GEOLOGIJA. 2009. Vol. 51. No. 1–2(65–66). P. 23–32
DOI: 10.2478/v10056-009-0003-3

Glacigenic landform features in marginal zone of Russell and Leverett glaciers, West Greenland

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Šinkūnas P., Česnulevičius A., Karmaza B., Baltrūnas V. Glacigenic landform features in marginal zone of Russell and Leverett glaciers, West Greenland. *Geologija*. Vilnius. 2009. Vol. 51. No. 1–2(65–66). P. 23–32. ISSN 1392-110X

During glacial ice melting, the sedimentation of transported material creates a variety of landforms depending on bedrock surface, glaciodynamic processes and features of sedimentation in glacial and periglacial environments in the ice marginal zone. The landforms created during sedimentation in glacial and periglacial environments are greatly dependent on the location or subenvironment of the sedimentation process, i. e. on whether it is taking place in subglacial, englacial, supraglacial, terminoglacial or proglacial subenvironments. The landform study at the marginal zone of the Russell and the Leverett glaciers in Western Greenland near Kangerlussuaq was carried out in glacial and periglacial environments. Besides morphological observations, the architecture of glacially accumulated forms was studied in outcrops. All these studies enabled to analyse the landforms in relation to glacial and periglacial facies. Marginal and proglacial forms in front of the Leverett Glacier were mapped in detail. Sedimentation of lodgement, basal, ablation and flow till deposits was observed in different subenvironments of the glacial environment in the marginal part of the glacier. These deposits in the form of till complexes in the periglacial environment were studied as landforms – lateral and end moraines formed in a terminoglacial subenvironment and basal till plains in a proglacial subenvironment left after ice retreat. Ice-cored moraines with a washboard moraine type surface of kettled topography with water ponds in kettle holes were studied in the ice divide area between the Russell and the Isunnguata glaciers. The whole complex of landforms of different origin was studied in the ice marginal zone of the Leverett Glacier, the south-western branch of the Russell Glacier. The data collected during this study indicate the importance of the climatological factors lying behind the exceptional geodiversity of the area and the glaciodynamic contribution to the richness of landforms in the marginal zone of the Russell and the Leverett glaciers.

Key words: glacigenic deposits, proglacial landforms, moraines, West Greenland

Received 03 January 2009, accepted 30 January 2009

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INTRODUCTION

The relationships between the lithofacies in glacigenic sequences allow the delineation of glacial events in areas of continental glaciations. However, the reflection of sedimentary environment in the structure and composition of glacigenic deposits is very complex. For this reason, it is not always easy to identify the processes of sedimentation during research dealing with glacigenic sediment sequences. Thus, to study the features of sedimentation in present glacial environments in order to find a key to identify them in sediment sequences of old continental glaciations is very important, along with the implication of the analysis method when the knowledge on the present day processes is the key for understanding the past ones. Therefore, the knowledge on contemporary glacier–landform interactions is the key for Quaternary palaeoglaciological reconstructions.

Eroded bedrock material transported by glaciers is derived either supraglacially from nunataks and valley sides or from erosion of the subglacial bed (Boulton, 1978). Debris eroded from bedrock is initially transported in the basal zone of traction, where particles undergo crushing and plucking. During ice melting, the sedimentation of transported material creates a variety of landforms reflecting the sedimentation environments in the ice marginal zone. The landforms created during sedimentation in glacial and periglacial environments greatly depend on the location or subenvironment of the sedimentation process – whether it is taking place in subglacial, englacial, supraglacial, terminoglacial or proglacial subenvironments (Brodzikowski, Van Loon, 1991). The terminoglacial subenvironment is considered as a space for the creation of a more spectacular landscape in most cases. Quite different landforms are created in a proglacial environment by meltwater streams transporting the glacial material and accumulating it along the stream passway and in places of its entrance into proglacial lakes. Therefore, the variety of places and conditions of sedimentation in glacial and periglacial depositional environments creates a high diversity of landforms.

FIELD SITES AND METHODS

The study area (Fig. 1) at the marginal zone of the Russell and the Leverett glaciers in Western Greenland lies near the Kangerlussuaq International Science Support (KISS) centre and can be easily reached from there. The general view of the Russell Glacier is presented in one of the publications of this issue, devoted to the characteristics of basal ice (Baltrūnas et al., 2009). The Leverett Glacier is the south-western branch of the Russell Glacier.

The observation of glacigenic landforms in the marginal area of the Russell and the Leverett glaciers was carried out in glacial and periglacial environments. Besides the morphological observations, the architecture of glacially accumulat-

