GEOLOGIJA. 2009. Vol. 51. No. 1(65). P. 33–41
DOI: 10.2478/v10056-009-0004-2

Transformation of landforms and sediments in the periglacial setting of West Greenland

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Česnulevičius A., Šeirienė V. Transformation of landforms and sediments in the periglacial setting of West Greenland. *Geologija*. Vilnius. 2009. Vol. 51. No. 1(65). P. 33–41. ISSN 1392-110X

The article deals with the cryogenic processes taking place in the terminal zone of the recessing glacier of SW Greenland, which modify the sediment layers and transform the landforms. The sediment horizons were examined in natural outcrops and in trenches. Structural analysis of periglacial sediments in the slopes has shown that subdued evaporation and shallow permafrost favour the development of cryoturbations. In relief declensions, the formation of polygonal surfaces is predetermined by shallow beds of magmatic rocks, permafrost and especially slow evaporation during short warm seasons. Aeolian processes are most active in the valleys sculptured by glaciofluvial flows where cold arid winds blow out or rework inequigranular deposits. Dust is blown out by wind erosion, whereas the coarse-grained material is transported by creeping or saltation. Sand ripple and embryo dune terrains are widespread in glaciofluvial valleys. Wind erosion processes forming pebble–boulder deflation pavements take place in relief declensions. Outcrops sized 10–60 m^2 and niches develop in the hill slopes. Diatoms indicate that sedimentation in small closed basins took place under cold, oligotrophic, acidophilous conditions.

Key words: sediments, forms of relief, aeolian, periglacial, cryoturbation, permafrost, sedimentary environment, diatoms, Russell Glacier, Greenland

Received 03 January 2009, accepted 30 January 2009

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INTRODUCTION

Long- and short-term climate oscillations in the periglacial zone predetermine the composition and intensity of epigenetic processes. Cryogenic processes, most intensively modifying the surface layer of powdery sediments and sculpturing specific landforms, are most intensive in the terminal zone of the transgressing glacier. Yet the surface sediment layer and landforms are shortly after destroyed by glacier advance.

The sediment layers modified by cryogenic processes and landforms created by them persist longer in the stagnant or recessing glaciers. The landforms in the terminal zones of glacier periphery during Pleistocene glaciation are dramatically and often unrecognizably transformed by temporal geomorphological processes.

Glacial and aquaglacial sediments and landforms in the periphery of the Russell Glacier in SW Greenland have not yet endured any marked transformations (Fig. 1). Their analysis may improve our understanding of the processes taking place in Central Europe and in the territory of Lithuania at the end of the Pleistocene.

The investigations carried out in September 2007 provided a basis for evaluating the intensity of limnoglacial, glaciofluvial, cryogenic, aeolian, thermokarst and organogenic processes, sediments and landforms in the terminal setting. Limnoglacial and glaciofluvial processes were analysed in special articles (this volume). The present paper is an overview of the activity of other processes.

In Greenland, diatoms are among the main primary produces. They are sensitive to many environmental variables,

