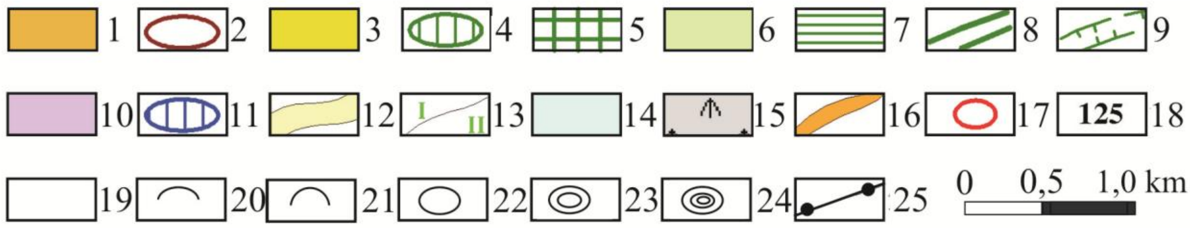


Fig. 9. Geomorphological map of the surrounding area of Skaudviliai kame terrace. Arbitrary signs and symbols see next page.



1 – ice margin relief; 2 – morainic hill; 3 – glaciofluvial intraglacial relief; 4 – kame; 5 – kame terrace; 6 – glaciofluvial plain; 7 – glaciofluvial terrace; 8 – tunnel-valley; 9 – relict stream channel; 10 – glaciolacustrine intraglacial relief; 11 – kame; 12 – flood plain; 13 – fluvial terraces above flood plain I and II; 14 – lacustrine plain; 15 – bog plain; 16 – slope; 17 – glaciokarst pit; 18 – prevailing altitude of land surface, in metres; 19 – flat plain (alternations of altitudes is within 1 m); 20 – slightly undulating plain (1–2 m); 21 – undulating plain (2–3 m); 22 – low hill (altitude 3–5 m); 23 – medium hill (5–10 m); 24 – high hill (10–20 m); 25 – line of the profile.

From east to west, the terrace is 5.5 km long. As a 0.5 km wide bench it extends from Girnikai through Rimučiai, Skaudviliai and Gervėnai to the Upper Dubysa. The terrace has two steps: the absolute altitude of the upper step is 125 m and the absolute altitude of the lower step 120 m. The steps are separated by a 4 m high well-developed and steep scarp. The Kurtuvėnai hill massif north of the terrace rises 10–15 m and in its western part 20–25 m above the terrace. The dominant absolute altitude of this part of Kurtuvėnai massif is 135–140 m. Some hills, such as Girnikai Mount, rise to 183 m. The kame terrace is separated from the Kurtuvėnai massif by a well-developed slope. The terrace is slopes slightly down to the Venta–Dubysa tunnel-valley. It is 10 m above the recent tunnel-valley surface. The slope between the terrace and the tunnel-valley is well developed and is in places partitioned by tributaries.

The tributary valleys partition the terrace surface from north to south. A 3–4 m deep glaciofluvial channel on the upper step of the terrace extends along the terrace from Gervėnai till Skaudviliai. Glaciokarst pits are rare on the terrace surface. Where they do occur they are 50–80 m wide, 2–4 m deep and filled with peat. The surface in the western part of the upper step of kame terrace is smooth; elsewhere it is undulating and in the lower step of the terrace it is slightly undulating. In the Gervėnai area there is a 10 m high and 70 m wide kame at the bottom of the terrace slope. The presence of these forms allows the identification of this terrace as a kame terrace rather than a glaciofluvial terrace.

The internal structure of the terrace is known from the Skaudviliai and Gervėnai gravel quarries, which demonstrate the variable sedimentology of the complex (glacioaquatic) kame terrace. In the lower part of the terrace, i.e. at the terrace bottom, there is a 4–6 m thick layer of glaciofluvial deposits. It is represented by sand with gravel or clayey various sand with gravel (2–60 mm up to 5%). The dominant gravel particles are 5–10 mm in diameter. In places, the deposits contain lenses of greyish brown silty sand up to 50 cm thick. The clayey deposits imply that the source was not far away and the meltwater streams did not have enough time to sort the material (Fig. 10.).

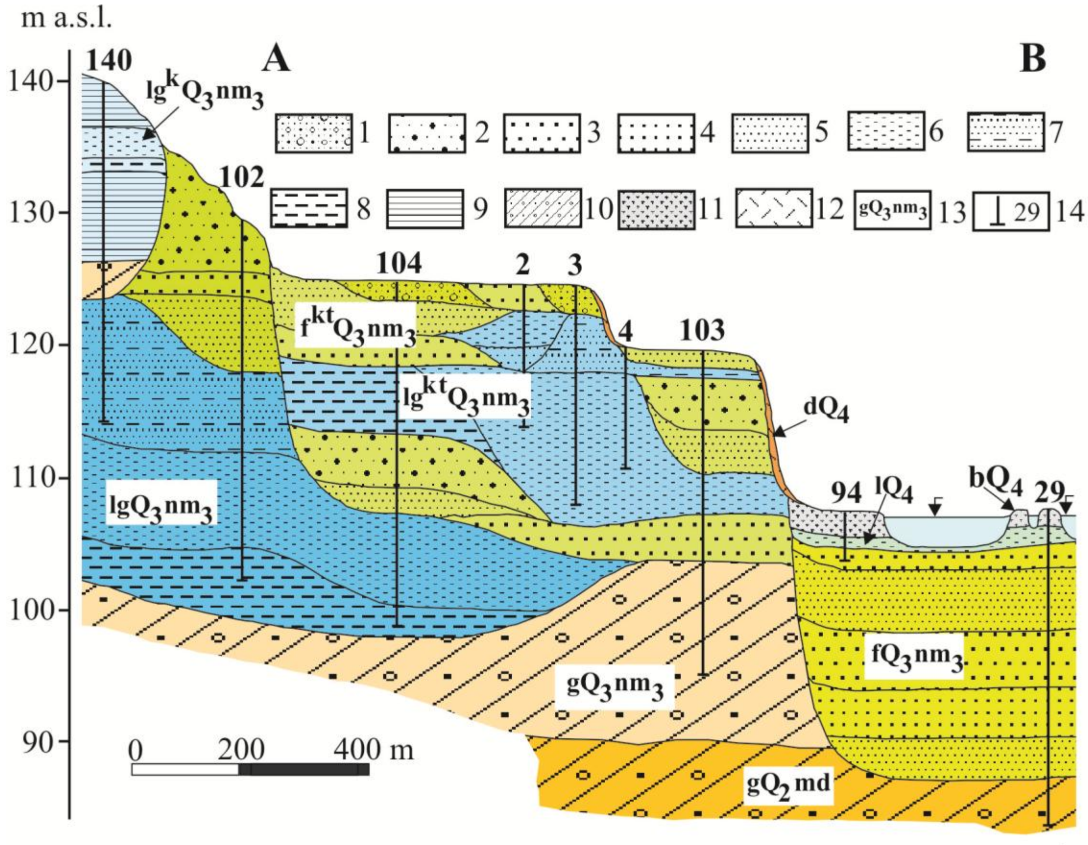


Fig. 10. Cross profile and deposits of Skaudviliai kame terrace. Profile site is shown in Fig. 9.:

