New methods to reconstruct clast transport history in different glacial sedimentary environments: Case study for Old Red sandstone clasts from polythermal Hørbyebreen and Bertilbreen valley glaciers, Central Svalbard

Martin Hanáček[1*], Daniel Nývlt[2,1], Jan Flašar[3], Václav Stacke[4], Peter Mida[5], Jiří Lehejček[6], Gabriela Tóthová[7], Michal Břežný[8], Barbora Procházková[5], Tomáš Uxa[5], Iva Křenovská[7]

[1]*Centre for Polar Ecology, University of South Bohemia, Na Zlaté stoce 3, 370 05 České Budějovice, Czech Republic*
[2]*Department of Geography, Faculty of Science, Masaryk University, Kotlářská 267/2, 611 37 Brno, Czech Republic*
[3]*Department of Geology and Palaeontology, Faculty of Science, Charles University in Prague, Albertov 6, 128 43 Praha 2, Czech Republic*
[4]*Centre of Biology, Geoscience and Environmental Education, University of West Bohemia, Klatovská 51, 306 19 Plzeň, Czech Republic*
[5]*Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague, Albertov 6, 128 43 Praha 2, Czech Republic*
[6]*Department of Silviculture, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences, Kamýcká 1176, 165 21 Praha 6 – Suchdol, Czech Republic*
[7]*Department of Geological Sciences, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic*
[8]*Department of Physical Geography and Geoecology, Faculty of Science, University of Ostrava, Chittussiho 10, 710 00 Ostrava - Slezská Ostrava, Czech Republic*

Abstract

The objective of this study were Little Ice Age (LIA) to recent subglacial tills, glaciofluvial sediments of proglacial sandur, esker sediments and sediments of moraine-mound complexes of Hørbyebreen polythermal valley glacier and LIA to recent sediments of lateral moraine, frontal moraine, ice-cored moraine and glaciofluvial sediments of proglacial sandur of Bertilbreen polythermal valley glacier. Fossil (probably early Holocene) subglacial and supraglacial tills and sediments of coarse-grained glaciomarginal delta of Bertilbreen have also been studied. The research focused on Old Red sandstone clasts, for which roundness, shape and striation presence have been investigated. The results from this research led to the proposal of new methodological approaches. It is mainly the covariant plot of striations and RA (the

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[*]Corresponding author: Martin Hanáček <HanacekM@seznam.cz>
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share of striated clasts versus the share of very angular and angular clasts), which effectively differentiate subglacial tills from glaciofluvial sediments and allows for identification of the source material of moraine-mound complexes, especially the oldest, more degraded parts near the maximum LIA glacier extent. The second is the covariant plot of distance and RS index (the distance from the starting point versus the share of subangular and subrounded clasts) to present downstream roundness trends in proglacial glaciofluvial sediments. The research confirmed the crucial role of lithological properties of thinly bedded rocks on the shape of these rock clasts in sediment and a minimum impact of passive and active transport on the clast shape modification.

Key words: clast striation, clast roundness, clast shape, Old Red sandstone clasts, glacial sedimentary environments, Svalbard

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Introduction

Clast roundness and shape and their changes due to the transport length are typically studied parameters in glacial sedimentary environments. The most commonly used recent method is graphical presentation of mutual relation between clast shape and roundness using the covariant plot of C_{40} and RA indices (*see* chapter Methods for further details; Benn et Ballantyne 1994). This plot allow a clear distinction between sediments dominantly being passively supraglacially transported and those, which have been actively subglacially transported and has been widely employed in many studies (*e.g.* Bennett et al. 1997, 1999, Hambrey et al. 1997, 1999, Adam et Knight 2003, Hambrey et Ehrmann 2004, Glasser et al. 2009, Hambrey et Glasser 2012). It is not possible to differentiate subglacial tills and glaciofluvial sediments basing on the shape and roundness of the clasts (Bennett et al. 1997). These sediments are nevertheless the main sources of the material in moraine-mound complexes (Hambrey et al. 1997). Recent moraine-mound complexes of Svalbard glaciers started to develop from the Little Ice Age (LIA) and are still developing with ongoing glacier retreat (Rachlewicz et al. 2007, Evans et al. 2012). We have chosen two valley glaciers located in northern part of Billefjorden (Hørbyebreen and Bertilbreen) for this study. The oldest moraine-mounds located at the LIA maximum glacier extent (frontal moraine) are often degraded and it is not possible to see their former internal structure originated by thrusting (Ewertowski et al. 2011). These are generally diverse convex or flattened elevations of morainic sediments. To identify the source of the material in moraine-mound complex of polythermal Hørbyebreen valley glacier we applied beside the traditional covariant plot of C_{40} and RA also a newly defined covariant plot of striation versus RA, which divides the sediments on the basis of striation and roundness (*see* chapter Methods for further details). Furthermore, we have studied the relationship of clast shape and the transport distance on one sedimentary rock type from the samples originating from Bertilbreen polythermal valley glacier and the possibility of effective graphical presentation of glaciofluvial sediments roundness changes in proglacial sandar of Hørbyebreen and Bertilbreen glaciers. Devonian Old Red sandstone clasts have been chosen for their significant amount, or often dominance in all studied sediments.

Fig. 1. Svalbard archipelago with red point indicating the studied area.

Study area

Hørbyebreen and Bertilbreen are valley glaciers located at the NW margin of Billefjorden, in the vicinity of Petuniabukta and Mimerbukta (Dickson Land, Central Svalbard, Fig 1). Larger amount of other individual and coalescent valley glaciers are present in this area. Hørbyebreen and Bertilbreen represent polythermal glaciers basing on the ice-contact and proglacial zone landforms (Evans et al. 2012, Hambrey et Glasser 2012). The upper parts of valley-sides in the uppermost part of glaciers are made of Late Paleozoic limestone and in lesser extent of Carboniferous sandstone and siltstone. Glacier floor and lower part of valley-sides are composed of Devonian Old Red sandstone. Glacier floor and lower valley-sides are also made of Precambrian orthogneiss and amphibolite (Dallmann et al. 2004) in the case of Hørbyebreen.

Hørbyebreen is ~8 km long and in the marginal part ~1 km wide glacier. Its proglacial zone has been geomorphologically mapped in detail by Evans et al. (2012). The present glacier front lies ~3,5 km upvalley from the LIA frontal moraine (Fig. 2). The LIA frontal moraine has in its terminal part a very pronounced hummocky surface, but is more degraded with a flat surface when continuing to the right lateral moraine. Hummocky moraine field bound morphologically to the frontal moraine in its backward part making a continuous moraine-mound complex. LIA frontal moraine and hummocky moraines are made of diamictons and gravels. They are covered by stripes of supraglacial angular detrit. A morphologically prominent line of elevations and ridges forming an esker stretches on the north side of the proglacial zone along the left lateral moraine. Braided glaciofluvial stream runs along the axis of the proglacial zone; cuts the frontal moraine and creates a sandur in its forefield.

Bertilbreen is ~4 km long and at its front only 100 m wide glacier (Fig. 3). This glacier lies in a much narrower valley then Hørbyebreen and is therefore surrounded by high LIA lateral moraines. The right lateral moraine is fed by the material from a small lateral glacier. The present glacier front has a character of ice-cored moraines and is located ~1,2 km upvalley of the LIA frontal moraine. Braided glaciofluvial stream runs along the axis of the proglacial zone. This erodes the frontal LIA moraine and Old Red sandstone bedrock in front of it making here small canyon. The proglacial stream creates a braided outwash fan (sensu Hambrey 1994) after leaving the canyon.