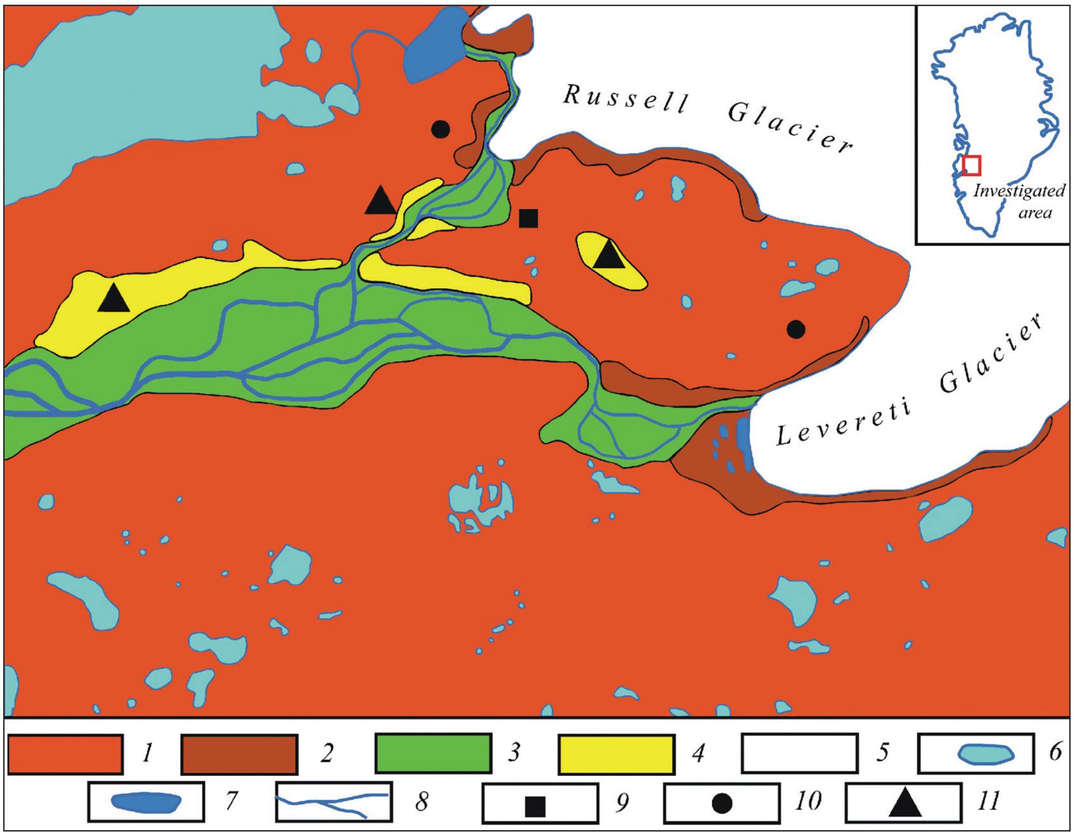

Fig. 1. The study area: *1* – erosion formation, *2* – glacial edge formation, *3* – glaciofluvial formation, *4* – aeolian formation, *5* – glacier, *6* – lakes, *7* – glaciolacustrine lakes, *8* – glaciofluvial streams, *9* – periglacial formations on the slopes, *10* – polygonal forms, *11* – aeolian dunes, niches and outcrops

1 pav. Tyrimų teritorija: *1* – eroziniai dariniai, *2* – ledyno pakraščio dariniai, *3* – fliuvioglacialiniai dariniai, *4* – eoliniai dariniai, *5* – ledynas, *6* – ežerai, *7* – limnoglacialiniai baseinai, *8* – fliuvioglacialinės tėkmės, *9* – periglacialiniai dariniai šlaituose, *10* – poligonalinės reljefo formos, *11* – eolinės kopos, daubos ir atodangos

including light, moisture conditions, temperature, current velocity, salinity, pH, oxygen, inorganic nutrients, organic carbon and organic nitrogen (Van Dam et al., 1994). Therefore, they are considered powerful indicators for environmental changes, including acidification, eutrofication and climatic changes, both in neo- and palaeoenvironmental studies. In our study, investigations of diatom flora help to understand the palaeoecological conditions of sedimentation in small closed basins.

METHODS

Sediment horizons in the terminal setting of glacier periphery zone were examined in several natural outcrops and in trenches and holes. The latter were shallow (to a depth of up to 1 m) and included only the active layer of the powdery sediment cover.

The morphometric parameters of biogenic, Aeolian, thermokarst and cryogenic landforms were measured using a tape-measure and a GPS device. The GPS device was employed for mapping homogeneous landform complexes: areas of polygonal surfaces, deflation pavements, areas of Aeolian ripple marks, deflation basins, sinks and niches, and solifluction lobes (Baltrūnas et al., 2008).

Diatom investigations were carried out in a little bog (Fig. 2) situated in the periphery zone of the Russel Glacier (67°05'35"N, 50°14'84). Samples were taken from the upper part of the section at 5 cm intervals deep to the frozen soil. The lithology of the section is described in Table.

Diatom frustules were extracted from the sediments in the conventional manner described by Battarbee (1986), Miller and Florin (1989). HCl was added to remove the carbonates and 30% H_2O_2 to oxidise organic matter. Decanting and flotation in heavy liquids (CdI_2 + KI) were applied to remove clay particles and mineral material. Afterwards, the residue was mounted in NBS Naphrax (R. I. = 1.74) and

Table. **Lithology of the section**
Lentelė. **Nuosėdų pjūvio litologija**

Depth (cm) Gylis (cm)	Lithology Litologija
0–0.25	Light brown laminated peat
0.25–0.49	Light brown silty peat, in the lower part gradually changed by dark brown peat
0.49–0.63	Dark brown peat, distinctly horizontally laminated
0.63–0.90	Dark brown silty peat, in the lowermost part 2 cm black peat layer