1 – gravely sand; 2 – sand with gravel; 3 – various sand; 4 – medium-grained sand; 5 – fine-grained sand; 6 – very fine-grained sand; 7 – silty sand; 8 – silt; 9 – clay; 10 – till; 11 – peat; 12 – clayey sand with gravel; 13 – genetic and stratigraphic index of deposits: *Middle Pleistocene Žeimena formation Medininkai sub-formation*: gQ_2md – till; *Upper Pleistocene Upper Nemunas formation*: gQ_3nm_3 – lodgement till; glaciofluvial deposits: $f^{kt}Q_3nm_3$ – kame terraces; fQ_3nm_3 – proglacial; glaciolacustrine sediments: $lg^kQ_3nm_3$ – kames; $lg^{kt}Q_3nm_3$ – kame terraces; lgQ_3nm_3 – proglacial basins; *Holocene*: lQ_4 – lacustrine sediments; bQ_4 – biogenic deposits; dQ_4 – deluvial formations; 14 – borehole site and its number.

Deposition by meltwater streams was interrupted by basin-wide sedimentation what accounts for the presence of glaciolacustrine sediments in the middle part of the kame terrace section.

The thickness of the sediment layer is 3–5 m and occasionally up to 10 m. They are composed mainly of very fine-grained sand and more rarely of brownish yellowish compact silt. Often sandy sediments include isolated gravel particles 2–6 mm in diameter. In places gravel particles 2–10 mm in diameter account for up to 3%. This is an indication that sedimentation conditions were not always calm. During seasonal warming, glacier meltwater streams transported coarser particles into the basin.

The upper part of the terrace deposits is associated with deposition from glacial meltwater streams. It is constituted of a 2–6 m or, on the lower step, a 10 m thick layer of fine-grained sand with gravel (up to 5–7%) or gravely sand.

Outcrops of gravely and various sand occur on the surface of the upper layer of the terrace. The surface of the lower step is dominated by various and fine-grained sand and, in some places by gravely sand. The gravely deposits are concentrated in the middle part of the upper and lower steps of kame terrace. The 5 m high wall of the test pit in the lower step of kame terrace in the Rimučiai area exposes 54% of gravel fraction (5–70 mm) at a depth of 0.2–1.7 m. Close to the very base of the wall (up to a depth of 4.8 m), the content of gravel decreases to 23% and the 5–10 mm fraction is dominant. At depths of 2.4–2.7 and 3.4–3.9 m the gravel fraction (up to 20 mm in diameter) accounts for about 50%. The gravel particles represent sedimentary, magmatic and metamorphic rocks of medium and good smoothness (semi-circular and circular in shape). The aggregate sand is brown, various, with dominant coarse-grained particles and polymictic.

The structure of the deposits varies in different parts of the terrace. In the eastern part of the terrace at Gervėnai, a 2–4 m thick layer of ablation till overlies a 4 m thick layer of gravely sand with gravel fraction (5–70 mm) accounting for 37% (the dominant fraction is 5–10 mm in diameter). The aggregate sand is various and clayey. The deeper part of the section, up to a depth of 15 m, is composed of medium-grained sand with up to 3% of gravel.

The average thickness of the deposits of Skaudviliai kame terrace is 10 m with the maximal thickness being 17.5 m. The deposits in the lower part of the terrace occur on the Upper Nemunas till. The deposits in the upper part of the terrace occur on glaciolacustrine sediments of the same age.

4. FORMATION OF KAME TERRACES IN THE UPPER NEMUNAS GLACIATION ZONE

The data obtained in Lithuania during the investigation of kame terraces in the Upper Nemunas glaciation zone serve as a basis for the interpretation of the palaeoglaciodynamic setting and palaeogeographical environment at the time of terrace formation. Analysis of the architecture of glaciofluvial and glaciolacustrine terraces shows that the terraces formed under different dynamic conditions of glacier decay and, concomitantly, in different sedimentary environments.

4.1. Formation of glaciolacustrine kame terraces

According to the palaeoglaciodynamic setting and palaeogeographical environment, glaciolacustrine kame terraces are classified into the ones that formed: terraces by the slopes of the elevations of older glaciations; along the distal slope of marginal ridges (terminoglacial); within lake basins in elevated areas, terraces in glacier crevices, melting patches and other cavities and terraces at the slopes of elevations formed at different stages of deglaciation (supraglacial).

The kame terraces by the slopes of the elevations of older glaciation formed behind the main body of ice (limited by a glacier only on one side). The theoretical model of glaciolacustrine kame terrace formation suggested by the author based on a case study of Vaitkūnai kame terrace is shown in Fig. 11.

A glacier ice masses is always specific layered laminar flow. When the glacier encounters an obstacle to flow the velocity is reduced and the ice can become stationary. After the pause of the glacier, for some time the ice mass continues to flow into its peripheral parts. The flow due to successive melting of layers is replaced by block movement, i.e. movement by plane of fault displacement. When a glacier meets an obstacle, its edge stabilizes (Fig. 11. A).