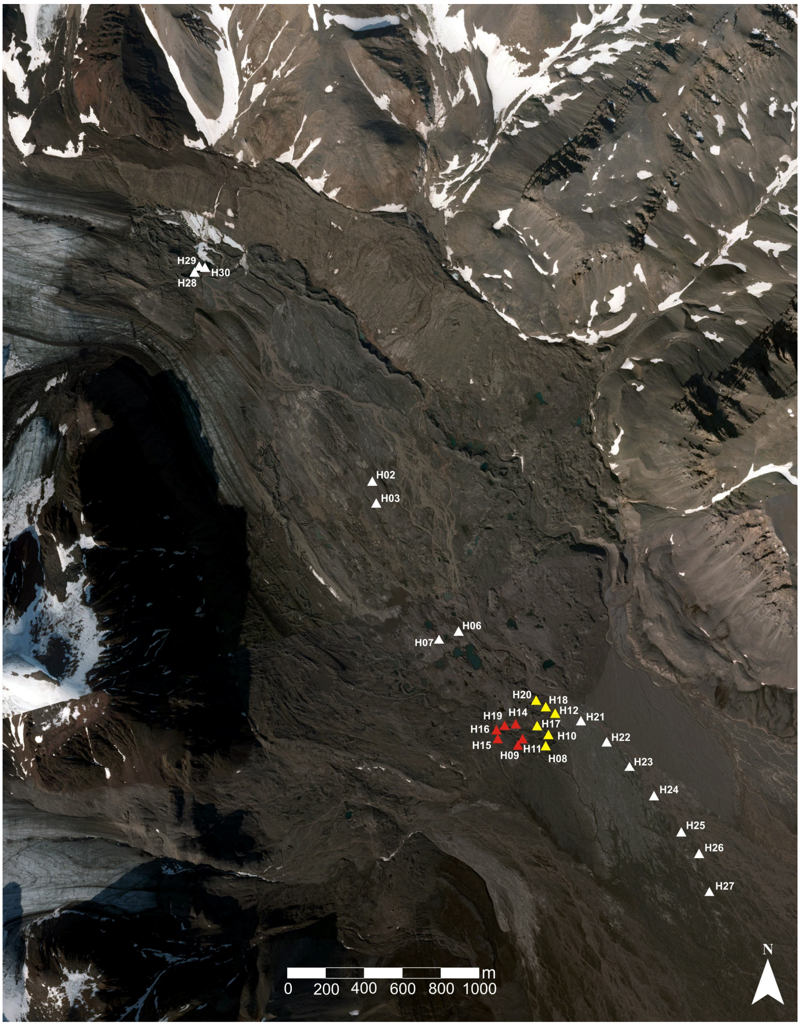

Fig. 2. Hørbyebreen with studied sample locations. Yellow triangles – terminal part of LIA frontal moraine; red triangles – lateral part of LIA frontal moraine; white triangles – other studied landforms.

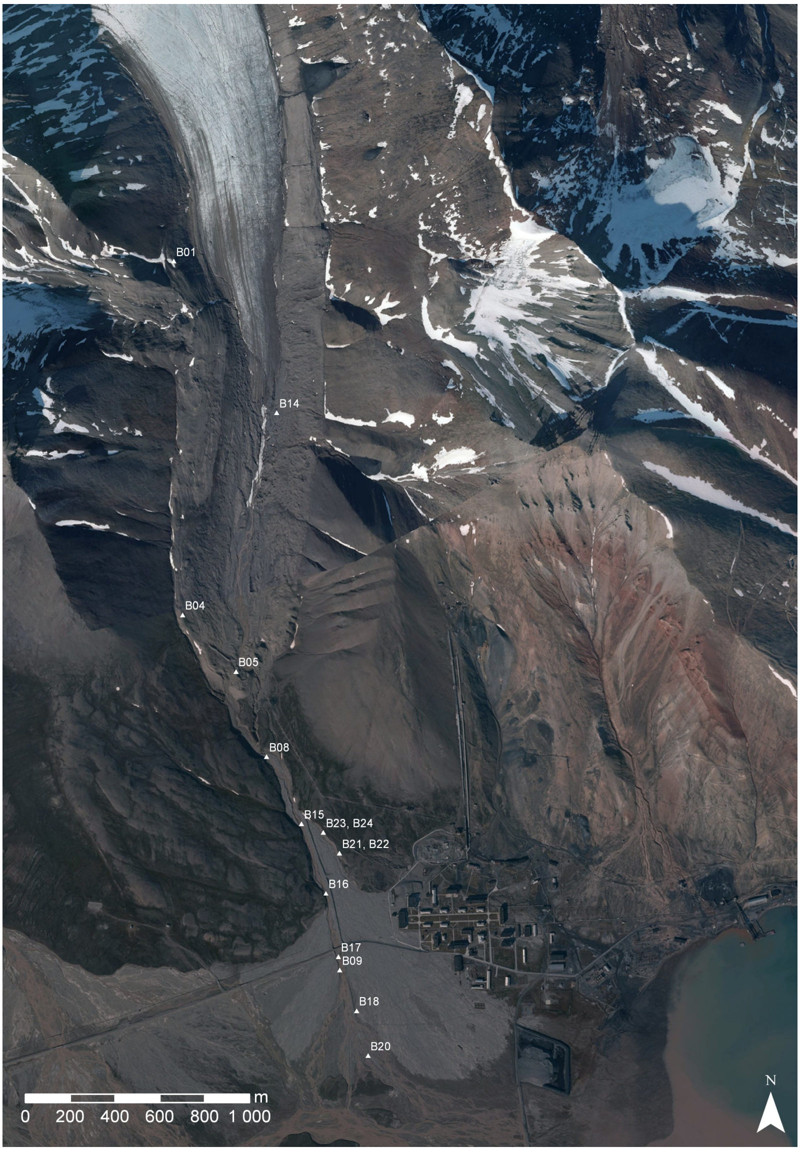

Fig. 3. Bertilbreen with studied sample locations.

Methods

Petrological analyses of gravel clasts have been undertaken from diverse sediments of both glaciers. Each sample contained 100 clasts, for which petrology and clast shape, roundness and surface features have been evaluated. Hørbyebreen sediments contain clasts of Old Red sandstone, Upper Palaeozoic limestone, Carboniferous sandstone and siltstone, orthogneiss and amphibolite. Bertilbreen sediments contain only clasts of Upper Palaeozoic limestone, Old Red sandstone, Carboniferous sandstone and siltstone. Old Red sandstone clasts have been used for a detailed study especially due to their relatively high shares in all analysed sediments. The amount of Old Red sandstone clasts in the samples used in this study lies between 30 and 64 for the LIA sediments (48 in the average and 65% of the samples contain at least 45 analysed clasts). Sediments of moraines, esker and proglacial glaciofluvial streams from LIA of both glaciers are rich in cobble (64–256 mm in b-axis) fraction. We have thus used this fraction for petrological study, which has been taken from a delimited area on the surface of the studied sedimentary bodies. Early Holocene fossil delta sediments and tills (B21–B24) contained even more Old Red sandstone clasts. The numbers of the clasts in samples lies between 78 and 90. Due to a limited outcrop dimension of deltaic sediments we sampled coarse pebble fraction (32–64 mm in b-axis) directly from cleared outcrop by sieving to evaluate their petrology. We measured the following parameters on all studied clasts: a-, b-, c- axis to evaluate clast shape using the ternary diagrams of Sneed et Folk (1958); roundness classes of Powers (1953); and the presence of striation to evaluate the relationship between striation and roundness, which has been evaluated only for samples with at least 10 striated clasts. Covariate plot of C_{40} and RA indexes (Benn et Ballantyne 1994) has been used for mutual evaluation of studied values of clast shape and roundness. The C_{40} index is the relative share of clasts with a c/a ratio of <0.4. The RA index is the share of very angular and angular clasts based on the Powers (1953) roundness classes. We newly used different covariant plots: the covariate plot of the share of striated clasts and RA index (striation/RA) and covariant plot of the transport distance and RS index (distance/RS) for samples of proglacial sandar. The RS (rather sub-) index corresponds to the share of subangular and subrounded clasts based on the Powers (1953) roundness classes.

Results

Till plateau sediments

Hørbyebreen LIA subglacial till (samples H02, H03) described as clast-rich intermediate to sandy diamicton according to the Moncrieff (1989) classification represent till plateau deposits (Fig. 4A). The matrix is of grey colour. Studied subglacial till compose relatively flat till plateau, which is located in front of vertically decaying glacier. Hummocky moraines field continues downvalley from the till plateaus toward the LIA frontal moraines.