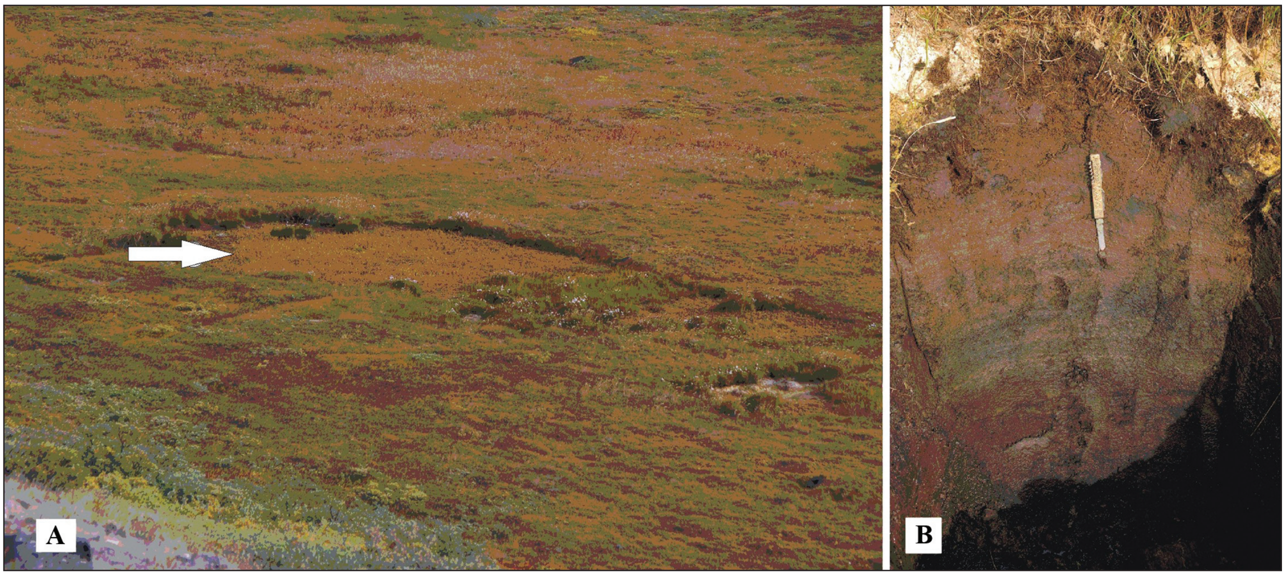

Fig. 2. Place of diatom investigations (*A*), study section (*B*)

2 pav. Diatomėjų pavyzdžių paėmimo vieta (*A*) ir tirtas kasinys (*B*)

examined under a light microscope with an oil immersion objective at a magnification of 1000×. The identification of species mainly followed Krammer and Lange-Bertalot (1988; 1991a, b; 1997). Diatoms were subdivided into groups according to ecological requirements (Hustedt, 1937–1939; Van Dam et al., 1994). The succession of the most frequent and ecologically important taxa is presented in percentage diagrams based on the total sum of the identified items. All spreadsheets and percentage diagrams were plotted using the TILIA and TILIA-GRAPH programs (Grimm, 1992). The zonation of the diatom diagram was performed according to the constrained incremental sum of square cluster analyses (CONISS) developed by Grimm (1992).

RESULTS

Cryogenic transformation of sediments. The structural dynamics of periglacial sediments was studied in a northward 40 m high and 156 m long slope with the slope angle ranging from 5–7 to 11–16° (Fig. 3). The average slope angle was 10°. The upper layer of slope sediments is composed of aleurite with rich peat intrusions. Medium-grained sand was detected only at the bottom of the slope at a depth of 3 m. Sand with gravel and pebbles is bedded at a depth of 0.6 m. The large slope angle provides for good drainage conditions. This is evident from the dry upper part of the slope where the active sediment layer reaches up to 1.0 m. The active layer at the slope bottom is considerably thinner (only 0.6 m).

Subdued evaporation and shallow permafrost retain the water of atmospheric discharges. These conditions predetermine rather intensive peat-forming processes in the declivitous slope, what is untypical of temporary climate conditions. Peat-formation takes place in aleurite sediments

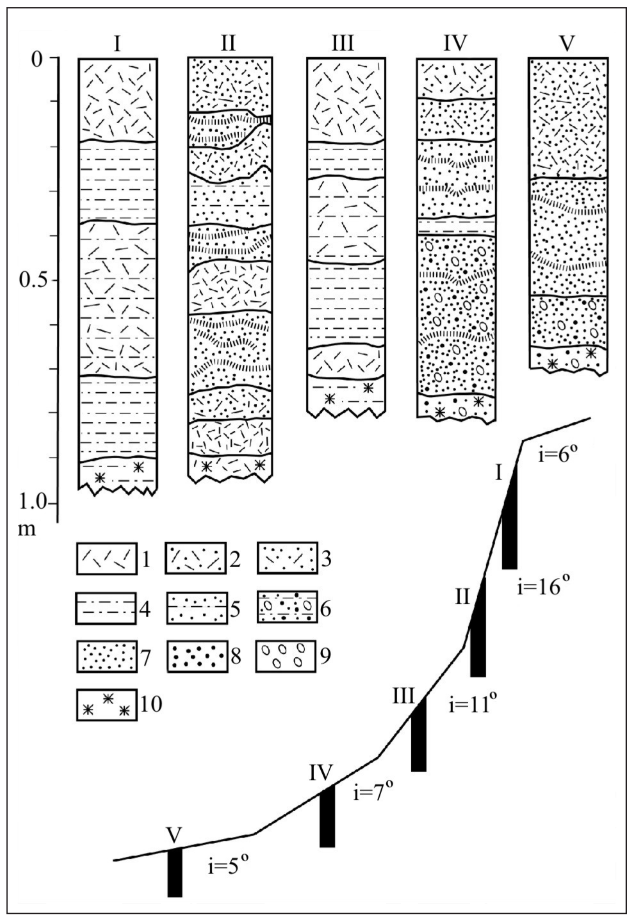

Fig. 3. Position of the boreholes on the slope: *1* – peat, *2* – sandy peat, *3* – sand with organic, *4* – silt, *5* – silty sand, *6* – pebbles, gravel, sand and silt, *7* – sand, *8* – gravel, *9* – pebbles, *10* – permafrost

3 pav. Kasinių išsidėstymas šlaite: *1* – durpės, *2* – smėlinga durpė, *3* – smėlis su organika, *4* – aleuritas, *5* – aleuritingas smėlis, *6* – gargždas, žvirgždas, smėlis ir aleuritas, *7* – smėlis, *8* – žvirgždas, *9* – gargždas, *10* – daugiametis įšalas which have been and still are depositing under conditions of intensive aeolian accumulation. A rather complex sedimentation cycle is characteristic of this slope of the northern exposition (Fig. 4).