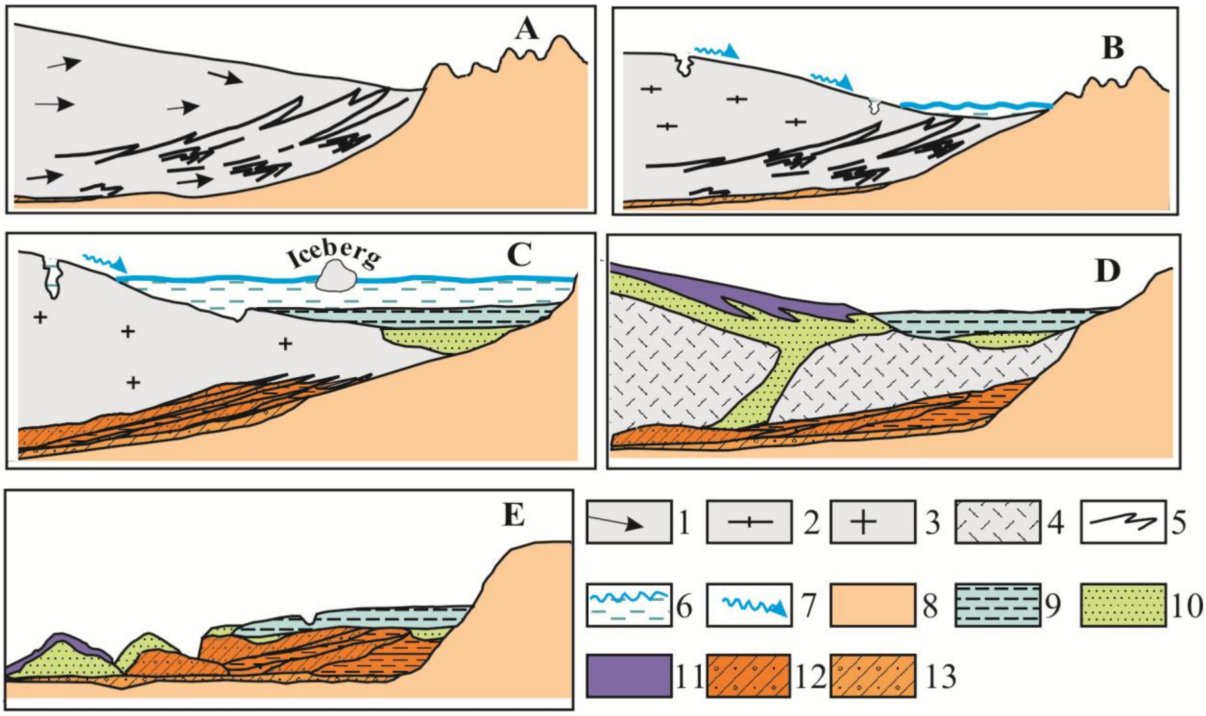


Fig. 11. Schematic formation model of kame terraces along the elevations of older glaciation:

A – active glacier stage; B – stage of frontal (terminoglacial) lake formation; C – stage of the frontal lake existence; D – stage of lake drainage and beginning of buried ice melting; E – end of the buried ice melting. 1 – active glacier and its advance directions; 2 – passive glacier; 3 – dead ice; 4 – buried ice; 5 – thrust-fold structure of ice and till; 6 – glacier meltwater basin; 7 – dominant direction of meltwater stream; 8 – relief left by the older glacier; 9 – frontal lake sediments; 10 – glaciofluvial (stream) deposits; 11 – ablation till; 12 – marginal till; 13 – lodgement (basal) till.

At the beginning of glacier degradation, ice melting intensifies at the interface between the glacier and the obstacle. The meltwater streams get dammed between the obstacle and the glacier (Fig. 11. B).

The water in the peripheral part of the glacier is dammed on the dead ice surface and forms supraglacial basins. The small meltwater basins expand as they are constantly supplied with glacier meltwater flows towards the glacier periphery. The meltwater streams carry clastic material from the melting ice mass, which is deposited on the basin (lake) bottom. The sedimentation is extremely rapid and leaves no time for the formation of the classic facies of marginal and bottom sedimentation. Thus, there occur many areas of supraglacial lacustrine sediments that could most relevantly be referred to as a "supraglacial lake complex" with characteristically rapid sedimentation rates (Fig. 11. C).

The constantly decaying glacier under the effect of supraglacial and subglacial meltwaters thins out in its peripheral part to such a degree that it no longer acts as a barrier damming the glaciolacutrine basin. The periglacial basin drains and sedimentation comes to an end. After the drainage of glaciolacustrine basin, bottom sediments are exposed on the surface. These sediments contain plenty of buried dead ice blocks (Fig. 11. D). Melting of these ice blocks generate glaciokarst pits of different sizes on the terrace surface. Melting of the dead ice buried under the lake bottom sediments takes longest. After their melting, the kame terrace sediments settle on the substratum. The proximal side of the terrace sediments borders on the elevation (Fig. 11. E).

The model of **kame terrace formation along the distal slope of marginal ridge** (based on a case study of Linkuva kame terrace) is suggested by the author together with co-authors.

Observation of the geomorphological and lithological characteristics of the kame terraces along the distal slope of the marginal ridges revealed that the terraces are morphologically bound to the ridges: the terraces border the ridges; the surface of terraces is 15–20 m above the adjacent glaciolacustrine plains; the strike of the terraces coincides with the ridges strike; the surface of the terraces is uneven, is inclined towards its slope and is partitioned by gullies and ravines; the base of the terraces is composed of a thick (even up to 21 m) layer of clay of massive texture (the Molupiai kame terrace); the clay layer contains gravel, pebbles and carbonate concretions accounting for about 3–5% of the total sediment mass; the clay sediments contain scanty sandy loam layers, which, presumably, may be interpreted either as an ablation till the flowed from the ridge or as a product of the melting of ice blocks in the basin.

Detailed investigation of the kame terraces bordering on the distal slope of marginal ridge led to a conclusion that kame terraces of this type formed between the passive glacier and zones of dead ice. The active glacier was close to but did not border on the zones of dead ice. Otherwise, the wide (0.5–2.0 km) depression filled with meltwater, where the accumulation of terrace sediments took place could not have occurred. A kame terrace can only form if there is a depression accumulating the meltwater between the marginal formations and the zone of dead ice. These conditions develop when new active ice lobe approaches the dead ice zone (Fig. 12. A).