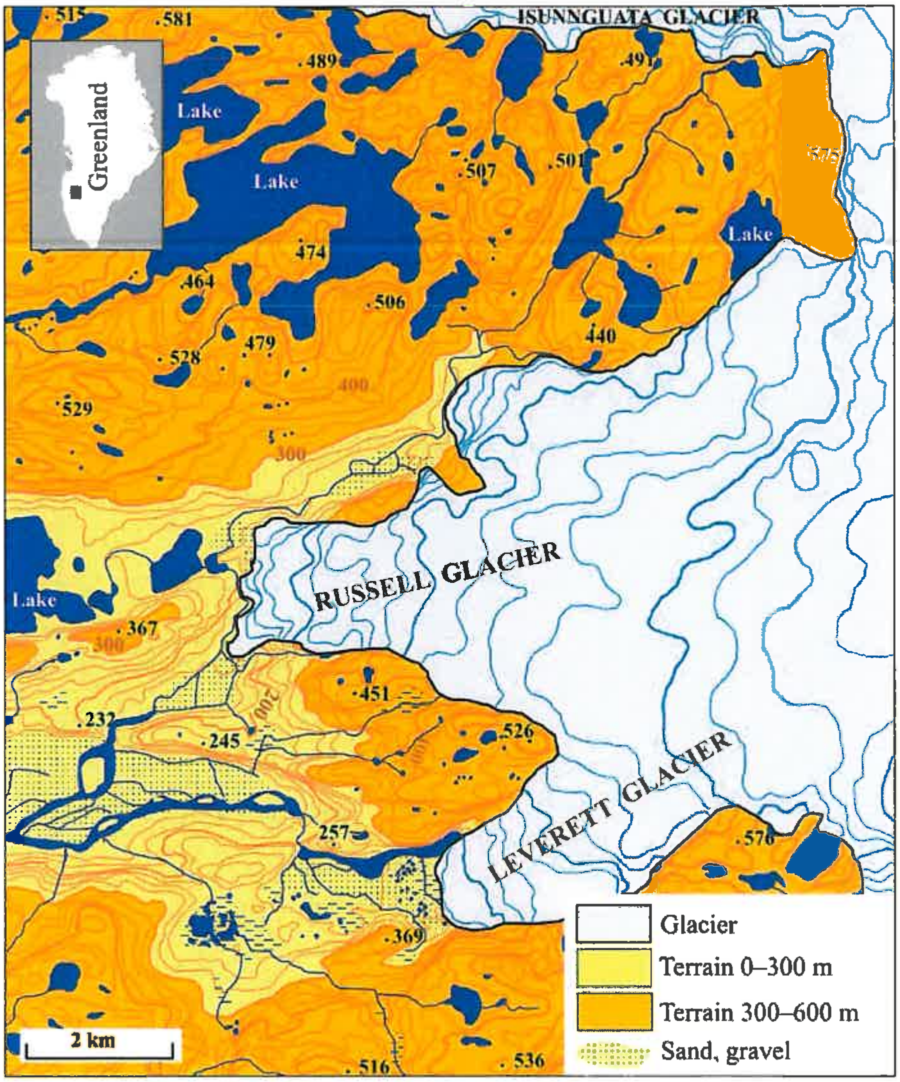

Fig. 1. Topography of Russell and Leverett glaciers area, West Greenland

1 pav. Russell ir Leverett ledynų bei apylinkių Vakarų Grenlandijoje topografija ed forms was studied in outcrops along with the description of bedforms, lamination, presence of buried ice, etc. carried out in excavations 0.8–1.0 m deep as well. Samples for grain-size measuring were taken from basal and end moraines. Ice-bearing till was analysed as well after the ice had melted and samples where dried in laboratory. All these studies enabled to analyse the landforms in relation to glacial and periglacial facies (Table; Figs. 2, 3).

The morphological features of landforms were measured using a tape-measure and a GPS navigation device. The GPS navigation device was used for the contouring of landforms and altitude measuring. Slope inclinations were measured with an optical hand clinometer. The aerial distribution of glacial and periglacial landforms was studied using simple satellite images found in the Internet and aerial photos, what enabled to delineate the areas of different glacial and periglacial landform types. The marginal and proglacial landforms in front of the Leverett Glacier were mapped in detail.

THE LANDFORMS STUDIED

Examination of the depositional setting of ice marginal deposits at the margin of the Russell and the Leverett glaciers by means of observation of exposures and landforms in West Greenland provided a possibility to evaluate an interrelation between glacial facies and landforms. Greenland was completely or almost completely covered with ice during most of the Quaternary, therefore, glacial deposits are widespread on ice-free land areas and on the adjacent shelf (Bonow et al., 2006). After the latest deglaciation had begun 14,000–10,000 years ago, the minimum position was reached approximately 5000 years ago when the ice margin was at least 15 km inland of its present position in West Greenland (Weidick et al., 1990). So, the margin of the Russell and the Leverett glaciers is situated at the present location after some re-advance. This re-advance could influence the character of landforms; however, it is quite complicated to recognize these features.

Sedimentation of lodgement, basal, ablation, flow and ice-raft till deposits can be recognized in different subenvironments of the glacial environment (Fig. 2) near the margin of the glacier. In the periglacial environment, these deposits are usually observed as till complexes composing lateral and end moraines as landforms formed in the terminoglacial subenvironment or basal till plains in proglacial subenvironment left after ice retreat (Fig. 3).

Sedimentation of **lodgement till** is restricted to a subglacial subenvironment where it is deposited in a contact zone between the ice and substratum during ice movement. Its observation in the marginal part of the Russell and the Leverett glaciers is limited to ice outcrops. Lodgement till deposits can be easier found there in contact between the basal ice and the substratum; however, such outcrops are unstable, appearing and disappearing year after year as the ice moves forward, melts and its edge is eroded by meltwater streams.

Table. **Presence of deposits of glacigenic facies in glacial and periglacial subenvironments (after Brodzikowski, Van Loon, 1991; Šinkūnas, Jurgaitis, 1998)**
Lentelė. **Glacigeninių facijų nuogulų paplitimas glacialinėje ir periglacialinėje subaplinkose (pagal Brodzikowski, Van Loon, 1991; Šinkūnas, Jurgaitis, 1998)**

Glacigenic facies	Deposits	Glacial environment				Periglacial environment	
		Subenvironments					
		Englacial	Subglacial	Supraglacial	Terminoglacial	Proglacial	Extraglacial
Melting ice	Lodgement till						
	Basal till						
	Ablation till						
	Ice-raft						
	Till complex						
Fluvial	Tunnel						
	Stream						
	Sheet- and streamflood						
	Fluvial complex						
Deltaic	Topset						
	Foreset						
	Bottomset						
	Deltaic complex						
Lacustrine	Lake margin						
	Bottomsets						
	Lake complex						
Aeolian	Dune						
	Coversand						
	Loess						
	Aeolian complex						
Mass transport	Flow till						