Polygonal surfaces. The classic polygonal surfaces form in shallow relief declensions. Their generation is predetermined by a few factors: shallow magmatic rocks and permafrost obstructing the penetration of atmospheric water into deeper layers and a very subdued evaporation during a short warm season. These factors are responsible for the intensive peat formation in blind surface declensions. In autumn, the water accumulated in peat freezes at extremely high rates, forming a network of ice wedges splitting irregular peat pentagons. The ice wedges observed in the upper part of the slope were up to 1.5 m deep and 0.1 m wide.

Climate warming entails degradation of ice wedges. The upper parts of ice wedges are melting. In summer time, ice blocks begin at a depth of 0.6 m. Narrow (0.1–0.5 m) and rather deep (up to 0.6 m) cracks form above them. In summer, these cracks stay dry (Figs. 5 and 6). The network of decaying ice blocks splits peat sediments into small segments.

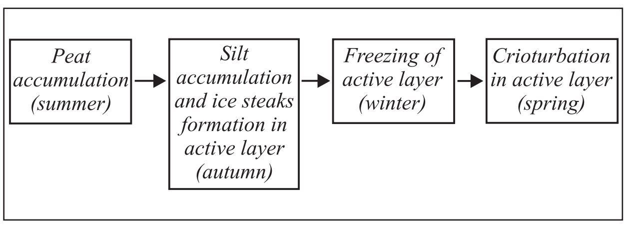

Fig. 4. Trend of sedimentation cycle
4 pav. Sedimentacinio ciklo raida

In warmer and more arid summers, a decomposition of plant wastes and concomitantly a degradation of the peat layer take place in the polygonal surfaces. As a result, the peat layer, performing the function of thermal insulation in summer, thins inducing the thawing of the underlying permafrost and thus contributes to the further transformation of the polygonal surface. When blind declensions are composed of magmatic rocks, a complete degradation of a polygonal surface is possible (Fig. 7). The degradation is enhanced by an intensive wind erosion in spring and in early autumn.

Aeolian processes. Most intensive Aeolian processes take place in valleys sculptured by glaciofluvial flows. In summer, the thawing glacier water deposits inequigranular sediments: from large blocks (Ø 2 m) to fine-grained sands (Ø 0.1–0.05 mm) and aleurites (Ø 0.05–0.002 mm). An especially intensive deposition takes place during floods recurring at 20-year intervals (Russell, 1989, 1993, 2006; Shakesby, 1985). The fine-grained sediments are most actively reworked by aeolian processes. In glaciofluvial sediments, wind erosion and accumulation processes take place simultaneously. The powdery material is blown out and accumulated at a distant environment. Depending on the wind direction and strength, aleurites accumulate at the glacier edge, in leeward slopes of erosion landforms, limnoglacial basins and fiords or in the ocean. Layers of the powdery fraction were formed in the bottom of the basin after a cataclysmic drainage.