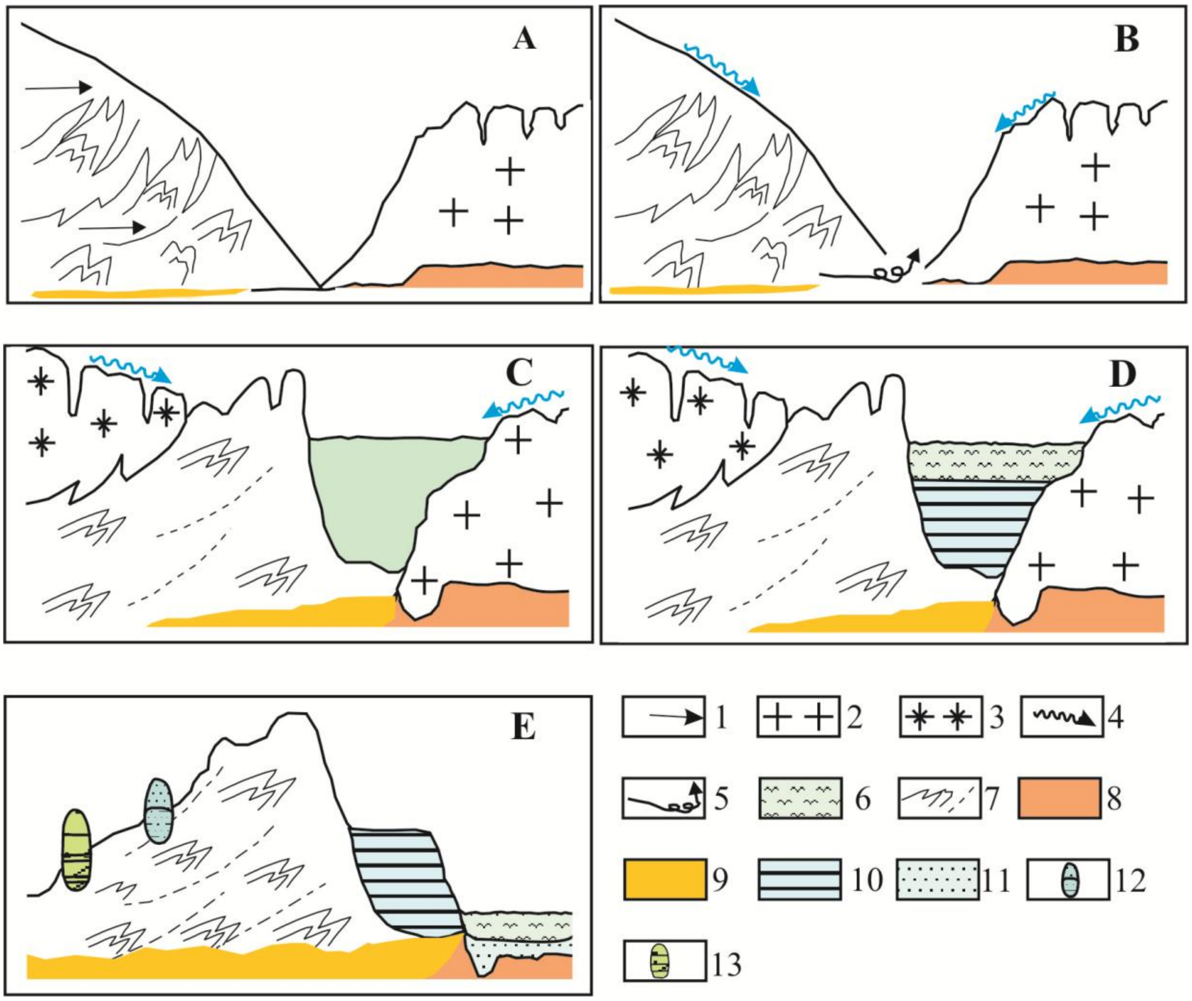


Fig. 12. Schematic map of formation of glaciolacustrine kame terraces along the distal slope of marginal ridge (after Bitinas et al., 2004; modified by the author):

1 – active glacier and direction of its movement; 2 – dead ice; 3 – dead ice of the new glacier flow; 4 – dominant direction of glacier meltwater stream; 5 – water at the glacier base; 6 – glacier meltwater basin; 7 – thrust-fold structure of ice and till; till formed by: 8 – older glacier; 9 – younger glacier; 10 – sediments of kame terrace; 11 – sediments of the proglacial glaciolacustrine basin; 12 – glaciolacustrine kame; 13 – glaciofluvial kame.

During deglaciation, till accumulates at the edge of glacier tongue. The basin in which glaciolacustrine sediments of kame terrace can accumulate form at the glacier/dead ice interface (Fig. 12. B).

Gradually, the body of the formerly active ice loses its energy and stagnates. The glacial meltwater reaches the glacier edge and accumulates in the depression between the dead ice zone and the developing marginal ridge. Under hydrostatic pressure, subglacial meltwater breaks free from under the glacier and is discharged to the glacier/dead ice interface. The closed basin is rapidly filled with glacial melt water (Fig. 12. C). The meltwater streams carry loose ice block material which accumulates on the basin bottom when the discharge of water diminishes (Fig. 12. D).

With climate warming there comes a moment when the dead ice ceases to provide a solid boundary to the glaciolacustrine basin. In the course of melting, the dead ice disintegrates into blocks and the lake water drains into the lower proglacial basin. The lake bottom sediments are exposed on the surface as a kame terrace. After the ice decay, if the sedimentation basin is surrounded by dead ice, the slope of the kame terrace will remain steep and unaltered (Fig. 12. E).

Kame terraces within lake basins in elevated areas were investigated based on the case study of Rubikiai and Alaušas terraces. Glacial lakes represent one of the most typical elements of glacier margins. They form in different spaces of glacial sedimentation depending on the glacier surface and location.

In the concave areas and in the zones where due to deglaciation the glacier base has thinned to a critical thickness, the continuous ice cover loses it flow plasticity and stagnates. The slowed melting and pulsation of the margin precede the invasion of a new glacier tongue into the dead ice zone. At the interface between the glacier tongue and the dead ice, a new active glacier front develops. There occurs a zone of higher horizontal tension which pushes the ice blocks through fault development. Under the conditions of this kind of ice movement, ice blocks with abundant debris eroded from the glacier base are squeezed onto the surface at the glacier tongue edges forming an ice mass uniqitously saturated with till all. With the weakening glacier pulsation, the glacier flow slows down and stops in the peripheral zone. At the same time, on the distal side, part of the plastic movement zone also slows down. In this, way two types of dead ice zone occur: dead ice with skeletal ice texture and dead ice with successively melting layers (the occurrence of the layers is close to horizontal). The degree of till saturation is the main difference between them. Supraglacial lakes of different size form at the interface of these dead ice zones.

The dead ice of the first type is saturated with till over the whole section whereas the dead ice of the second type contains till concentrated mainly in its basal part. The sediments of kame terraces accumulate in the supraglacial lakes which in subsequent stages of deglaciation were dammed between two structurally different dead ice zones. It is assumed that the basins of the supraglacial lakes had an asymmetrical shape.

The lakes were shallower in the zones where the water accumulated on the skeletal ice surface and flowed in the direction of the dead ice with successively melting layers. The basin of the supraglacial lake resembled a “deep ice-cold tub” surrounded by steep ice walls. During a very short warm season, the “tub” would be filled with silty and clayey particles washed out from the main body of the glacier and transported by temporary surface glacier meltwater streams. The heavier silty particles would settle during the short warm time spans whereas the lighter particulate clayey ones would settle during longer cold time spans when the lake was covered with ice. Faintly banded silty-clayey material composed of very thin (a few millimetres) yellowish grey silt and thicker dark brown clay laminae accumulated on the basin bottom. After the deglaciation of the ice shores surrounding the basin, the lake water would drain completely or partially to leave small relict lakes in the deepest part of the basin which persist even near the recent kame terraces. The clayey-silty lacustrine sediments would accumulate on the ice surface forming terrace areas (Fig. 13.).

Fig. 13. Surface of Alaušas kame terrace.

Some terraces display deformation of the layers. They occur when the terrace projects on a substrate after complete melting of the ice in deposits. Deformations of this kind are identified in the Alaušas kame terrace.

The Rubikiai and Alaušas kame terraces formed in the lake supraglacial basins. Kame terraces of this type have more than singly-level. For example, the Rubikiai kame terrace has four levels.

Kame terraces formed in glacier crevices, melting patches and other cavities (case study of Viečiūnai kame terrace). During ice melting and recession, a glacier becomes immobile and large areas become isolated from the main ice mass. The peripheral part of the glacier base, i.e. sub-glacial relief elevations and the periphery of the ice cover, was the best place for the formation of dead ice zones. The edge of the decaying glacier has many longitudinal and transverse fissures and cracks which often extend across the entire margin. The cracks and melting patches also occur when glacier meltwater accumulates of the glacier surface. Further thermal processes involve the melting of the dead ice and the widening and deepening of the fissures and cracks. Meltwater accumulates in these cracks and fissures forming supraglacial and intraglacial lakes.