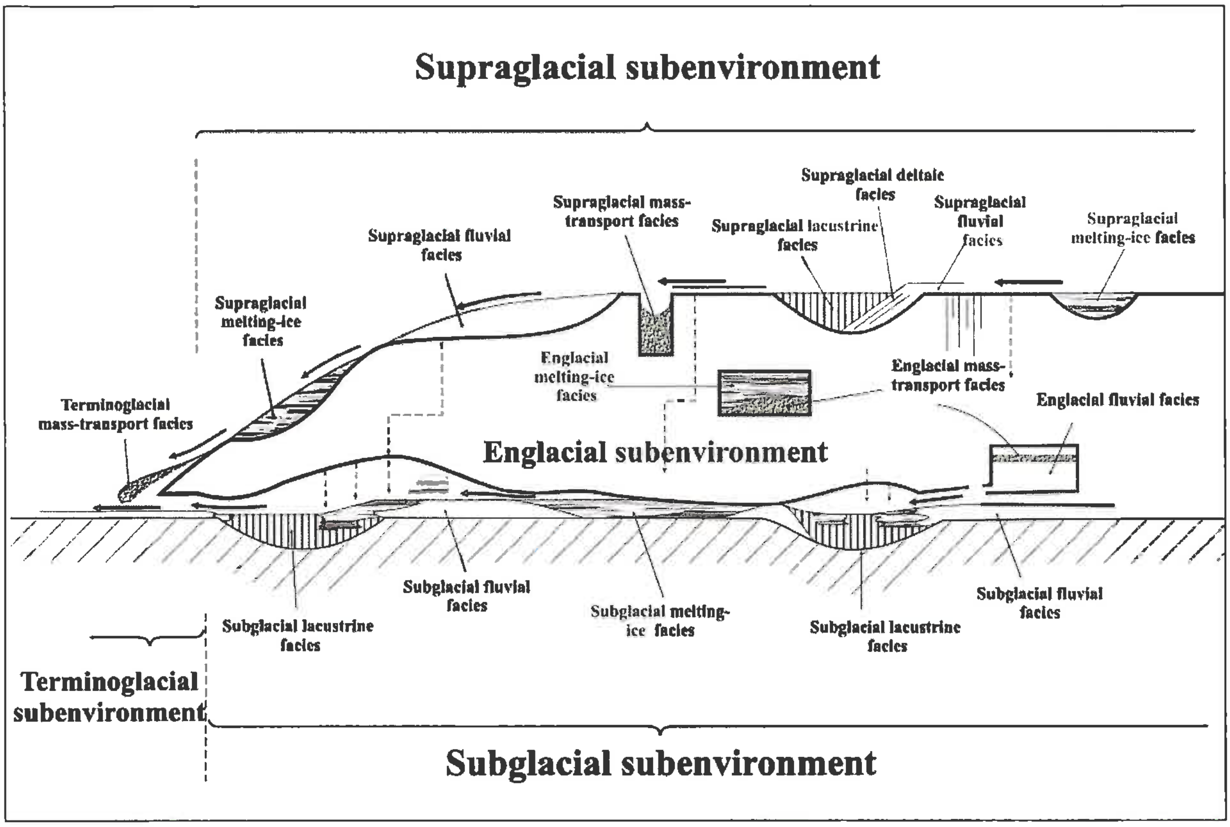

Fig. 2. Glacial environment of sedimentation under continental conditions (modified after Brodzikowski, Van Loon, 1991)

2 pav. Ledyninė sedimentacijos aplinka žemyno sąlygomis (pagal Brodzikowski, Van Loon, 1991)

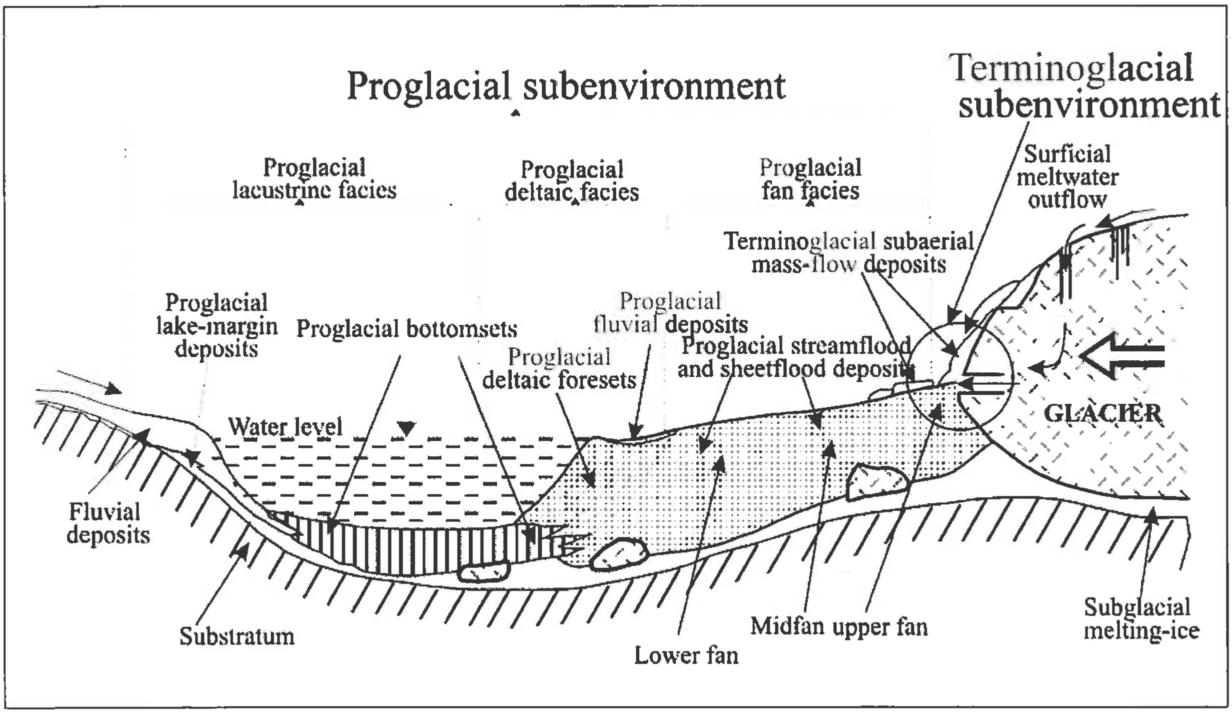

Fig. 3. Terminoglacial and proglacial subenvironments (modified after Brodzikowski, Van Loon, 1991)

3 pav. Terminoglacialinė ir proglacialinė subaplinkos (pagal Brodzikowski, Van Loon, 1991)

The observation of **basal tills** as *in situ* formed subglacial diamicts is in a similar situation. However, in river or meltwater stream eroded glacial sediment sequences, basal tills in front of the Russell and the Leverett glaciers are more frequently observed in the present proglacial subenvironment in areas of the former passive ice melting.