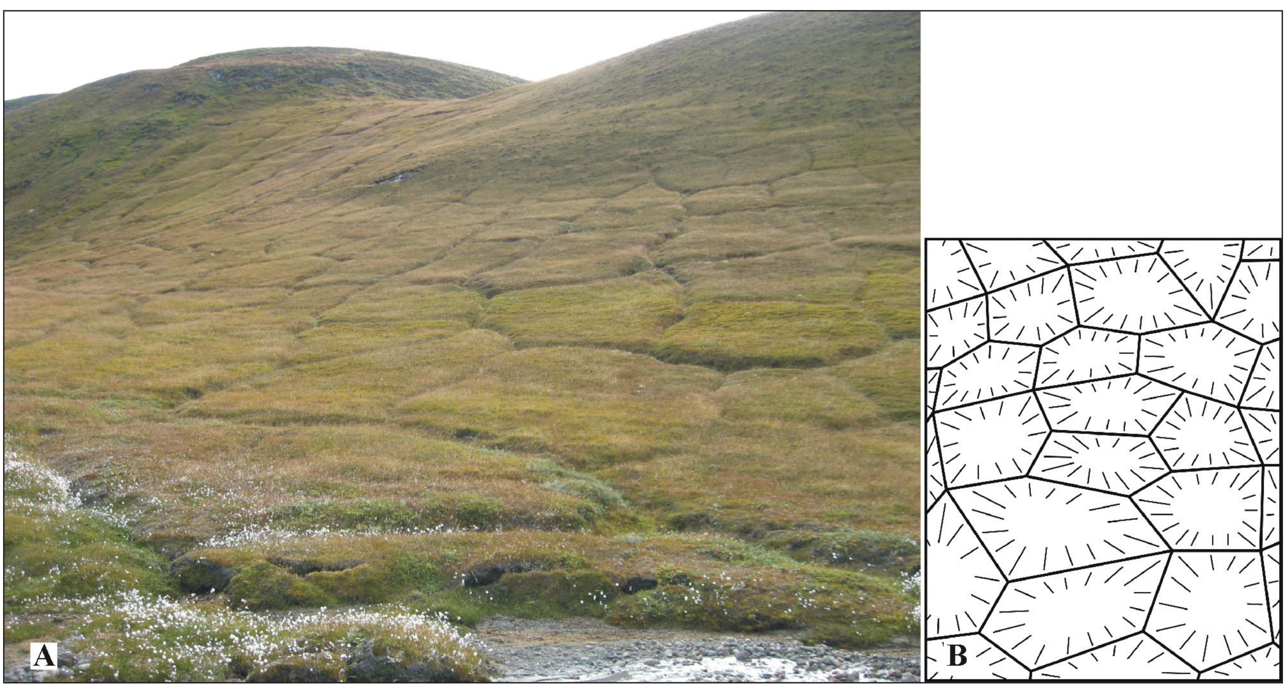

Fig. 5. Permafrost surfaces: *A* – photo, *B* – scheme
5 pav. Poligonaliniai paviršiai: *A* – nuotrauka, *B* –schema

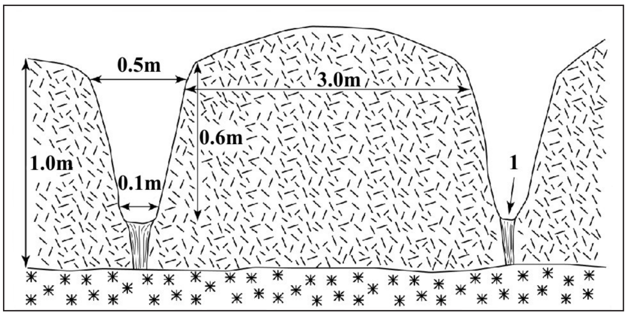

Fig. 6. Cross-section of permafrost surface: *1* – ice wedge

6 pav. Poligonalinio paviršiaus segmento pjūvis: *1* – ledo kylis

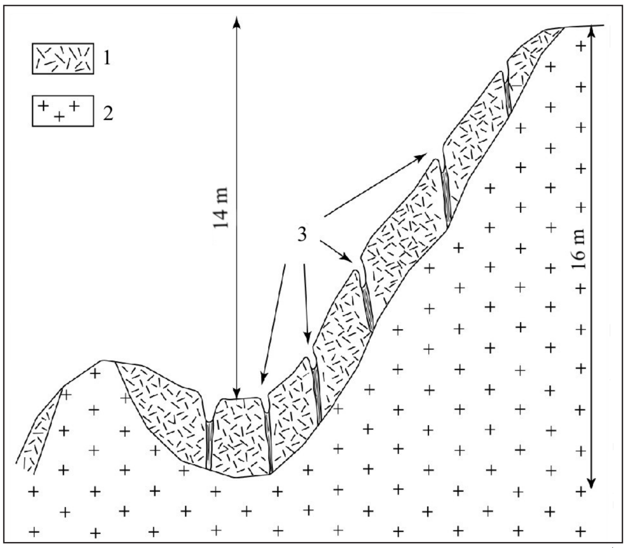

Fig. 7. Cross-section of permafrost surface on the slope: *1* – peat, *2* – magmatic rocks, *3* – ice wedge

7 pav. Poligonalinio paviršiaus pjūvis šlaite: *1* – durpės, *2* – magminės uolienos, *3* – ledo kylis

A rather rapid drying of accumulated sediments takes place in the higher peripheries of glaciofluvial valleys where drainage conditions are better. The cold arid winds blowing from the glacier (v = 10–15 m/s) blow out the dust and fine-grained, medium-grained and coarse-grained sand from the glaciofluvial sediments. Coarse material is transported by creeping and saltation. Ripple marks on the sand and embryo dunes are generated by one combined deflation–accumulation process. The altitude of the dunes reaches 0.4–0.6 m. The embryo dunes form in 10–12 hours at a wind velocity of 8–12 m/s.

In relief declensions whose longitudinal axes coincide with the dominant wind direction, deflation processes prevail. An intensive blowout was observed in a saddle mountain between the Russell and the Leverett glaciers (Fig. 8). The deflation pavements at the bottom of the saddle mountain extend along the NE–SW line. Sediments of the pavement are composed of pebbles (Ø 7–10 cm) and boulders (Ø 10–20 cm). Due to wind turbulence, the slopes of the saddle mountain are exposed to strong local vortexes. Deflation niches and outcrops appear as a result (Fig. 9). Figure 10 demonstrates a typical view of an outcrop. Its altitude is 1.3–1.7 m and the length is 30 m. The outcrop shows three sediment layers. The upper homogeneous 0.5–0.6 m layer is composed of accumulated aleurite. The middle heterogeneous layer is composed of sandy aleurite with pebbles. They have former landslide debris that covered the lower sandy aleurite layer. The latter layer represents a cover generated by physical gelation weathering. The sophisticated sediment structure and shapes of landforms are the imprints of the activity of aeolian and erosion epigenetic processes in surfaces with a slope angle 7–10°.