Fig. 4. ➞ Photographs of typical studied sediments.
A. Subglacial till - clast rich intermediate diamicton. Hørbyebreen.
B. Hummocky moraine of moraine-mound complexes of Hørbyebreen (sample H06).
C. Proglacial sandur 1.2 km in front of the Hørbyebreen LIA frontal moraine (sample H26).
D. Sandy cobble gravel Hørbyebreen esker (sample H29).
E. Cobble gravel and clast-rich intermediate to sandy diamicton. Terminal part of the Hørbyebreen LIA frontal moraine (sample H20).
F. Egg gravel esker facies as a part of the Hørbyebreen LIA frontal moraine.
G. Ice-cored moraine of recent ice-contact zone of Bertilbreen (sample B14).
H. Fossil (probably early Holocene) coarse-grained delta in the Bertilbreen forefield; foreset (B23) and topset (B24) samples indicated.


A
0,5 m
B
C
D
1 m
E
0,2 m
F
G
0,5 m
H
B24
B23
3 m

Fossil subglacial till of Bertilbreen (sample B21) lies at the base of glacigenic-glaciomarginal deltaic sequence of very probably early Holocene age, which could be seen in erosional face of recent proglacial stream 0.7–1 km downstream of the LIA frontal moraine. It has originally (Hanáček et al. 2011) been due to a poor exposure as glaciofluvial accumulation of the advancing phase of Bertilbreen from LIA. Subglacial till rests on the Old Red sandstone bedrock. It is a clast-rich intermediate diamicton to clast-rich muddy diamicton. The matrix has a reddish colour, which corresponds to the colour of underlying sandstone. These sediments are characterized by relatively abundant striated clasts. Their shares lie in the range 43–68% and around 65% for the Hørbyebreen LIA subglacial tills and Bertilbreen fossil subglacial till respectively (Fig. 5). Furthermore, low values of RA and RR indices and the dominance of subangular and subrounded roundness classes is typical. Hørbyebreen subglacial till contains predominantly isometric clasts, on the other hand Bertilbreen subglacial till contains more slab clasts.

Lateral moraine sediments

LIA lateral moraine studied only at Bertilbreen is predominantly composed of coarse-grained angular debris with only limited amount of matrix. Sample B01 shows high value of RA index and the absence of striation (Fig. 8).

Glaciofluvial sediments of proglacial sandar

Hørbyebreen has a very elongated sandur with a length of 2.5 km extending from the LIA frontal moraine towards the Petuniabukta coast (Fig. 2). Sandur deposits (Fig. 4C) shows clear downstream fining from cobble gravel in proximal part to pebble gravel to pebble sand in its distal part. Predominantly diffuse gravel sheets and longitudinal bars are developed in shallow channels (Smith 1974, Boothroyd et Ashley 1975, Hein et Walker 1977). Bertilbreen proglacial sandur has on the other hand a rather different general morphology (Fig. 3). The proglacial stream erodes into the Old Red sandstone bedrock starting from the LIA frontal moraine. The depth of erosional cut increases with longer downstream distance from the LIA frontal moraine. The proglacial stream thus flows in the LIA frontal moraine forefield through a narrow canyon producing typical valley sandur. The stream draing the right side of the glacier erodes the bedrock in the same way. Coalescent erosional cuts create a wide canyon. The proglacial stream creates broad and relatively short braided outwash fan (sensu Hambrey 1994) after leaving the canyon (*see* Fig. 3). Braided outwash fan sediments correspond to Hørbyebreen sandur sediments. The only difference is the missing downstream fining and the whole fan is made up of cobble gravel.

We have studied the proximal part of Hørbyebreen sandur downstream to 1.4 km from the LIA frontal moraine (samples H21–H27). Cobbles are an essential component of the sediments to a distance of 1 km from the LIA frontal moraine (to the sample H25). Pebble-cobble gravel with prevailing pebbles predominates further downstream (samples H26, H27). The absence of clear downstream trends in roundness, clast shape and striation share (Figs. 6, 12) is typical for this sediments.

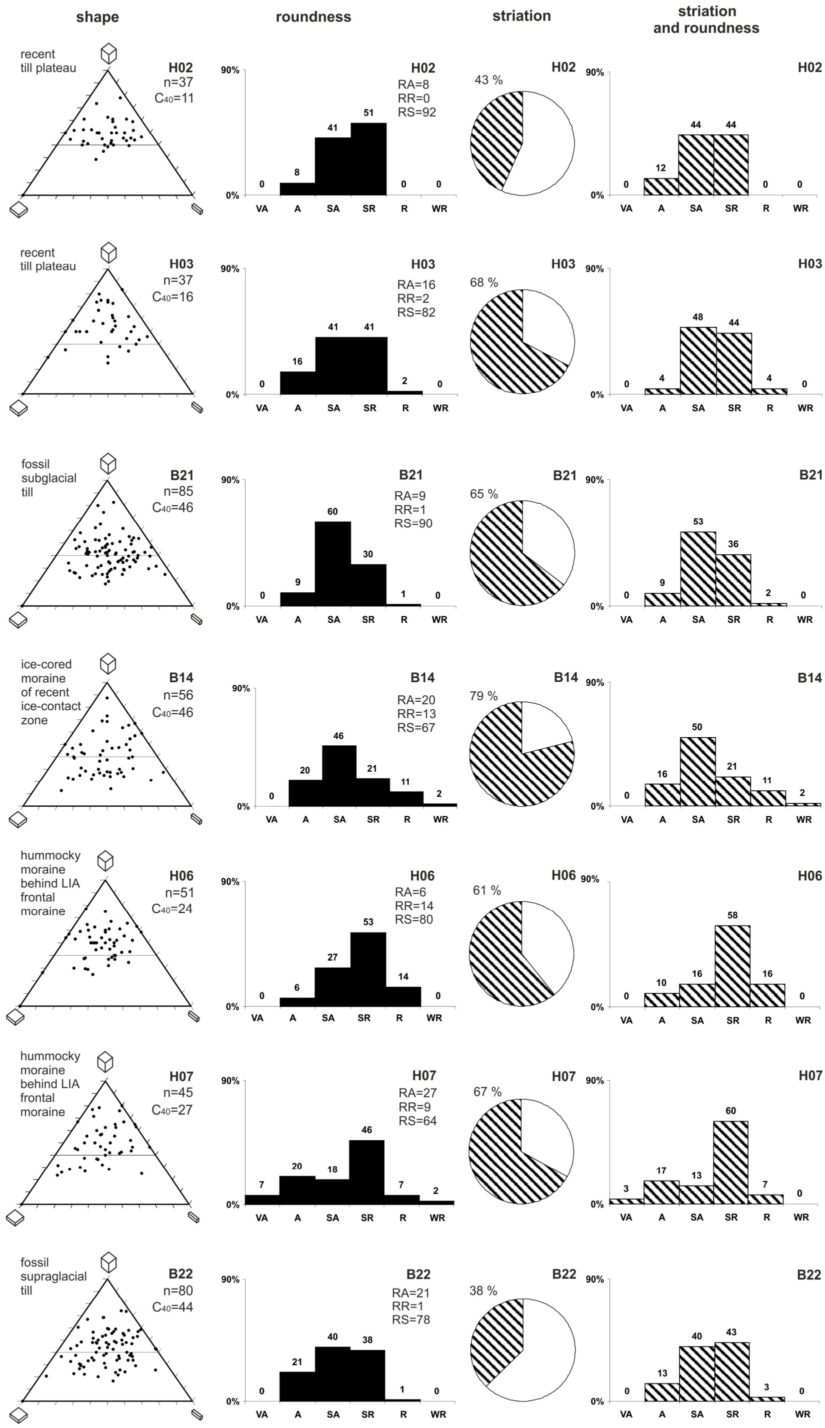

Fig. 5. Shape, roundness and striation of the clasts from subglacial tills and supraglacial sediments composed of subglacial material. Samples from Hørbyebreen and Bertilbreen glacial systems.