Conditions of ice melting (or sublimation) due to temperature rise during the warm season are favourable for **ablation till** accumulation more or less *in situ* on glacier surface in supraglacial and terminoglacial subenvironments. In some places, the middle moraine material exarated from nunataks and transported within the glacier feeds the accumulation of till on its surface due to subaerial ice melting. The existence of slopes on the undulated or irregular surface of glaciers favours the mass transport process. Due to plastic flowage, especially on slopes of ice at the glacier margin, the water-saturated material of ablation till is easily involved into mass transport and becomes a **flow till**.

As very little is known about the relationship between grain-size distribution and glacigenic meltout or subaerial mass movement and because the grain-size analysis may reveal possible sedimentation mechanisms, samples for grain-size comparison were taken from basal ice, ablation (flow?) till on the glacier surface, lateral and end moraines. It is obvious from grain-size data (Fig. 4) that silt size and finer particles are the first ones to leave the diamicton under the glacial sediment rewashing with water and further resedimentation.

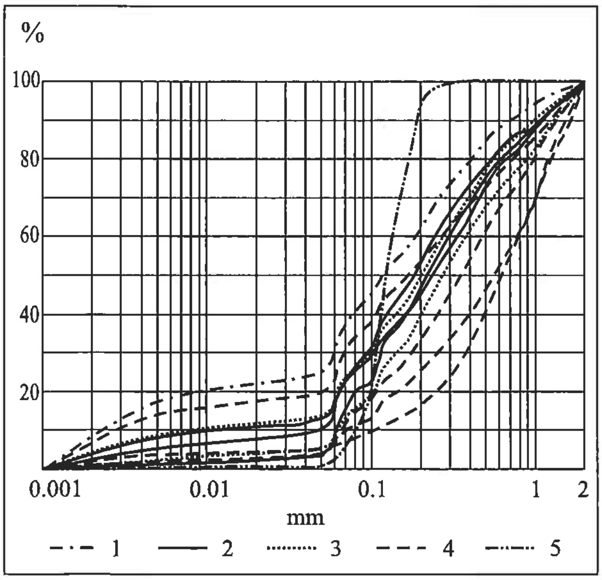

Fig. 4. Cumulative curves of grain-size distribution of clastic material from: *1* – basal ice, *2* – ablation (flow?) till, *3* – lateral moraines, *4* – end moraines and *5* – aeolian deposits

4 pav. Nuotrupinės medžiagos pasiskirstymo pagal dydį kumuliacinės kreivės: *1* – pamatinio ledo, *2* – abliacinės (tekėjimo?) moreninės medžiagos, *3* – šoninės morenos, *4* – galinės morenos ir *5* – eolinių nuogulų granuliometrinės sudėties

The melt-out material is falling and creeping from subaerial slopes of ice at the glacier edges along the Russell and the Leverett glaciers margins forming end and lateral moraine ridges, especially in places free of steep rock barriers in front of the ice. The terminal moraine ridges as landforms resulting from till accumulation at the glacier margin are well expressed on the surface. The **lateral moraines** are prominent along the northern fringe of the Russell Glacier tongue between the Upper and the Lower Russell lakes. The lateral moraine ridge 180–200 m long and 15–20 m high is separated from the glacier by an ice meltwater stream which is giving source from beneath the glacier at the outlet site of the drainage system of Lake Upper Russell described in a publication of this issue (Česnulevičius et al., 2009). There are two small glaciokarst depressions with lakes in them on the ridge surface. Samples for grain-size measurements were taken at the higher surface sites on the ridge from the depth of 0.3 m. Well expressed lateral moraine ridges can be traced along the southern fringe of the Russell Glacier as well.

The western end of the Russell Glacier tongue is moraine-rimmed (Fig. 5). The **end moraine** ridges accumulated on eroded Proterozoic gneisses are intersected by an ice meltwater stream. At the south-westernmost glacier end corner, the meltwater stream separates the end moraine ridge from the glacier, eroding the glacial ice wall, and keeps it steep. From higher parts of this end moraine ridge 250 m in length, 10–50 m in width and 15–20 m in height, glacial sediment samples for grain-size measurements were taken.

Quite an intricate **moraine complex** is formed on the north-eastern edge of the Russell Glacier in ice divide area between the Russell and the Isunnguata glaciers tongues. The ice divide there is formed by nunatak of crystalline rocks, their surface reaching 500 m a. s. l. The moraine complex in the ice stream divide is expressed by a variety of landforms.

At the proximal side of the end moraine ridge, the glacial ice and ice-cored thrust moraines are covered with subglacial material delivered by meltout and thrusts to the supraglacial position (Roberts et al., 2008). The surface of debris-covered glacial ice and ice-cored thrust moraine is expressed as subparallel stripes 1–2 m in height, stretching parallel to the ice margin (Fig. 6). Like washboard moraines, they possibly mark the annual dynamics of ice by small end moraine ramparts formed during winter advance phases (Ehlers, 1996) or covering ice by melt-out material at the edge of a glacier in summer and thus protecting it from melting. The kettled topography with water ponds in kettle holes at the surface of the ice-cored thrust moraine is formed due to buried ice melting.

The entire complex of landforms of different origin was studied in the ice marginal zone of the Leverett Glacier – the south-western branch of the Russell Glacier. The surface of the Leverett Glacier, due to its bedrock topography, lowers gradually to the front of the glacier and equals to the bordering terminal moraines up to 10 m in height (Fig. 7).

Fig. 5. End moraine ridge at the western end of Russell Glacier tongue

5 pav. Galinės morenos gūbrys vakariniame Russell ledyninio liežuvio gale

Fig. 6. Kettled topography with water ponds in kettle holes and washboard surface of ice cored thrust moraine in ice divide area between Russell and Isunnguata glaciers

6 pav. Glaciokarstinis reljefas su ežerėliais įgriuvose ir skalbimo lentą primenantys gūbriukai morenos su ledo branduoliu paviršiuje

The proglacial area in front of the Leverett Glacier is presented by an end moraine complex stretching about 800 m along the glacial margin and separated from it by a small proximal sandur plain formed by braided glaciofluvial streams. The surface of the end moraine complex, about 450 m wide and 15–20 m high, is expressed by smaller glacial ridges up to 3 m in height and glaciokarst ponds (Fig. 8). The pronounced conical mound 10 m high on the surface of the end moraine complex was interpreted by H. Scholz and M. Baumann (1997) as an open-system **pingo**, as a most conspicuous structure generated in the permafrost region – a conical hill containing ice lens.