The supraglacial fissures are constantly deepened and widened. The supraglacial basins have an asymmetric shape. Since the meltwater is constantly circulating in these fissures, some of them get dammed with meltwater containing washed out till which settles on the bottom. Through other fissures, the meltwater migrates into deeper layers of the glacier forming intraglacial water reservoirs. During the later stages of ice melting, the dead ice domes over the reservoirs collapse to form supraglacial lakes. One side of the water basin is represented by compact ice whereas the other side along the longitudinal axis of the fissure is represented by the dead ice of the collapsed ice dome. The ice interface slope forms in the bottom of the fissure, between the dead ice and deposits. The expansion rate of supraglacial water basin and sedimentation rate in the basin bottom are identical. As a result, under conditions of relatively stable water level in the basin, the sediment layer aggrades towards the proximal part of the glacier.

4.2. Formation of glaciofluvial kame terraces

Glaciofluvial kame terraces were deposited by glacial meltwater streams along the glacier margin between the zones of dead ice and the slopes of elevations or marginal formations.

The genetic model of glaciofluvial kame terraces compiled by the author based on a case study of Užventis kame terrace present the stages of terrace formation (Fig. 14.).

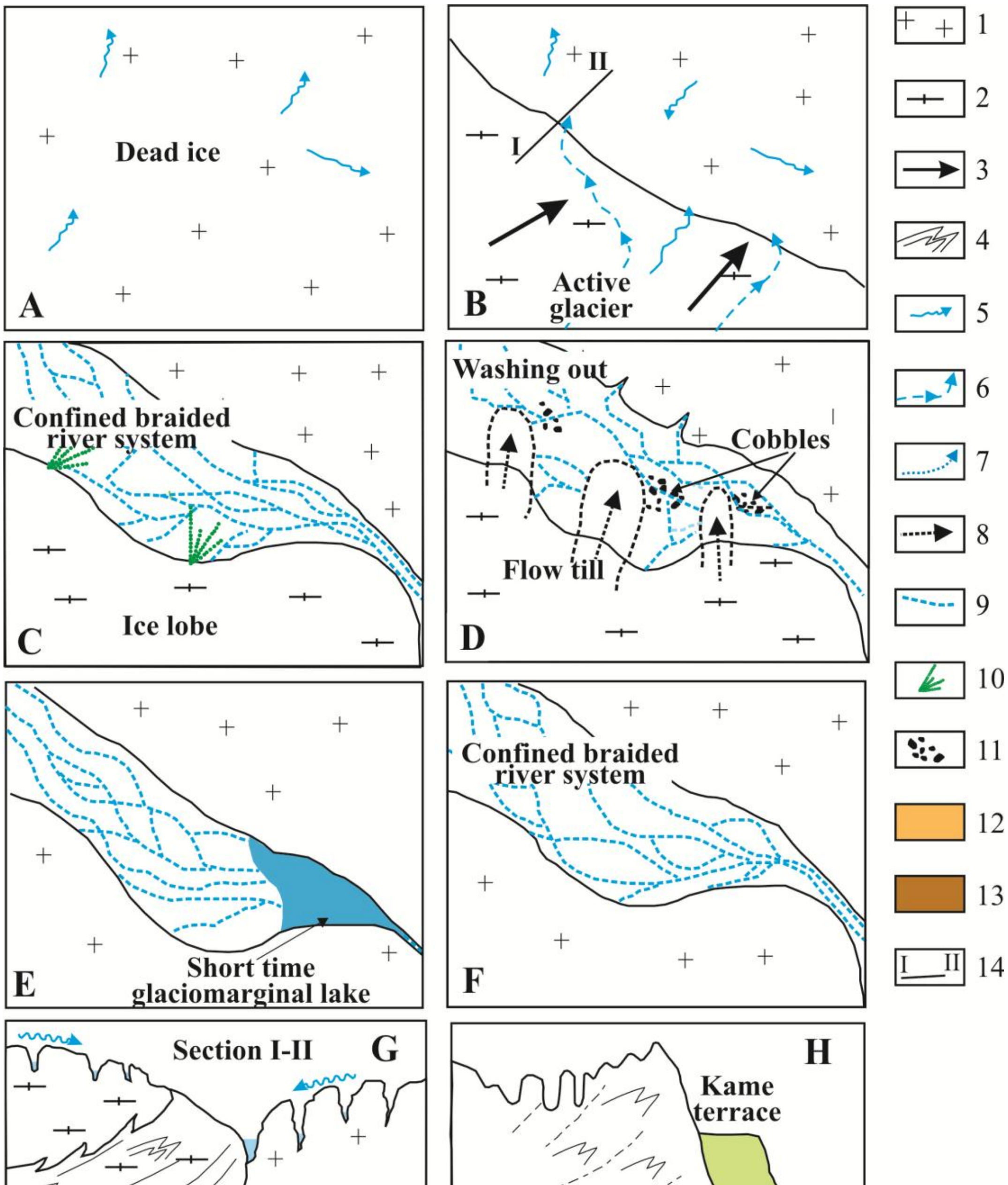


Fig. 14. Model of assumed formation of glaciofluvial kame terraces: A, B, C, D, E, F – in the plan, G, H – in the profile.

1 – dead ice; 2 – active glacier; 3 – direction of glacier advance; 4 – thrust-fold structure of ice and till; 5 – supraglacial wandering water streams; 6 – intraglacial water flows; 7 – subglacial meltwater; 8 – direction of flow till; 9 – water flows wandering in a limited area between the glacier edge and wall of the dead ice; 10 – outwash fan; 11 – cobbles; till formed by: 12 – older glacier; 13 – younger glacier; 14 – profile line.

The plastic flow of a glacier resulting from successive melting of its layers is replaced by block movement, i.e. displacement along a fault plane, when a glacier meets an obstacle. When the energy of the glacier gets exhausted and the ice cover reduces to a critical thickness, the glacier stagnates and large areas turn into dead ice (Fig. 14. A).

Glacier pulsations generate new active ice flows which invade into the fields of dead ice (Fig. 14. B).

The permanently advancing active ice body carries new loads of till into peripheral zones where marginal till formations are deposited.

With the beginning of deglaciation, glacier melting intensifies and the formerly active ice flow becomes passive. For some time, the passive glacier margin remains connected to the main active ice mass. Meltwater permanently circulates in the ice fissures further deepening and widening them. The meltwater streams flood in with intensified ice melting. The interface between the older dead ice zones and the newly deposited marginal formations act as the main arteries of meltwater streams. The powerful glacier meltwater streams are routed between the glacier margin and the dead ice slope because the amount of redeposited material is extremely large in comparison to the water content. The sedimentation associated with these streams is interrupted by outwash fans opening into the channel (Fig. 14. C).

Further melting of the glacier releases huge amounts of clastic material that are transported to the peripheral zone by meltwater flows. Supraglacial and subglacial drainage redeposit and sort the till. The processes of deposition and redeposition take place synchronously: in some places, the meandering streams deposit the load and in other places erode them. Strong and powerful streams lift and transport all finer particles leaving only the cobbles as a lag (Fig. 14. D, Fig. 15.).