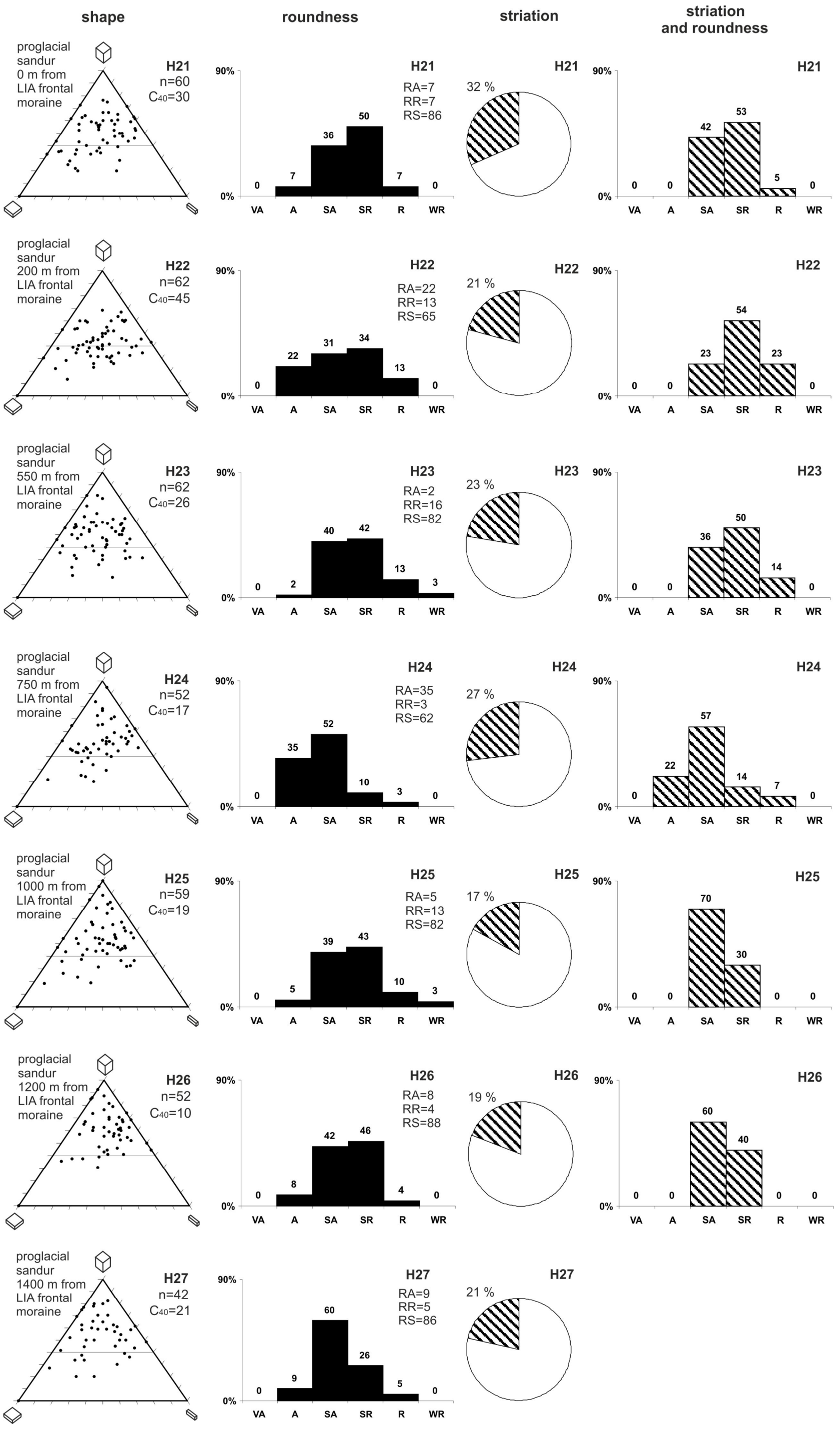

Fig. 6. Shape, roundness and striation of the clasts from glaciofluvial sediments of proximal part of recent Hørbyebreen proglacial sandur.

Bertilbreen sandur has been sampled along its entire length (Figs. 3, 7). Equal shares of all roundness classes could be found in valley sandur sediments in the canyon (samples B08–B16). They generally have lower roundness values comparing to the braided outwash fan (samples B17–B20). This effect is particularly evident when using the RS index (Fig. 12).

Esker sediments

An esker extends along the northern part of Hørbyebreen proglacial zone from the recent glacier front to the LIA frontal moraine. Its sediments are composed of sandy cobble gravel, pebble gravel and gravely sand (Fig. 4D). Admixture of up to ~50 cm large boulders could be found in cobble gravel. Samples B28–B30 have been taken from sandy cobble gravel in the proximal part of the esker. Intermediate roundness values (high RS index values) and the minimum or absence of striation are typical for esker clasts (Fig. 8).

Moraine-mounds complexes sediments

This group contains Hørbyebreen LIA frontal moraine and hummocky moraine field in its background, Bertilbreen LIA frontal moraine, ice-cored moraine at the ice-contact zone of Bertilbreen and fossil supraglacial till in the forefield of Bertilbreen LIA frontal moraine.

Hørbyebreen LIA frontal moraine is made of clast-rich intermediate to sandy diamicton with boulder admixture and at some place even cobble gravel (Fig. 4E, F). The part of frontal moraine southwest of proglacial stream has been studied. The terminal part adjacent to the proglacial stream has a pronounced hummocky relief. The lateral part, located more towards the southwest, has a degraded flat surface. Each of the frontal moraine's morphologically different parts has been studied individually. Samples H08, H10, H12, H17, H18, H20 originate from terminal part of frontal moraine. Samples H09, H11, H14, H15, H16 originate from lateral part of frontal moraine. Lateral part has markedly better-rounded clasts, than the terminal part (lower RA values, higher RS values and higher RR values for some samples). The lateral part shows higher dispersion of striated clasts' shares (10–45%), than the terminal part (7–24%). Clast shapes are basically concordant in both parts of the frontal moraine.

Bertilbreen LIA frontal moraine has been studied in its terminal (sample B05) and lateral (sample B04) parts. It is composed of clast-rich intermediate to sandy diamicton with boulder admixture. Terminal part is richer in striated clasts and has more variable clast shapes and higher values of RA index when compared with its lateral part.

Hørbyebreen hummocky moraine bounds morphologically to the LIA frontal moraine (samples H06 and H07). It is made of clast-rich intermediate to sandy diamicton with boulder admixture (Fig. 4B). Hummocky moraine field lies behind the LIA frontal moraine. High share of striated clasts, more common subrounded clasts and higher variability of RA index is typical for hummocky moraine. The ice-cored moraine at the ice-contact zone of Bertilbreen (sample B14) is composed of clast-rich sandy to intermediate diamicton, which covers the decaying ice-cored elevations (Fig. 4G).