The distal part of the sandur surrounds the second-end moraine complex at its distal part. The meltwater streams originated in the glacial environment in the terminoglacial

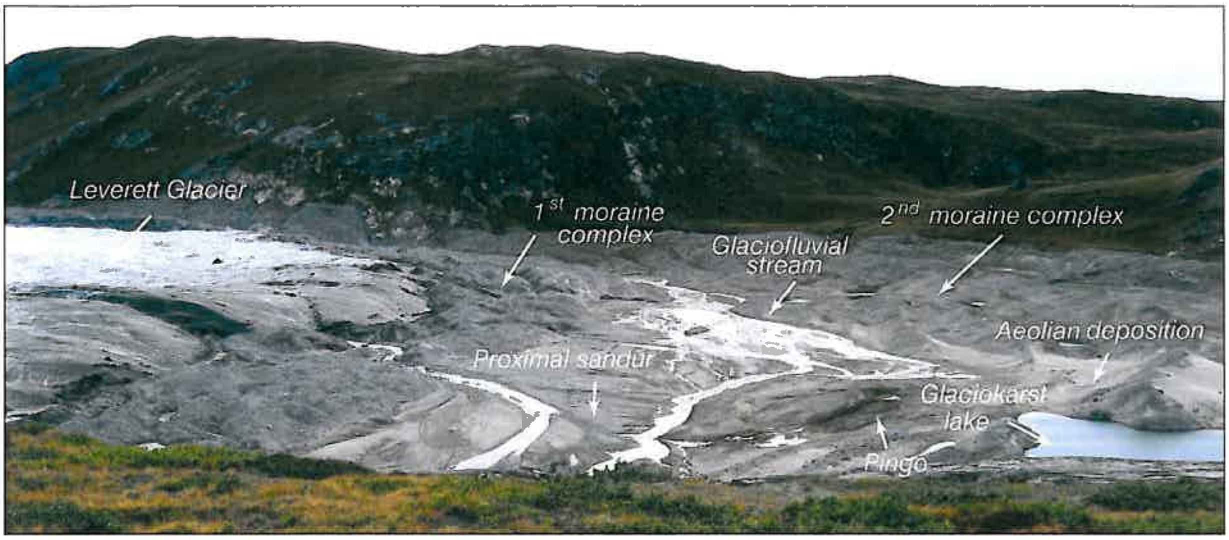

Fig. 7. Terminoglacial and proglacial subenvironments of Leverett Glacier

7 pav. Leverett ledyno terminoglacialinė ir proglacialinė subaplinkos

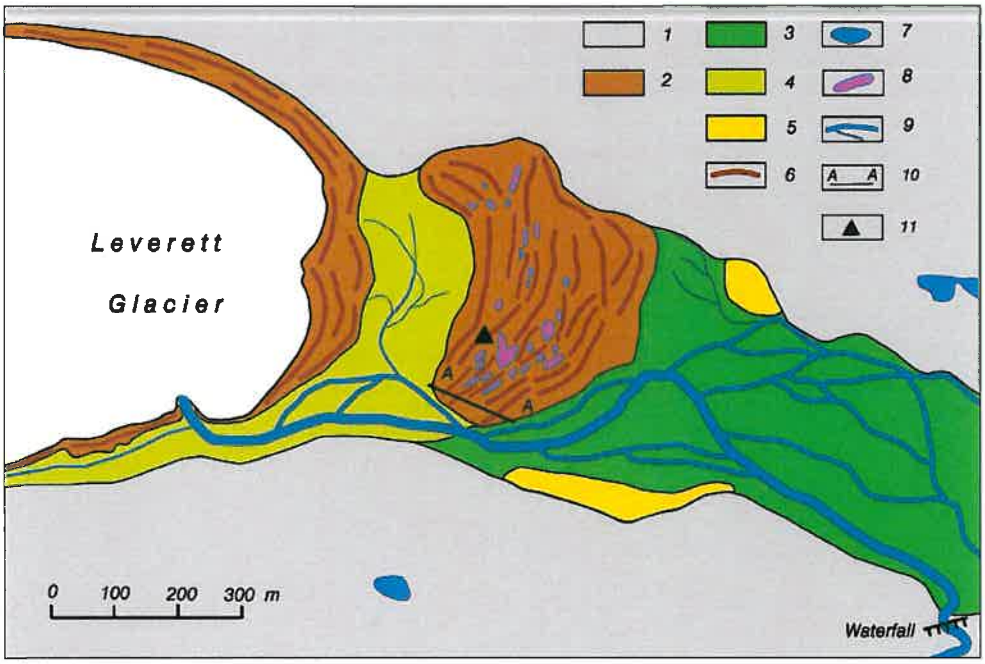

Fig. 8. Terminoglacial and proglacial landform complexes of Leverett Glacier: *1* – bedrock, *2* – end moraine complex, *3* – distal sandur, *4* – proximal sandur, *5* – aeolian complex, *6* – moraine ridges, *7* – lakes, *8* – glaciokarst ponds, *9* – meltwater streams, *10* – outcrop, *11* – pingo

8 pav. Leverett ledyno terminoglacialinio ir proglacialinio reljefo kompleksas: *1* – pagrindo uolienos, *2* – galinių morenų kompleksas, *3* – distalinis zandras, *4* – proksimalinis zandras, *5* – eolinis kompleksas, *6* – moreniniai gūbriai, *7* – ežerai, *8* – glaciokarstiniai ežerėliai, *9* – ledyno tirpsmo vandens srautai, *10* – atodanga, *11* – degraduojantis hidrolakolitas

Fig. 9. Section of end moraine complex in marginal zone of Leverett Glacier
9 pav. Galinės morenos pjūvis Leverett ledyno marginalinėje zonoje

subenvironment form the **ice-marginal streamways (prodolinas)** that run parallel to the ice front. Such meltwater streams passing the terminoglacial subenvironment form rivers fed by ice meltwater. The relief, the amount of meltwater and the debris determine the depositional pattern in these streamways. **Aeolian** sedimentation takes place over the entire streamway area, whereas glaciofluvial sedimentation, however, prevail over the deposition of wind-blown material. Drift sands, small dunes and coversands are found along the Watson River formed by a concentration of ice meltwater channels. The grain-size data of aeolian sand (Fig. 4) are the sieving results of an aeolian sand sample taken in the Watson River valley near Kangerlussuaq. The aeolian coversands exist also in the proglacial area of the Leverett Glacier.