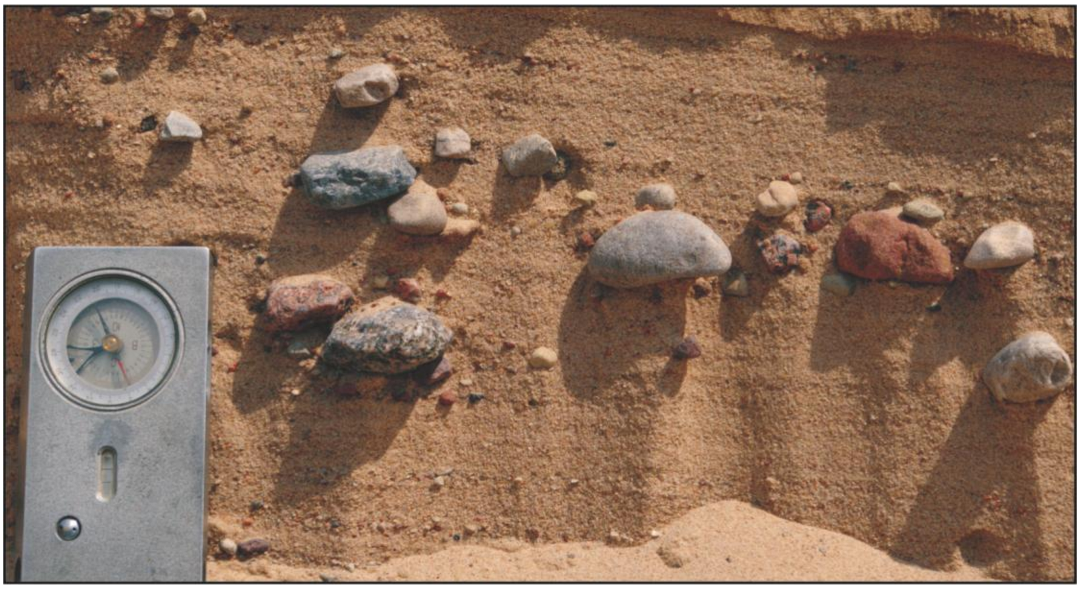


Fig. 15. Sand with pebble strips and cobbles in the Užventis kame terrace.

Permanently sliding down from the glacier surface, till forms flow till facies. Poorly-sorted deposits get into the channel confined by the glacier margin and dead ice wall where they remain weakly redeposited (Fig. 16.).

Fig. 16. Poorly sorted deposits in the Survilai kame terrace.

The flow till facies indicate slower flow rates or, perhaps, the change of the location of flow branch. In the course of glacier decay, the sedimentary conditions in the channel change rapidly due to daily and seasonal temperature fluctuations. This is reflected in the variations in particle size (Fig. 17.).

Fig. 17. Variations of granulometric composition in the Survilai kame terrace.

Even small glacier pulsations may condition the advance of glacier tongue in which case the channel can be dammed and a shallow temporary terminoglacial lake developed (Fig. 14. E). Deposits in such a lake settle down under the conditions of very weak currents (Fig. 18.).

Fig. 18. Fine-grained sand settled in weakly drained basin during the plane sedimentation phase (the Užventis kame terrace).

After the thawing of the margin of the glacier tongue, the dammed lake water is drained to lower areas and the later sedimentation phase means the return to the wandering stream system in a restricted area (Fig. 14. F).

5. MORPHOGENETIC CLASSIFICATION OF KAME TERRACES

The present study showed that the morphology and architecture of kame terraces in the Late Nemunas glaciation area in the territory of Lithuania are highly variable. However the implications of these detailed analyses for the accurate classification of these diverse kame terraces has previously received little attention in scientific publications.

The author suggests a morphogenetic classification of kame terraces based on individual investigations. The classification is based on the evaluation of the specific character of the Late Nemunas glaciation and embraces all kame terraces identified in different orographic macroforms. The morphology of the kame terraces, the specific features of their constituent lithological formations (deposits and sediments), the location of the terraces at the time of formation with respect to glaciers, and epigenetic changes to the terrace surfaces were all taken into consideration (Table 5.1.).

According to the position with respect to a glacier, kame terraces are classified as: terminoglacial (formed at the glacier edge) and supraglacial (formed on the glacier surface) kame terraces.

According to geomorphological location, terraces are classified into: terraces formed by the slopes of the elevations of older glaciation, terraces by the slopes of tunnel-valleys, terraces along the distal and proximal slopes of marginal ridges, terraces formed within lake basins in elevated areas, terraces in glacier crevices, melting patches and other cavities, and terraces at the slopes of elevations formed at different stages of deglaciation.

Kame terraces may form directly, i.e. right on the ice glacier base, and by inversion, when a terrace projects on the base only after complete melting of the ice buried in the deposits. The structural and textural features of the internal structure of terraces serve as criteria for attributing them to these different groups.

Table 5.1. Morphogenetic classification of kame terraces.

According to position with respect to glacier	According to geomorphological location	According to the internal structure
Terminoglacial Supraglacial	Terraces by the slopes of the elevations of older glaciation Terraces by the slopes of tunnel-valleys Terraces along the distal slope of marginal ridges Terraces along the proximal slope of marginal ridges Terraces within lake basins in elevated areas Terraces in glacier crevices, melting patches and other cavities Terraces at the slopes of elevations formed at different stages of deglaciation	Glaciofluvial kame terraces Glaciolacustrine kame terraces Complex (glacioaquatic) kame terraces

Table 5.1. (sequel)

According to formation mode	According to morphography	According to plane morphology	According to the number of levels	According to the type of the initial relief
Direct Inversion	Elementary Composite	Elongated Segmented type	Singly-level Multilevel	Flat plain Slightly undulating plain Undulating plain

Table 5.1. (continued)

According to epigenetic transformations of the surface	Terrace slopes
Flat Hillocky With holes and hollows Dissected by ravines	Straight Meandering Serrated

The internal structure of kame terraces depends directly on the factors associated with their formation. Usually terraces form as a result of continuous deposition. According to whether terrace sediments or deposits where deposited under conditions of flowing or still meltwater, they are classified as glaciofluvial or glaciolacustrine. The combined action of flowing and still glacier meltwater formed complex (glacioaquatic) kame terraces.

According to their morphography, terraces are elementary and composite. The surface of elementary terraces is smooth and even across almost the whole terrace; commonly it is represented by a flat or slightly undulating, occasionally undulating, plain.

The surface of composite kame terraces is commonly complicated by a great number of alternating positive and negative forms. Isolated kames or groups of kames and isolated eskers or chains are superimposed on a background of undulating relief. The declensions at the slopes of kames terraces and eskers are filled with lacustrine sediments and peat. The terraces have plentiful glaciokarst kettles and pits. Some kettles are infilled with peat or have turned into small lakes.