Deflation niches are widespread on both slopes of the glaciofluvial valley. Their size ranges from 10–12 to

Fig. 8. Deflation pavement

8 pav. Defliacinis grindinys

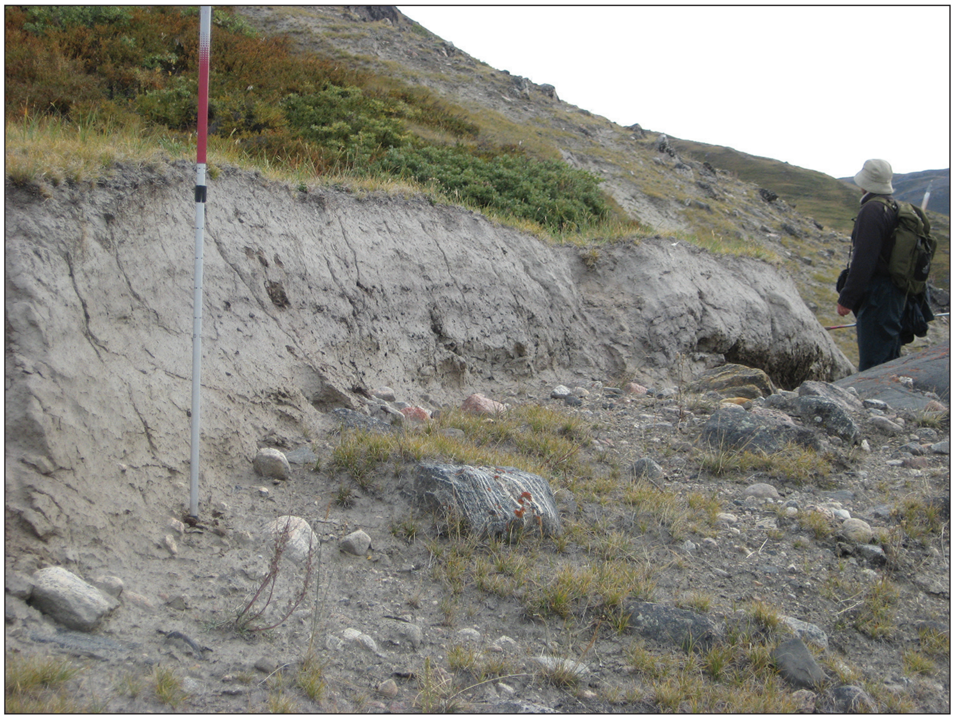

Fig. 9. Deflation outcrop

9 pav. Defliacinė atodanga

50–60 m^2. The niches border on low (1–2 m in height) relief scarps. The blown out slopes of the scarps show outcrops of a weathered debris cover mixed with material reworked by solifluction.

Diatom investigations. Diatoms were examined in 25 peat samples. A rich diatom complex, in total 102 taxa belonging to 24 genera, was recorded. Three diatom zones were distinguished according to diatom flora development throughout the section (Fig. 11).

In the lowermost part of the section (64–90 cm), the genus *Eunotia* species (*E. implicata, E. praerupta, E. bilunaris*) comprised a large part of the total diatom flora. *Eunotia* is a strong indicator of acid, fresh, oligotrophic water, rich in oxygen and poor in organic nitrogen compounds. Many *Eunotia* species are able to live at places which are not permanently submerged. Such epiphytic species as *Tabellaria fenestrata, Gomphonema parvulum, Gomphonema accuminatum* and typically nordic *Achnanthes minutissima* are abundant in this zone as well. Here, the highest variety in diatom species through the section is registerd.

The next diatom zone could be distinguished at a depth of 34–64 cm. The *Eunotia* species decreased markedly and are dominated by *Eunotia praerupta* which thrives from circumneutral to slightly acidic, humic, shallow water with a high dissolved organic carbon (Pienitz, Smol, 1993). The genus *Pinnularia* species, indicative of acid and oligotrophic freshwater, appear and the species *P. viridis* and *P. aestuari* prevail among them. The species *Caloneis tenuis* has a wide distribution as well.

The uppermost part of the section (5–34 cm) is dominated by *Pinnularia* species (*P. viridis, P. borealis, P. aestuari, P. brevicostata*), and the species *P. borealis* is dominant among them, reaching up to 60%. This is an aerophilous species occurring commonly in subaerial environments, often living exposed to air and not totally submerged under water. One more aerophilous species, *Hantzcshia amphioxys*, is also common (up to 10%) in this zone. A great variety of the *Navicula* species is registered as well (*N. semen, N. pussila, N. Navicula placentula* f. *rostrata*).

Some presence of planktonic species such as *Cyclotella radiosa, Cyclotella ocellata*, *Thalassiosira excentrica* is registered in the lowermost part of the section, indicating a higher water level.

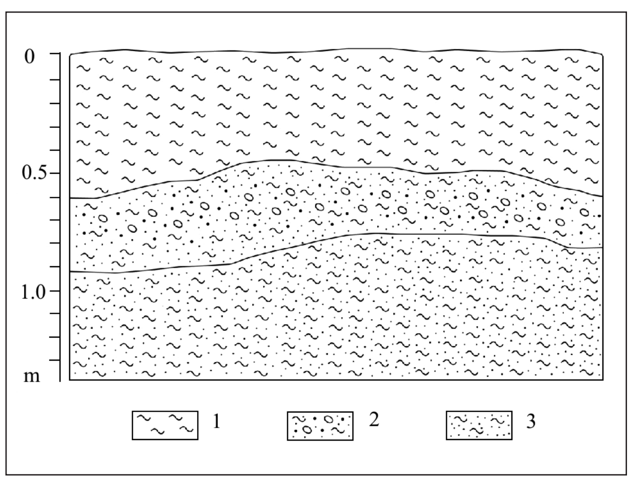

Fig. 10. Typical scheme of a deflation outcrop: *1* – silt, *2* – pebbles, gravel, sand and silt, *3* – silty sand