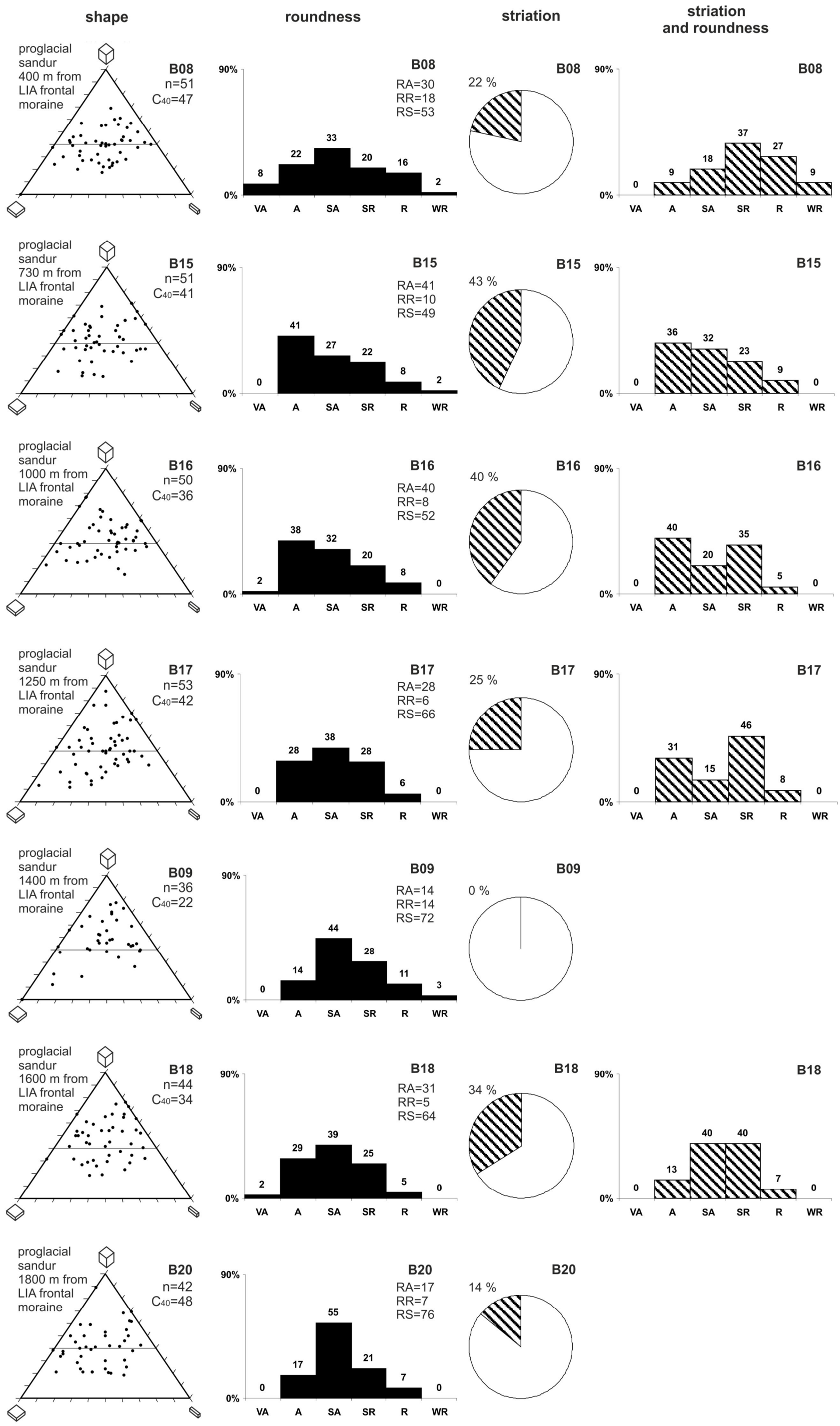

Fig. 7. Shape, roundness and striation of the clasts from glaciofluvial sediments of recent Bertilbreen proglacial sandur.

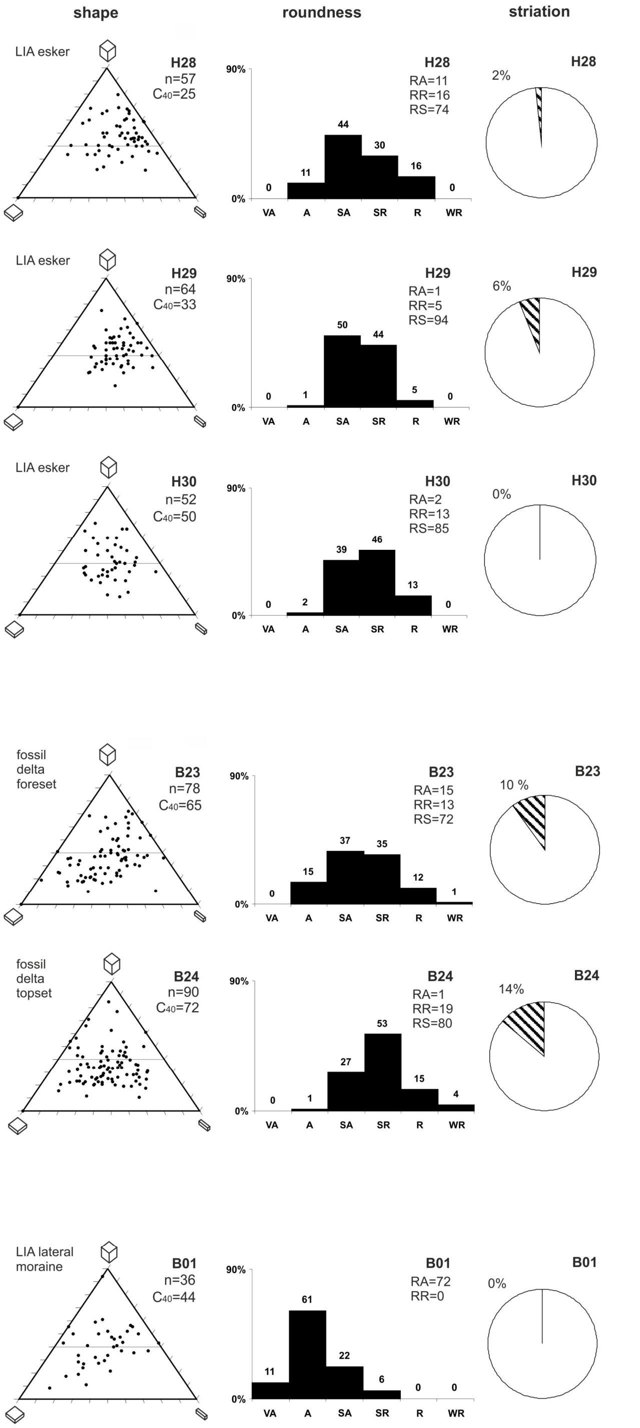

Fig. 8. Shape, roundness and striation of the clasts from Hørbyebreen LIA esker; foreset and topset of Bertilbreen fossil delta and Bertilbreen LIA lateral moraine.

Cobbles in this accumulation are often inclined. The ice-core moraine is characterized by a high share of striated clasts (~80%) and high clast shape variability. Fossil supraglacial till of Bertilbreen (sample B22) rests on the subglacial till (sample B21). The supraglacial till is clast-rich sandy to intermediate diamicton with clast shape and roundness similar to ice-cored moraine, but with significantly lower share of striated clasts.

Bertilbreen fossil glaciomarginal deltaic sediments

Deltaic sediments rest on the sequence of subglacial and supraglacial tills (samples B21 and B22) and are exposed in an erosional cut of the recent proglacial stream after leaving the canyon in the Bertilbreen forefield (Fig. 4H). Foreset consists of inclined beds of pebble gravel, pebble-cobble gravel, granule gravel and sand of the thickness of ~6 m. Sample B23 originates from pebble-cobble gravel bed. Sample B24 is from a topset made of alternating beds of matrix- to clast-supported cobble gravel and clast supported pebble gravel. Cobble gravel beds and clast-supported pebble beds represents longitudinal bars and open framework gravel on the bar surfaces (Smith 1974, Bridge 2003), respectively. Gravel braidplain sediments compose topset. Sample B24 has been taken from matrix- to clast-supported cobble gravel. The depositional environment generally forms coarse-grained glaciomarginal delta. Foreset and topset clasts are nearly identical in shape and have similar shares of striation. They differ mostly in clast roundness. RA index decreases noticeably and the share of subrounded clasts increases in the topset.

Interpretation and discussion

Till plateau sediments

The analysed clasts of subglacial tills of both glaciers correspond to the described characteristics of these till types (Bennett et al. 1997, Kjær 1999, Hambrey et Glasser 2012). The share of striated clasts increases in tills made of sedimentary rocks (Bennett et al. 1997, Hambrey et Glasser 2012). Subglacial till clasts underwent active transport based on these features (Boulton 1978). A relatively large difference in striated clasts shares between samples H02 and H03 could be caused by a higher share of reworked older glaciofluvial material in sample H02. The absence of striation in subglacial tills is considered as a proof of the material originating from glaciofluvial sediments (Hambrey et Ehrmann 2004). Clast shape is predisposed by the primary rock properties. A trend towards more isometrical clasts could be seen in subglacial till of Hørbyebreen. This is caused by the tendency of local Old Red sandstone to disintegrate into blocky debris. The Old Red sandstone in the Bertilbreen valley is on the other hand in some layers thinly bedded and it disintegrates into slab debris. This difference is explained by a diverse movement of isometric and slab forms of clasts in subglacial environment, where primary isometric debris rotates easily and its shape becomes even more equidimensional (Boulton 1978).