The planar configuration of kame terraces is variable with elongated forms or chains of terrace segments being most common.

According to the number of levels, the terraces are singly-level or elementary and multilevel kame terraces.

The terrace relief is typically represented by a flat, slightly undulating or undulating plain often slightly or steeply inclined towards the terrace slope. The surface of the glaciofluvial kame terraces is inclined in the direction of meltwater flow. The initial relief of the terraces has often been transformed by epigenetic processes. The surface has become hummocky, patterned with glaciokarst kettles and pits and partitioned by periglacial ravines. The kettles and pits in the terrace surface usually occur in the distal part near the edge, i.e. in the part of the youngest deposits. In the proximal part of the terrace, pits are fewer since, presumably, the buried ice melted before the end of sedimentation and deposition. Thus, the pits that formed earlier were filled with deposits. Some pits represent small lakes or are filled with peat.

Every kame terrace in its lower part is limited by a well-developed slope representing the old slope of the dead ice. Ice-contact slopes have developed in all deposition/dead ice interfaces. Straight continuous ice contact slopes occur only in isolated areas. Usually, the slopes are meandering or serrated, partitioned by small bogs and declensions, and in places punctuated by hills. The complex, i.e. meandering, serrated and partitioned, slopes reflect the varied ice-marginal geometry of the glacier margin associated with their formation.

The classification presented here is based on investigations of the morphology, morphometry and structure of kame terraces in the territory of Lithuania. A more extensive classification of kame terraces in the Late Nemunas glaciation area of Lithuania's territory requires detailed investigations of kame terraces in other regions affected by the same glaciation.

CONCLUSIONS

1. Kame terraces were identified in the Baltija stage relief of the Late Nemunas glaciation. No kame terraces were identified in the relief associated with the Grūda stage. Terraces formed in the marginal Baltija and Žemaičiai insular uplands and at the distal and proximal slopes of these uplands and marginal ridges at different stages of glacier degradation.

2. Kame terraces are independent ice-marginal formations generated between the forms of relief sculptured in supraglacial and terminoglacial sub-environments. The slope of the glacier margin forms only one of the boundaries of this sedimentary environment.

3. Morphologically and structurally, kame terraces are distinguished by accumulative slopes, distally-inclined surfaces (top of terraces), glaciokarst kettles and pits concentrated in the distal part of terrace surface, and faults in the terrace architecture.

4. The structure of the deposits found within glaciofluvial kame terraces is horizontally and vertically variable. The beds of deposits are composed of inclined series of sand and gravel and horizontally-bedded sand layers that occasionally

contain sandy loam and loam interlayers and blocks. The thickness of these deposits varies from 2–3 to 38 m. The average thickness is 8–10 m.

5. According to their size, the glaciofluvial kame terraces vary from small (terrace segments) to large mesoforms. The length of terraces ranges from 100–300 m to 8–12 km. The width is usually around 1.0 km. The surface of the terraces is characterised by undulating plain relief which in places merges into flat slightly undulating and ridged plains. The kames and eskers on the terrace surface are relatively older formations structurally extending to the base of the constituent deposits.

6. The glaciolacustrine kame terraces are composed of massive and laminated clay, and occastionally of silt and fine sand. The thickness of the clay layers is variable; sometimes it is unusually thick up to 24 m. The average thickness is 10–12 m.

7. The length of glaciolacustrine kame terraces ranges from 200–300 m to 22 km. The width ranges from 50–100 m to 5.5 km. The average width is 1.0 km. The dominant type of relief is a flat plain, although in some instances it is represented by a slightly undulating or undulating plain.

8. Based on an extensive analysis of kame terrace morphology, morphometry and structure, terraces were classified into: terraces formed by the slopes of the elevations of older glaciation; terraces by the slopes of tunnel-valleys; terraces along the distal and proximal slopes of marginal ridges; terraces within lake basins in elevated areas, terraces in glacier crevices, melting patches and other cavities, and terraces at the slopes of elevations formed at different stages of deglaciation.

VĖLYVOJO NEMUNO APLEDĖJIMO KEIMINIŲ TERASŲ MORFOGENEZĖ IR JŲ ERDVINĖ SKLAIDA

SANTRAUKA

Vėlyvojo Nemuno (Weichselian) kontinentinio apledėjimo degradacijos metu formavosi keiminės terasos, kurios užima svarbią vietą visoje glacigeninio reljefo formų sistemoje. Keiminės terasos Lietuvos teritorijoje yra aptinkamos Nemuno apledėjimo Baltijos stadijos ledyno paliktame reljefe. Morfologiškai ir morfometriškai jos turi daug panašumo su prieledyninėmis fliuvioglacialinėmis terasomis.

Darbo aktualumas. Paskutiniaisiais metais, vykdant Lietuvos teritorijos geologinį kartografavimą stambiu ir detaliu masteliu, buvo išskirtos keiminės terasos. Iki tol keiminių terasų nuogulos buvo tapatinamos su prieledyninėmis fliuvioglacialinėmis nuogulomis arba limnoglacialinėmis nuosėdomis. Keiminės terasos, Lietuvoje paplitusios Vėlyvojo Nemuno apledėjimo srityje, pasižymi didele morfologijos, genezės ir sandaros įvairove. Identifikuoti keimines terasas kartografuojant ir atkurti jų susidarymo sąlygas, labai svarbi yra keiminių terasų klasifikacija, kurios iki šiol nebuvo.

Tyrimų objektu pasirinktos keiminės terasos, identifikuotos skirtingose orografinėse makroformose. Tirtos keiminės terasos formavosi marginalinėse Baltijos aukštumose ir Žemaičių sališkoje aukštumoje, o taip pat ties faziniais marginaliniais gūbriais.

Pagrindinis šio darbo tikslas – Vėlyvojo Nemuno apledėjimo srityje esančių keiminių terasų paplitimo, jų morfologijos, sandaros, kilmės ir padėties ištyrimas bei detalios klasifikacijos sukūrimas. Siekiant užsibrėžto tikslo, buvo iškelti sekantys **uždaviniai:**

- atlikti keiminių terasų morfologijos ir sandaros analizę;
- rekonstruoti keimines terasas sudarančių nuogulų sedimentacijos sąlygas;
- atskleisti keiminių terasų nuogulų ir nuosėdų granuliometrinės sudėties kaitą horizontaliame ir vertikaliame pjūviuose;
- pagrįsti keiminių terasų susidarymo sąlygas atsižvelgiant į ledyno pakraštinės dalies dinamiką;
- sudaryti morfogenetinę keiminių terasų klasifikaciją.