The key characteristics of the end moraine complex in the proglacial zone of the Leverett Glacier are presented in a special publication of R. I. Waller and G. W. Tuckwell (2005). The presence of a large stream-cut exposure (Fig. 9) allows examination of its internal structure and surface morphology. It is built up of layers composed of different proportions of ice and sediment, including debris-poor ice, ice-rich diamicton and ice-rich gravel. Ice and sediment units are glaciotectonized and show features of a major fault and an associated drag fold, a planar, erosional unconformity, and a variety of small-scale folds. The structural characteristics are explained by a two-phase model involving ice advance and proglacial or ice-marginal compression, followed by overriding and subglacial deformation and erosion tentatively related to ice advance. This interpretation opposes the explanation that the sequence simply represents a buried basal ice layer. The polygenetic origin of this ice-marginal, glaciotectonic landform can be considered as a contrast to the majority of Arctic push-moraines. They are largely considered to be a result of proglacial deformation and a stacking of imbricate thrust sheets of frozen sediment. This contrast probably reflects differences in the thickness and spatial continuity of permafrost within the glacier foreland, and adds to the range of ice-marginal landforms associated with glacier-permafrost interactions (Waller, Tuckwell, 2005).

CONCLUSIONS

The variety of sedimentation places and conditions in glacial and periglacial depositional environments in the marginal zone of the Russell and the Leverett glaciers resulted in a high diversity of landforms.

The initial material creating landforms in different subenvironments of a glacial environment is lodgement, basal, ablation and flow till deposits in a periglacial environment, observed as till complexes composing lateral and end moraines formed as landforms in a terminoglacial subenvironment or basal till plains after ice retreat left in a proglacial subenvironment.

Debris-covered glacial ice and ice-cored thrust moraines, marking the annual dynamics of ice, are widespread in the very margin of the glaciers with a common kettled topography.

The complex of landforms of different origin, studied in the ice marginal zone of the Leverett Glacier, is very representative of ice marginal zones. There it is expressed by bordering terminal moraines, an end moraine complex with smaller glacial ridges and an open-system pingo on it, proximal and distal sandur plains and ice-marginal streamways with aeolian landforms taking place. The presence of an open-system pingo within a system of moraine ridges is quite unexpected.

The structural characteristics of the internal structure of the end moraine complex in the proglacial zone of the Leverett Glacier, well exposed and studied in a large stream-cut exposure, are best explained by a two-phase model involving ice advance and proglacial or ice-marginal compression, followed by overriding and subglacial deformation and erosion, tentatively related to ice advance.

Data assembled during this study indicate that primarily climatological factors lie behind the exceptional glacial geodiversity of the area, and glaciodynamics contributes to the wealth of landforms under particularly favourable conditions in the marginal zone of the Russell and the Leverett glaciers.

ACKNOWLEDGEMENT

The research was supported by the Lithuanian State Science and Studies Foundation within the projects T-06029 and C-07008. The authors are thankful to the Danish Polar Centre and the Kangerlussuaq International Science Support (KISS). Great thanks go to Keele University researcher and experienced glacier expert Dr. R. I. Waller for consultations and kindly presented areal photos.

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GLACIGENINIO RELJEFO YPATYBĖS RUSSELL IR LAVERETT LEDYNŲ PAKRAŠTYJE VAKARŲ GRENLANDIJOJE

Santrauka

Vakarų Grenlandijoje Russell ir Leverett ledynų marginalinės zonos pradinėje stadijoje kaupiasi dugninė, pagrindinė ir abliacinė moreninė medžiaga. Abliacinė moreninė medžiaga kaupiasi ledyno paviršiuje. Vandeninga moreninė medžiaga dėl gravitacijos ir supraglacialinių bei intraglacialinių ledyno tirpsmo vandens tėkmių poveikio pažemėjimuose ir jų šlaituose virsta tekėjimo (*flow till*) morenine medžiaga. Moreninė medžiaga ledyno pakraštyje kaupiasi formuodama poligenetinės medžiagos kompleksus – galinių ir šoninių morenų reljefo formas. Šoninės ir galinės morenos išsiskiria raiškiais gūbriais, kurių paviršių paįvairina glaciokarstas, įdubose sukurdamas nedidelius, dažnai laikinus ežerėlius.

Ties Russell ir Isunnguata ledynų kristalinių uolienų ledoskyra iškilęs stambus moreninis masyvas pasižymi glaciomorfologinių reljefo formų įvairove. Čia paplitusios glaciokarstinės dubės, vidurinės morenos gūbriai, kurių paviršių dengia įstriži lygiagretūs neaukšti gūbriukai, primenantys skalbimo lentą. Jų formavimasis susijęs su ledyno tirpimu ir kasmetine jo pakraščio kaita.

Leverett ledyno gale susidaręs „klasikinis" ledyno pakraščio darinių kompleksas apima kelis moreninės ir fliuvioglacialinės kilmės reljefo ruožus. Pačiame ledyno gale formuojasi kelias osciliacinių gūbrių grandines turintis galinės morenos ruožas. Už jo prasideda tipiškas nuolaidus proksimalinis zandras, suformuotas laikinų, nuo ledyno tekančių, klaidžiojančių tirpsmo vandens tėkmių. Proksimalinis zandras siekia senesnįjį moreninių darinių ruožą, turintį 6–8 osciliacinių gūbrių grandines. Šiame komplekse vyksta glaciokarstiniai ir eoliniai procesai, kurių veiklos rezultatas – glaciokarstiniai ežerėliai, eolinės dangos ir degraduojantis hidrolakolitas (pingas). Nuo Laverett ledyno tekantis koncentruotas fliuvioglacialinis srautas, jungdamasis su kitais panašiais srautais, sudaro ledyno tirpsmo vandenimis maitinamą upę. Nešmenimis užpildžiusi buvusį platų egzaracinį duburį ji už moreninių darinių ruožo suformavo distalinę zandro dalį. Zandrą sudarančios ir prieledyninės upės suneštos nuogulos vietomis perpustomos į eolinio smėlio dangas ir kopas.