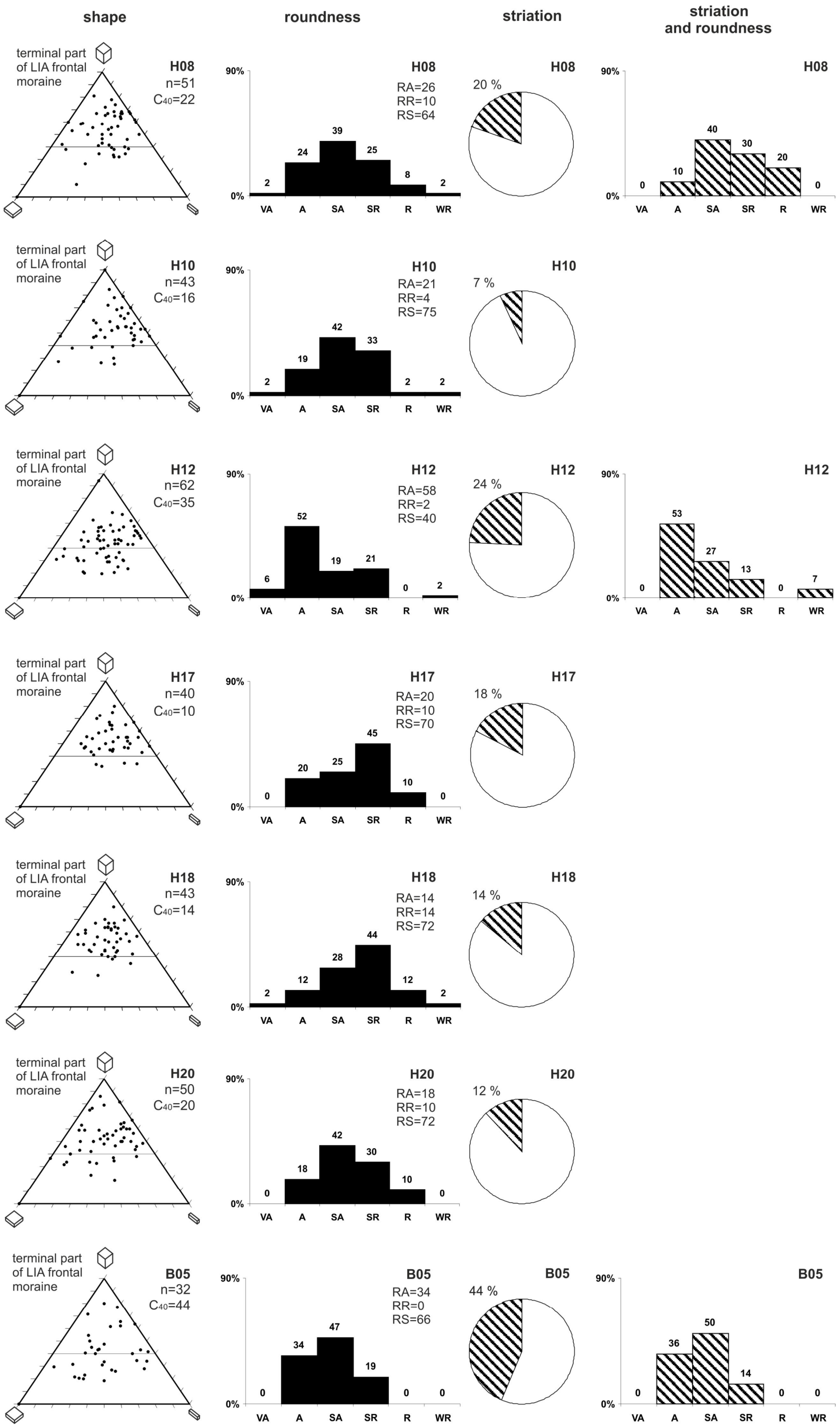

Fig. 9. Shape, roundness and striation of the clasts from terminal part of Hørbyebreen and Bertilbreen LIA frontal moraines.

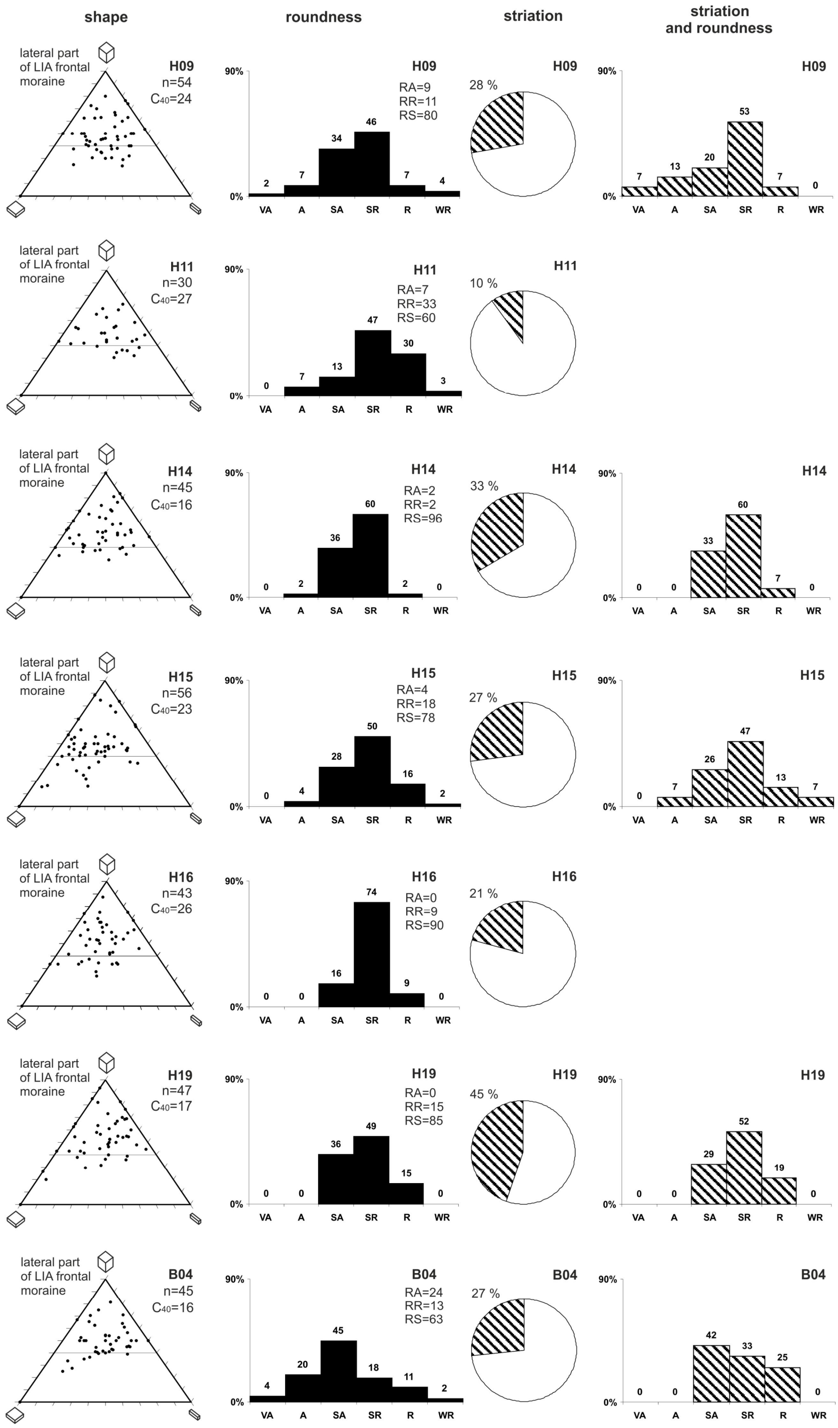

Fig. 10. Shape, roundness and striation of the clasts from lateral part of Hørbyebreen and Bertilbreen LIA frontal moraines.