Pagrindiniai ginami teiginiai:

- Keiminės terasos yra savarankiškos ledyninio reljefo formos, priskiriamos pakraštiniams dariniams.
- Keiminių terasų nuogulų ir nuosėdų susidarymas vyko supraglacialinėje ir terminoglacialinėje subaplinkose.
- Keiminių terasų morfologijos, morfometrijos, sandaros, nuogulų struktūros ir tekstūros įvairovę lėmė sedimentacijos sąlygų skirtumai.
- Fliuvioglacialinės ir limnoglacialinės kilmės keiminių terasų sedimentacijos sąlygų įvairovę apsprendė ledyno ir atskirų ledo blokų pakraščio padėtis stambių reljefo formų atžvilgiu ir ledyno tirpsmo vandens hidrodinamika.

Mokslinio darbo naujumas. Šiame darbe pirmą kartą pateikiama dabartinių keiminių terasų paviršiaus morfologinė ir morfometrinė charakteristika, gauti ir apibendrinti duomenys apie terasų sandarą. Pirmą kartą detaliai ištirta limnoglacialinių terasų nuosėdų granuliometrinė sudėtis ir nustatyti morfologiniai skirtumai tarp keiminių fliuvioglacialinės ir limnoglacialinės kilmės terasų. Apibrėžtas keiminių terasų susidarymo mechanizmas Vėlyvojo Nemuno apledėjimo metu, nustatyti keiminių terasų paplitimo erdviniai dėsningumai ir sukurta Lietuvos teritorijoje esančių keiminių terasų morfogenetinė klasifikacija.

Praktinė darbo reikšmė. Atlikti tyrimai svarbūs fundamentiniu aspektu, nusakantys skirtingų keiminių terasų morfogenetinius tipus, jų sandarą ir paleogeografines susidarymo sąlygas Vėlyvojo Nemuno ledyno deglaciacijos metu. Darbo duomenys gali būti panaudoti kituose regionuose sprendžiant analogiškų formų susidarymo problemas. Šie tyrimai svarbūs praktiniu aspektu, kadangi keiminių terasų nuogulos ir nuosėdos yra statybinių naudingųjų iškasenų (žvyras, molis) resursai. Disertacinio darbo rezultatai gali būti naudojami paleogeografinių sąlygų rekonstrukcijai, taip pat gali būti pritaikomi teritorijos planavimui.

IŠVADOS:

1. Keiminės terasos Lietuvos teritorijoje formavosi Vėlyvojo Nemuno apledėjimo Baltijos stadijos metu. Terasos aptinkamos marginalinėse Baltijos ir sališkoje Žemaičių aukštumose ir ties jų bei atskirų ledyno degradacijos fazių marginalinių gūbrių distaliais ir proksimaliais šlaitais. Grūdos stadijos metu suformuotame reljefe keiminių terasų Lietuvos teritorijoje neaptikta.

2. Keiminės terasos yra savarankiški ledyno pakraščio dariniai, susidarę supraglacialinėje ir terminoglacialinėje subaplinkose. Ledyno ledo dangos šlaitas buvo tik viena iš jas sudarančių nuogulų sedimentacinės erdvės ribų.

3. Keiminių terasų morfologinėje struktūroje išskiriamas akumuliacinis šlaitas, distalia kryptimi nuolaidus paviršius (terasinė aikštelė), jos paviršiuje susidariusios glaciokarstinės dubės ir daubos bei sprūdžiai, dislokuojantys nuogulų storymę.

4. Fliuvioglacialinių keiminių terasų nuogulų sandara yra labai kaiti horizontalia ir vertikalia kryptimis. Nuogulų storymę sudaro įkypų smėlio ir žvirgždų sluoksnelių serijos bei horizontalūs smėlio sluoksneliai su moreninio priemolio ir priesmėlio intarpais ir luistais. Nuogulų horizonto storis kinta nuo 2-3 m (minimalus) iki 38 m (maksimalus). Didžiojoje tirtų terasų dalyje vidutinis nuogulų horizonto storis siekia 8-10 m.

5. Fliuvioglacialinės keiminės terasos gali sudaryti nedidelius segmentus (kelių ha ploto) ar stambias mezoformas (keliolika km² ploto). Fliuvioglacialinių keiminių terasų ilgis kinta nuo 100-300 m iki 8-12 km, vidutinis terasų plotis – 1,0 km. Šių terasų paviršiui būdingos banguotos lygumos, vietomis pereinančios į plokščias, silpnai banguotas ar keteruotas lygumas. Terasų paviršiuje aptinkami keimai ir ozai yra santykinai senesni dariniai, struktūriškai siekiantys terasas sudarančių nuogulų storymės padą.

6. Limnoglacialines keimines terasas sudaro masyvus ir juostuotas molis su aleurito ir smulkučio smėlio sluoksneliais. Molio sluoksnio storis įvairus: nuo 1–2 m (minimalus) iki – iki 24 m (maksimalus). Dažniausiai pasitaikantis vidutinis molio sluoksnio storis siekia 10–12 m.

7. Limnoglacialinių keiminių terasų ilgis kinta nuo 200-300 m iki 22 km. Terasų plotis kinta nuo 50-100 m iki 5,5 km, o vidutinis siekia 1,0 km. Vyraujantis limnoglacialinių keiminių terasų paviršiaus reljefo tipas – plokščia lyguma su ja keičiančiais silpnai banguotos ar banguotos lygumos plotais.

8. Atliktas tyrimas leido detaliau klasifikuoti Lietuvos keimines terasas. Klasifikacija pagrįsta terasų padėtimi, pirminio reljefo pobūdžiu, jų morfologija, susidarymo būdu, morfometriniais rodikliais, lygių skaičiumi, nuogulų sandara, epigenetiniu performavimu. Išskirtos terasos, susiformavusios palei ankstesniojo apledėjimo aukštumų šlaitus, klonių šlaitų terasos, terasos išilgai marginalinių gūbrių

distalaus ir proksimalaus šlaitų, aukštumų ežerų duburių terasos, ledynų plyšių, protirpų bei kitokių ertmių terasos ir terasos palei aukštumų, susidariusių atskiruose nuledėjimo etapuose, šlaitus.

LIST OF PUBLICATIONS REPORTING THE RESULTS OF THE PRESENT DISSERTATION

Scientific articles published in refereed scientific periodical publications included by the *Institute for Scientific information – ISI – in the database Thomson Reuters Web of Science* ***(ISI WOS)*** and have an index of impact factor in the database of Journal Citation Report.

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Bitinas, A., **Karmazienė, D.**, Jusienė, A. 2004. Glaciolacustrine kame terraces as an indicator of conditions of deglaciation in Lithuania during the Last Glaciation. *Sedimentary Geology, 165,* 285–294. ISSN 0037-0738.

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Karmazienė, D., Zinkutė, R., Karmaza, B., Česnulevičius, A. 2011. Clay as a natural isolating cover: its formation in supraglacial and proglacial subenvironments in North Lithuania. *The 8th International Conference Environmental Engineering, May 19-20, 2011, Vilnius, Lithuania. Selected papers. Vol. I. Edited by D. Cygas and K. D. Froehner.* 155–161. ISSN 2029-7106 print / ISSN 2029-7092 online, ISSN 978-9955-28-831-2 CD (ISI Proceedings).

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