10 pav. Defliacinė atodanga: *1* – aleuritas, *2* – gargždas, žvirgždas, smėlis ir aleuritas, *3* – aleuritingas smėlis

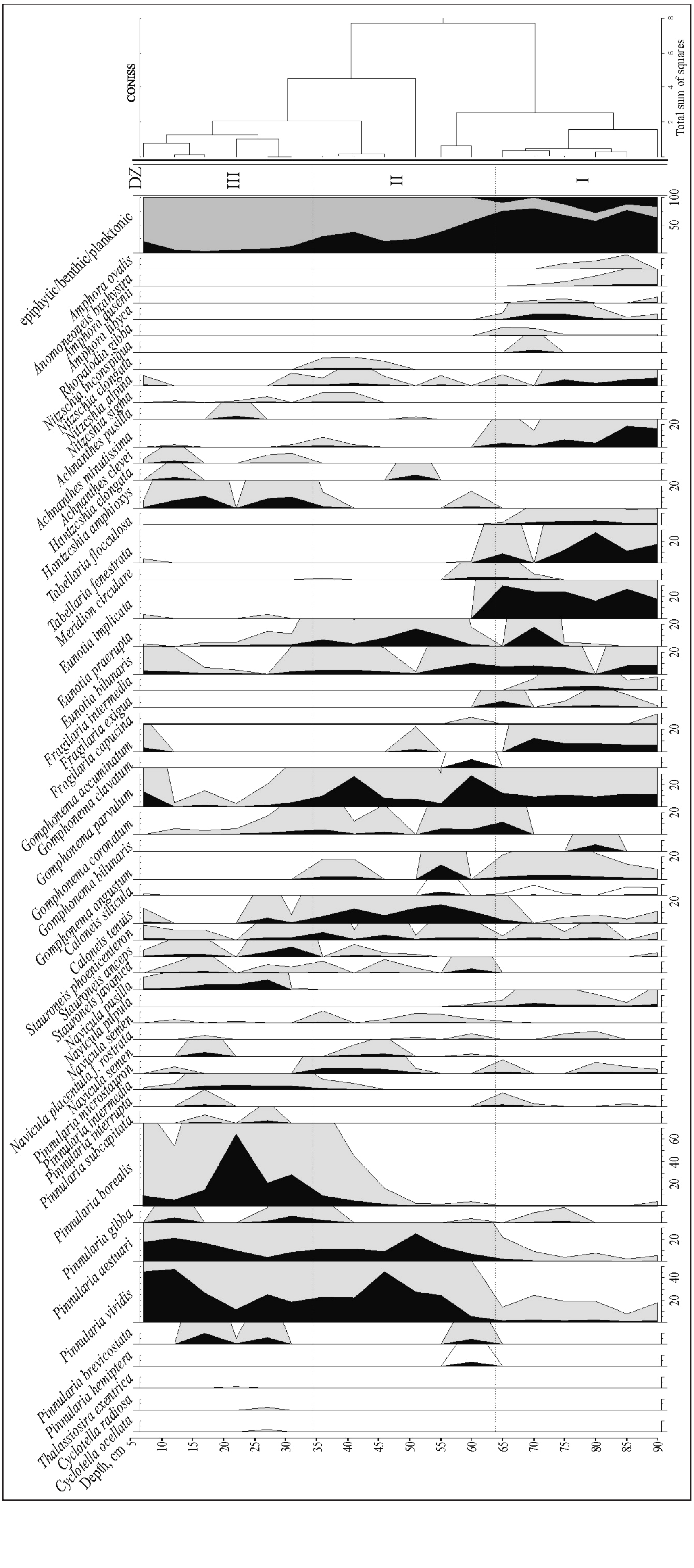

Fig. 11. Diagram of the sediment section studied
11 pav. Tirto nuosėdų pjūvio diatomėjų diagrama

CONCLUSIONS

The investigation has shown that cryogenic processes modifying the sediment layers and transforming the generated landforms are most intensive in the terminal zone of the recessing glacier. The sediment horizons of the terminal zone of the recessing glacier could be explored only in a few natural outcrops. Due to permafrost, only shallow trenches and holes could be dug for analysis of sediment transformation. They included only the layer of powdery sediments and could be hardly applied for interpretation of sediment transformations.

Structural analysis of periglacial sediments in slopes showed that subdued evaporation and shallow permafrost were favourable conditions for cryoturbations. Typical polygonal surfaces develop in relief declensions as a result of shallow magmatic rocks, permafrost and especially subdued evaporation in short warm seasons. Abrupt freezing of the water accumulated in peat generates a network of irregular ice wedge pentagons splitting the peat into small segments. In warmer and more arid summers, the peat layer thinning and the whole polygonal surface gets transformed.