Lateral moraine sediments

The material of Bertilbreen LIA lateral moraine corresponds to unmodified scree basing on the clast characteristics. Scree is an important component of lateral moraines (Boulton 1978, Benn et Ballantyne 1994, Hambrey et Ehrmann 2004). The present subangular and subrounded clasts could originate by scree/rock and snow avalanches (Hambrey et Ehrmann 2004). Subglacially actively modified debris could also be found in lateral moraines (Benn et Ballantyne 1994, Bennett et al. 1999). The absence of striation on Old Red sandstone clast surfaces and outcrops of this rock directly in steep valley slopes above the lateral moraine suggest their origin from above-mentioned avalanches.

Glaciofluvial sediments of proglacial sandar

The absence of visible downstream changes in clast characteristics at a distance of 1.4 km has also been found in other proglacial sandar (Gustavson 1974). The degree of roundness increases generally with the glaciofluvial transport distance (Gustavson 1974, Huddart 1994, Bennett et al. 1999, Hambrey et Ehramann 2004, Hambrey et Glasser 2012). Interesting is the persistence of striation of clast surfaces, which is usually not preserved in glaciofluvial environment (Hambrey et Ehrmann 2004, Hambrey et Glasser 2012). The most proximal part of sandur (samples H21) is influenced by a heterogeneous material of LIA frontal moraine and supraglacial debris on its surface. The variability of diverse shares of rounded clasts and striation persistence in other samples are probably caused by the transport of the material towards the fan by the left-hand tributary, which erodes LIA frontal moraine, the most distal part of LIA esker and diverse fossil sediments preserved at the side of the valley (Fig. 2). Stream tributaries are an important factor influencing the trends in clast features in the main streams of sandur (Huddart 1994). Glaciofluvial transport at a distance <1.4 km from the LIA frontal moraine has not probably been long enough to reach a significant clast form modification. The reason for the different clast roundness between valley sandur and braided outwash fan in front of the Bertilbreen LIA frontal moraine is the incorporation of the material eroded from Old Red sandstone bedrock, which is also supported by the abundant presence of angular clasts. The RA indices are usually lower for the braided outwash fan. Noticeably higher shares of striated clasts in samples B15 and B16 might be caused by the erosion of fossil subglacial and supraglacial tills (samples B21 and B22) by recent proglacial stream, because these sediments have been encountered in these parts of valley side. The till could originally extent also in place, where recent sandur is present and become thus a source of the material for recent glaciofluvial stream. The persistence of striation on clasts of the braided outwash fan could have the same cause. Clast roundness is almost constant throughout the whole length of braided outwash fan. Sandstone clast shape remains unchanged in the whole proglacial sandur. RS index value changes in proglacial sandar of Bertilbreen and Hørbyebreen show also a rather inhomogeneous distribution of better-rounded material (Figs. 6, 7, 12).

Esker sediments

Hørbyebreen esker cobble gravel has high values of RS index with equal shares of subangular and subrounded clasts. Field evidences show, that esker clasts might dominantly be subangular, subrounded or even well rounded in the case of egg gravel facies (Bennett et al. 1997, Huddart et al. 1999). Egg gravel facies have also been found at some places of Hørbyebreen esker.

Sediments of Hørbyebreen moraine-mound complexes

Hummocky moraines field concurs to the partly hummocky frontal moraine in the Hørbyebreen proglacial zone. They are therefore not differentiated in the landsystem interpretation of Evans et al. (2012). Morphological connection of frontal moraine and hummocky moraine in its background into a single wide belt of moraine-mound complexes has also been used in other studies (Hambrey et al. 1997, Bennett et al. 1999). Therefore, we evaluate them together. Hummocky elevations behind the LIA frontal moraine are regarded as outermost belt of moraine-mound complex.

The origin of the material from moraine-mound complexes of polythermal valley glaciers might be very variable (Hambrey et al. 1997, 1999, Bennett et al. 1999). The same is true for end moraines of temperate glaciers (Glasser et al. 2009) or ice-marginal moraines of ice sheets (Adam et Knight 2003). Moraine-mound complexes material mostly represents reworked subglacial tills and glaciofluvial gravelly sediments.

The differentiation of sources of morainic sediments is problematic, because subglacial tills and glaciofluvial sediments could not be differentiated unambiguously (Bennett et al. 1997). Samples from Hørbyebreen frontal and hummocky moraines have in the covariant plot of C_{40} and RA (Fig. 11) the same position as samples from subglacial diamicton of till plateau, esker samples and proglacial sandur gravel. Our C_{40}/RA covariant plot clearly shows the impossibility of differentiation of glacial sediments basing on clast shape and roundness, which supports the results of Bennett et al. (1997). The covariant plot of striation and RA (Fig. 11) shows on the other hand two different groups. Samples from proglacial sandur, esker and frontal moraine lie in the group with lower shares of striated clasts. On the other hand samples from subglacial till and hummocky moraines lie in the group with higher shares of striated clasts. This clearly shows that the clasts of the Hørbyebreen frontal moraine contain material from pre-LIA proglacial sandur or esker. Material of hummocky moraine is on the other hand compound of reworked subglacial tills.

The covariant plot of striation and RA catches also the difference between terminal and lateral part of frontal moraine of Hørbyebreen. Clasts from terminal part cluster together with subglacial till clasts, esker clasts and proglacial sandur clasts, as it is seen in the covariant plot of C_{40}/RA. However, the covariant plot of striation versus RA unambiguously differentiate terminal part of frontal moraine clasts and subglacial till clasts and shows the similarity of the terminal part of frontal moraine material with proglacial sandur. Esker shows even lower share of striated clasts. Terminal part of Hørbyebreen frontal moraine is basing on this analysis composed of reworked material originating from pre-LIA proglacial sandur. Lateral part of frontal moraine shows higher degree of clast roundness (lower RA values, Figs. 10, 11) when compared with its terminal part (Figs. 9, 11). Differentiation from subglacial tills, proglacial sandur and esker is not so distinct. The covariant plot of striation versus RA nevertheless shows the relation of lateral part of the frontal moraine mainly to proglacial sandur and only partially to esker and subglacial till. Some samples of lateral part resemble to esker (and best rounded samples of proglacial sandur) and to subglacial till basing on the roundness and striation, respectively. This feature could reflect multitransport history of the clasts, which might have originally been components of pre-LIA eskers or proglacial sandar. After erosion of these landforms by advancing glacier has this material been transported and modified (striated) in subglacial zone as basal debris and subsequently deposited as part of the LIA frontal moraine (*e.g.* concordant share of striated clasts in samples H02 and H19). Material of the lateral part of the Hørbyebreen frontal moraine is thus therefore composed mostly of reworked material from eskers and proglacial sandar, which has partly been actively modified (striated) in subglacial zone. The reworking of former material from esker to the frontal moraine of Hørbyebreen is also supported by frequent appearance of egg gravel facies (Bennett et al. 1997, Huddart et al. 1999) in this moraine (Fig. 4F).