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ОСОБЕННОСТИ ГЛЯЦИГЕННОГО РЕЛЬЕФА МАРГИНАЛЬНОЙ ЗОНЫ ЛЕДНИКОВ РУССЕЛЛ И ЛЕВЕРЕТТ В ЗАПАДНОЙ ГРЕНЛАНДИИ

Резюме

На исследованном в Западной Гренландии участке в маргинальной зоне ледников Русселл и Леверетт в начальной стадии накапливается материал донного, основного (базального) и абляционного тиллов. Абляционные отложения накапливаются на поверхности ледника, в понижениях и их склонах; вследствие гравитации, а также потоков супрагляциальных и интрагляциальныж талых вод они становятся тиллом (мореными отложениями) течения (flow till). Моренный материал в краевой части ледника накапливается в виде полигенетических комплексов, среди которых наиболее распространены такие формы рельефа, как конечные

и боковые морены. Эти морены выделяются четкими гребнями, поверхность которых деформируется под воздействием гляциокарстовых процессов, в результате чего образуются небольшие временные озерки. На ледораздельном участке ледников Русселл и Исуннгуата возвышается крупный моренный массив, характеризующийся обилием гляциоморфологических форм рельефа. Здесь распространены гляциокарстовые просадки и впадины, гребни срединных морен. На склонах последних наблюдаются косонаправленные невысокие параллельные гребешки, в совокупности напоминающие стиральную доску. Их образование связано с таянием ледника и с ежегодной динамикой его краев.

У конечной части ледника Леверетт наблюдается „классический" комплекс краевых ледниковых образований, охватывающий две полосы ледникового и водно-ледникового генезиса. В краевой части ледника формируется участок краевых морен в виде нескольких осцилляционных гребней. Вслед за ними начинается сформированный временными талыми ледниковыми водами типичный наклоненный проксимальный зандр. Он отделяет упомянутый краевой моренный комплекс от более древнего, представленного 6–8 вереницами осцилляционных гребней. В этом моренном комплексе протекают гляциокарстовые и эоловые процессы, результатом которых являются гляциокарстовые озерки, эоловые покровы и деградирующий пинго. Основной концентрированный флювиогляциальный поток, берущий начало от ледника Леверетт, сливаясь с другими подобными потоками, образует флювиогляциальную реку, отложениями заполняющую широкую экзарационную долину.

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Eos, Vol. 89, No. 35, 26 August 2008

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 89 NUMBER 35
26 AUGUST 2008
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Jökulhlaup Observed at Greenland Ice Sheet

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On 31 August 2007, about 35 kilometers upstream from the town of Kangerlussuaq, in western Greenland, a roughly 0.5-square-kilometer permanently ice-dammed lake on the northern flank of the Russell Glacier—an outlet glacier of the Greenland Ice Sheet—suddenly broke free and drained into the Watson River (Figure 1). A 25-meter drop in the lake water level resulted over an approximately 17-hour period (Figure 3a). A glacial outburst such as this is known by the Icelandic term jökulhlaup, derived from the words jökull (glacier) and hlaup (meaning sprint or burst) [*Robert*, 2005].

Before 2007, the last known jökulhlaup from this glacier was in July 1987; jökulhlaups at this location occur once every 8–10 years on average. The 2007 jökulhlaup occurred after the most intensive melt season—with the biggest melting area and melt index (defined as the melting area times the number of melting days)—on the Greenland Ice Sheet since the first satellite observations in 1979 [*Tedesco*, 2007]. The ice dam broke after 4 days with a temperature range of 4.0°–17.0°C, averaging 9.5°C, resulting in glacier ablation, and with a rainfall total of 33 millimeters (Figure 2a).

At the Watson River's drainage basin outlet at Kangerlussuaq, six discharge measurements were conducted during low flow in June 2007 as a part of a recently started research program: Stage and discharge were lower than 14.5 meters and 150 cubic meters per second, respectively. River stage was measured every 20 minutes during the runoff season from June to September, and it was recorded with a pressure transducer placed approximately 75 meters upstream from where two bridges cross the river at well-defined, stable cross sections on bedrock. These discharge measurements were used to develop a stage-discharge relationship ($R^2 = 0.91$) and to convert the stage measurements into a river discharge time series. The relationship had an accuracy of 5–10% during low flows; peak flow estimates were less accurate because all of the discharge measurements for developing the stage-discharge association were made during low flows.

The 2007 summer stage hydrograph shows that the rising limb of the short-lived jökulhlaup began at 3:00 A.M. local time (UT – 2 hours) on 31 August, and the stage peaked approximately 11 hours later at 2:00 P.M. The direct contribution of the jökulhlaup to the enhanced runoff appears to have ended at 8:00 P.M. on 31 August. At its peak, the river stage was 4.25 meters above the average August water level (Figure 2a).

On the basis of the stage-discharge relationship, the maximum Watson River discharge during the jökulhlaup is calculated to have been approximately 540 cubic meters per second, and the total runoff during the event is estimated to have been 28.8 million cubic meters (Figure 2b). Outflow from the ice-dammed lake is estimated to have been 11.3 million cubic meters; the additional 17.5 million cubic meters is due to frictional melting of ice as the flood traveled in contact with the glacier, together with an input from base flow.

Most jökulhlaups in western Greenland are undetected and occur far from populated centers with at-risk infrastructure. As in this case, though, jökulhlaup events can sometimes pose a serious risk to nearby communities [*Roberts*, 2005]. If the stage had crested even 1 meter higher during peak time on 31 August, the water line may have washed out bridges and cut off the water supply to Kangerlussuaq (Figure 3b). Furthermore, the two bridges that span Watson River also may have failed during the peak event. If the jökulhlaup had occurred during mid-July or mid-August, when the ice melt contribution from the Greenland Ice Sheet was very high, the river stage would have been substantially higher and most likely would have resulted in considerable infrastructure damage.