The most intensive aeolian processes take place in the valleys generated by glaciofluvial flows. The inequigranular sediments deposited by ice thaw water are blown out or reworked by cold and arid winds. Powdery material is blown out during the process of wind erosion, whereas the coarser material is transported by creeping or saltation. Sand ripple marks and embryo dunes are widespread in glaciofluvial valleys. Deflation processes, generating deflation pavements composed of pebbles and boulders, take place in declensions of the erosion relief. Deflation outcrops and niches sized up to 10–60 m² form in the hill slopes.

The diatom complex observed in peat sediments describes history from a local, cold basin influenced by glacial meltwater to a subsequent development toward oligotrophy and a lower pH.

ACKNOWLEDGEMENTS

The authors are thankful to Prof. V. Baltrūnas and Dr. B. Karmaza for the help in the fieldwork and valuable discussions. We thank reviewers for helpful comments on the paper. The research was supported by the Lithuanian State Science and Studies Foundation (No C–07008 "Paleoklimatas").

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RELJEFO FORMŲ IR NUOGULŲ TRANSFORMACIJOS PERIGLACIALINĖMIS SĄLYGOMIS (VAKARŲ GRENLANDIJA)

S a n t r a u k a

Vakarų Grenlandijoje atlikti tyrimai leido įvertinti kriogeninių procesų intensyvumą recesuojančio ledyno terminalinėje zonoje. Kriogeniniai procesai smarkiai paveikia nuosėdinių uolienų storymę ir jau susidariusias reljefo formas. Dėl daugiamečio įšalo nuogulų sluoksnių transformacijas galima ištirti tik negausiose natūraliose paviršiaus atodangose bei sekliuose kasiniuose.

Reljefo formų šlaituose, kur susikaupia pakankamai stora (1,5–2 m) periglacialinių nuogulų danga, negiliai esantis daugiametis įšalas, magminės uolienos bei silpnas garavimas sudaro palankias sąlygas kriotarbaciniams procesams. Čia formuojasi tipiški poligonaliniai paviršiai. Durpingose nuogulose esančios drėgmės ir vandens staigus užšalimas rudens pradžioje skatina ledo kylių susidarymą, dėl to susiformuoja netaisyklingų penkiakampių tinklas – poligonaliniai paviršiai. Šiltesnėmis ir sausesnėmis vasaromis aptirpus ledo kyliams pakinta ir poligonaliniai paviršiai.

Intensyviausi eoliniai procesai vyksta fliuvioglacialinės kilmės paviršiuose. Neišrūšiuotas ištirpusias ledyno nuogulas ledo tirpsmo vandenų tėkmės vasarą gabena ir suklosto fliuvioglacialiniuose slėniuose. Nuo ledyno pučiantys stiprūs vėjai perklosto ir išrūšiuoja nuogulas, suformuodami eolines reljefo formas: smėlio ruzgas, embrionines kopas. Išpustymo metu suformuojamos žvirgždo ir gargždo dangos, dažniausiai paplitusios šlaitų papėdėse. Defliacinės atodangos ir nišos formuojamos kalvų šlaituose, o atskirų formų plotas siekia 10–60 m².

Rastos diatomėjos liudija, kad sedimentacija uždaruose vandens baseinuose vyko rūgščioje šaltoje oligotrofinėje aplinkoje.

Альгимантас Чяснулявичюс, Вайда Шейрене

ТРАНСФОРМАЦИЯ ФОРМ РЕЛЬЕФА И ОСАДОЧНОГО МАТЕРИАЛА В ПЕРИГЛЯЦИАЛЬНЫХ УСЛОВИЯХ (ЗАПАДНАЯ ГРЕНЛАНДИЯ)

Резюме

Исследования, проведенные на западе острова Гренландия, позволили оценить интенсивность криогенных процессов, происходящих в терминальной зоне рецессирующего ледника. Криогенные процессы сильно влияют на толщу осадочного покрова, а также изменяют формы рельефа, созданные другими геоморфологическими процессами. Исследование криогенных процессов было осложнено присутствием многолетней мерзлоты, вследствие чего трансформацию отложений можно было изучать лишь на малочисленных обнажениях и в неглубоких шурфах.

На подножиях и склонах форм рельефа, где накопился достаточно толстый слой рыхлых отложений (до 1, 5–2 м^2), многолетняя мерзлота и слои магматических пород, а также незначительное испарение создают благоприятные условия для криотурбации. Здесь формируются типичные полигональные грунты. Резкое замерзание воды и влаги, находящейся в торфистых отложениях, приводит к формированию ледяных клиньев, вследствие чего образуется сеть пятиконечных полигонов. В более теплые и сухие летние периоды ледяные клинья тают, одновременно изменяя и поверхность.

Наиболее интенсивные эоловые процессы протекают в мелкозернистых флювиогляциальных отложениях. В летнее время флювиогляциальные потоки промывают несортированный ледниковый материал и откладывают его на днищах долин. Сильные ветры, дующие со стороны ледника, сортируют и переоткладывают материал, а также создают эоловые формы: песчаные волны и эмбрионные дюны. Дефляционные процессы создают многочисленные гравийно-галечные покровы, распространенные на подножиях склонов. Дефляционные обнажения и ниши формируются на склонах холмов, площади отдельных форм достигают 10–60 м^2.

В донных осадках бывших замкнутых мелких водоемов присутствие диатомей указывает на то, что седиментация происходила в холодной олиготрофической среде.