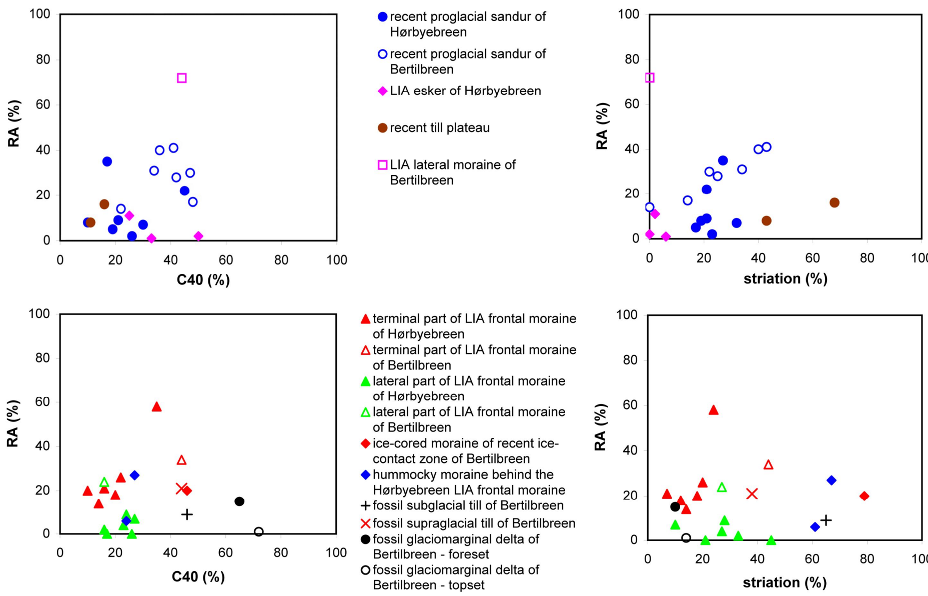

Fig. 11. Covariant plots of C_{40}/RA and striation/RA for individual studied samples.

Possibility of the use of clast characteristics to reconstruct the transport history and downstream trends

The Hørbyebreen frontal moraine example shows, that the covariant plot of striation versus RA could be used for the assessment of transport history of the material in moraine-mound complexes. It can be used to supplement the covariant plot of C_{40}/RA, which effectively differentiate passively and actively transported clasts (Benn et Ballantyne 1994). We used the RA index on the y-axis of this covariant plot to maintain good comparability with C_{40}/RA covariant plot.

The share of subrounded and subangular clasts increase in proglacial glaciofluvial sediments according to many field studies (Gustavson 1974, Huddart 1994, Bennett et al. 1999, Hambrey et Ehrmann 2004, Hambrey et Glasser 2012). For appropriate graphic presentation of downstream clast roundness changes the covariant plot of the distance from a starting point and the RS index (distance/RS covariant plot) has been employed. This might be the recent glacier front, frontal moraine or other landform (depending on the aim of the study). A similar plot of the trends in clast roundness using all roundness categories has been used by Gustavson (1974). Other forms of graphical presentations of these changes have also been presented in the literature (*e.g.* Huddart 1994, Nývlt et Hoare 2011). It is useful to combine subangular and subrounded categories into the RS index (rather sub-) for a relatively short proglacial sandar, as there is no important shift towards the subrounded roundness due to a short transport distance. For long proglacial zones might be helpful to present the share of subrounded clasts versus the transport distance, *i.e.* the distance from the starting point.

The use of the C_{40} index is limited by the primary lithological properties of the rocks. Clast shape in subglacial diamictons is affected by the lithology only for the rocks with distinct foliation, while this effect has not been found for blocky disintegrating rock according to Bennett et al. (1997). Isometric debris in subglacial zone rotates more easily and is therefore exposed to larger abrasion action; this is why the subglacial transport affects more equidimensional debris (Boulton 1978). Sandstones in the Bertilbreen valley are thinly bedded, which affects the shape of the clasts. Similar C_{40} values and differrent roundness have Bertilbreen samples of the following landforms: lateral moraine, terminal part of frontal moraine, fossil supraglacial till, ice-contact moraine at ice-contact zone, recent proglacial sandur and also fossil subglacial till (*see* Fig. 11). These sediments contain clasts with similar shapes, although they have different transport histories, as evidenced by the absence of striations on the lateral moraine clasts and high abundance of striated clasts in other sediments (*see* covariant plot of striations vs. RA in Fig. 11). Fossil supraglacial till differs from the subglacial till only in higher share of angular clasts and a lower share of striated clasts. It is probably due to the presence of abundant supraglacial unmodified debris. It is clear from the analyses of Bertilbreen fossil tills and deltaic sediments (samples B21–B24) that the C_{40} index increases with higher roundness (Figs. 5, 8, 11). The highest roundness and C_{40} values are found in the topset of coarse-grained delta, where at the same time highest shares of subrounded, rounded and well-rounded clasts were found. Topset represents the environment with the highest flow velocity (gravelly braided stream) and also with the highest rate of resedimentation of formerly deposited material (foresets, moraines). Further clast modification intensification took place during this resedimentation of former foresets. High-energy fluvial transport therefore does not lead to more isometric pebble shapes as is the case by subglacial traction (Boulton 1978, Kjær 1999), but to a more evolved slab shapes. The sediments of coarse-grained glaciomarginal delta and other glacial sedimentary environments could be distinguished basing on the C_{40} index.

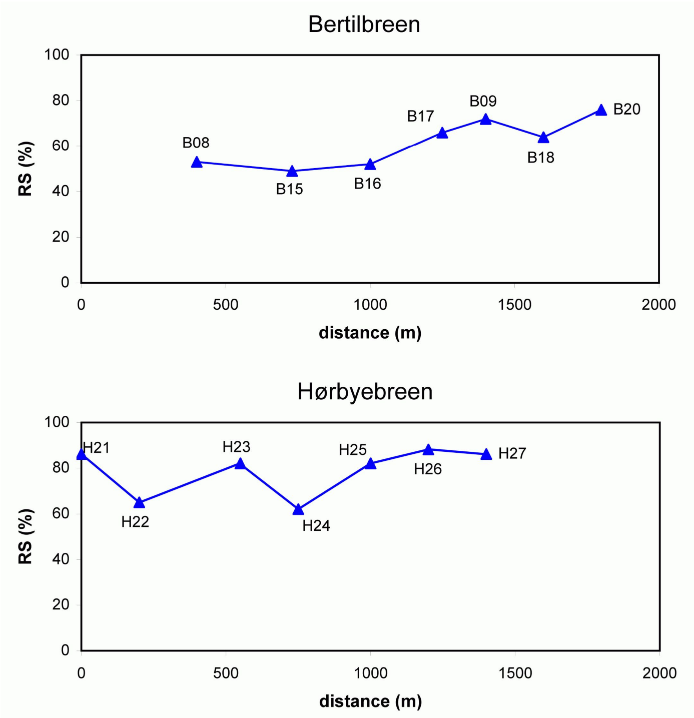

Fig. 12. Downstream changes of clast shape of Hørbyebreen and Bertilbreen proglacial sandar shown by the covariance plot of distance and RS index (covariant plot of distance/RS).

Conclusions

- Sediments of pre-LIA proglacial sandar, eskers and subglacial tills have been the main sources for the material of Hørbyebreen moraine-mound complexes. On the other hand the material of proglacial sandar and eskers compose LIA frontal moraine and the subglacial till material composes hummocky moraine in the background of LIA frontal moraine.
- The shape of Old Red sandstone clasts in sediments is generally controlled by their primary bedding, along which they disintegrate. Passively transported glacial debris could thus have identical C_{40} index as actively transported glacial debris or glaciofluvially transported material. Considerably higher C_{40} values have sediments of glaciomarginal coarse-grained delta.
- The covariant plot of striation and RA index is very suitable to identify the source of the material in moraine-mound complexes. This plot clearly differentiates subglacially modified and glaciofluvially modified debris. The plot shows the share of glacially striated clasts (x-axis) against the share of very angular and angular clasts – RA index (y-axis). Striation is a typical feature of active subglacial clast modification. Striated clasts are common in subglacial till, but nearly absent in glaciofluvial sediments. The share of striated clasts can therefore be effectively used for their discrimination. The covariant plot of

striation versus RA index well complements the covariant plot of C_{40} versus RA of Benn et Ballantyne (1994).

- The covariant plot of RS index with the distance (distance/RS index covariant plot) from the starting point (frontal moraine, recent glacier front etc.) is well suitable for the reconstruction of downstream roundness changes in proglacial sandar. RS index represents the share of subangular and subrounded clasts that are dominant in proglacial sandar. The evaluation of downstream changes of subrounded clasts might be preferred for long sandar (*e.g.* valley sandur) due to the increasing roundness with longer distance.

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