In a warmer climate, there may be an increase in the frequency and impacts of these jökulhlaups [*Evans and Clague*, 1994]—due to increasing future air temperature, increasing melting, and increasing runoff—but a decrease in their magnitude due to changes in glacier/ice sheet dynamic processes.

Acknowledgments

Thanks to Mark Begnaud, VECO Polar Resources, for the photographs, and

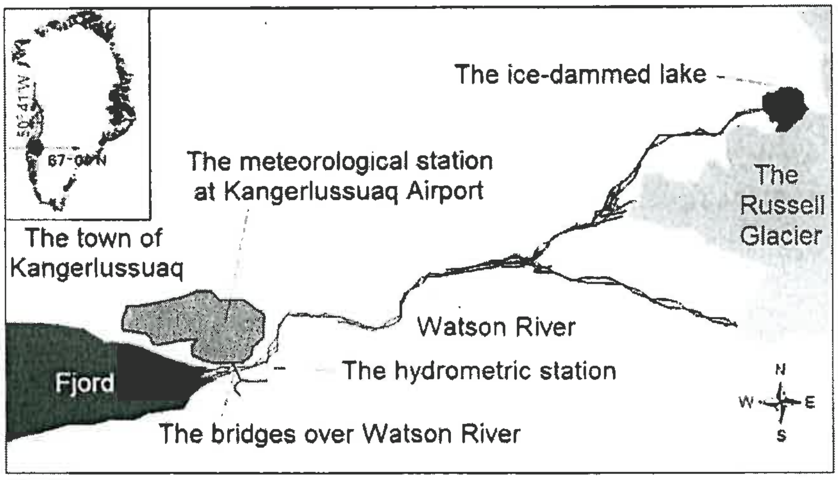

Fig. 1. Kangerlussuaq area, western Greenland (black dot in inset map), including the location of the ice-dammed lake and the hydrometric station at the drainage basin outlet. The figure is out of scale. The lake is approximately 35 kilometers upstream from the station.

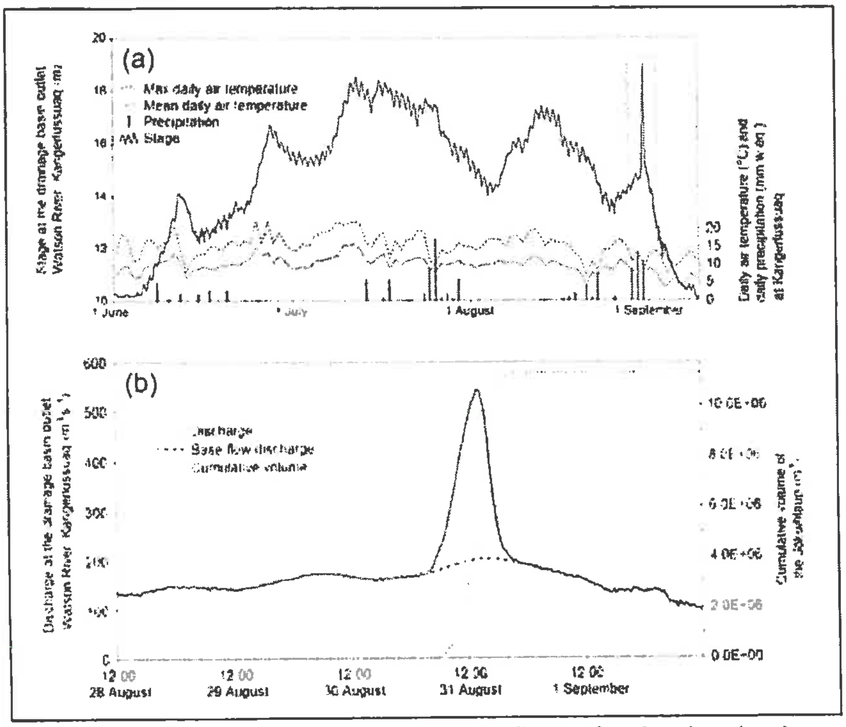

Fig. 2. (a) Variations in stage during the 2007 summer runoff season from June through early September at the drainage basin outlet at Kangerlussuaq. The dotted rectangle indicates the jökulhlaup. (b) Enlargement of the discharge variations during the short-lived jökulhlaup from the period 28 August through 1 September.

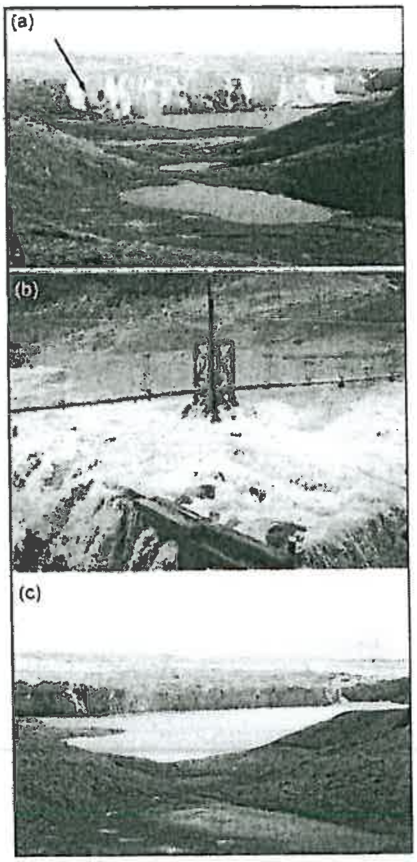

Fig. 3. (a) The ice-dammed lake on 2 September 2007 after the jökulhlaup. The arrow indicates the water level in the lake before drainage. (b) The water supply pipeline just upstream from the two bridges over the Watson River at the drainage basin outlet at Kangerlussuaq during peak time on 31 August 2007. (c) The ice-dammed lake on 10 August 2008. Photos by Mark Begnaud, VECO Polar Resources.

Matthew J. Roberts, Icelandic and Meterological Office, for the insightful review.

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