CZECH POLAR REPORTS 10 (2): 189-202, 2020

Longitudinal development of clast shape characteristics from different material sources in Hørbye River, Central Svalbard

Lenka Ondráčková[1,2]

[1]*Department of Geography, Faculty of Science, Masaryk University, Kotlářská 2, 611 37, Brno, Czech Republic*
[2]*Department of Water Management Studies, ENVIPARTNER, s.r.o., Vídeňská 55, 639 00, Brno – Štýřice, Czech Republic*

Abstract

The sediment transport in polar regions is highly changeable and it is getting faster in connection with a climate change. This study describes the Hørbye River catchment located in the northern Billefjorden, Central Svalbard. The Czech Arctic Station and AMUPS - Adam Mickiewicz University Polish Polar Station are located in near this locality Petunia Bay. The material for this study was sampled in August 2016, during the summer research campaign of Czech Arctic Station together with a cooperation between Masaryk University in Brno and the University of Oslo via Norway Grants. The catchment area is 60 km^2. The area of interest lies around the 10 km long Hørbye River in its braidplain, which is 2.3 km wide and 4.5 km long. In the Hørbye Glacier forefield, 27 sediment sampling localities were selected and defined into seven groups: (i) esker complex; (ii) debris stripes; (iii) till plain; (iv) hummocky moraine; (v) post-LIA braidplain; (vi) LIA moraine; (vii) LIA braidplain. Three main petrological types of rocks were studied (SVP – sandstone, VAP – limestone, ORT – orthogneiss). Lithology and roundness of the clasts were evaluated in order to study clast shape properties from various glacial sediments. The results show the dominant role of lithology on the clast shape modification in the Hørbye Glacier forefield.

Key words: proglacial stream, bedload sediment, Svalbard, material sources, sediment grain-size

DOI: 10.5817/CPR2020-2-15

Received September 17, 2020, *accepted* December 27, 2020.
[*]Corresponding author: L. Ondráčková <lenkaondrackova@mail.muni.cz>
Acknowledgements: This research has been supported by the project: NF-CZ07-INS-6-263-2015. The author also thanks Jon Ove Hagen, Department of Geosciences, University of Oslo, for his collaboration on the project. Jirka Ondráček and other field assistants are also gratefully acknowledged. Martin Hanáček and Daniel Nývlt are acknowledged for consultations, and Grzegorz Rachlewicz for valuable review comments. This contribution was supported by the Masaryk University Project MUNI/A/1356/2019.

Introduction

The sediment transport is a highly presented topic in connection with proglacial river changes due to ongoing climate change. Bedload sediments are typically studied in fluvial systems with respect to downstream changes but can be affected by lateral inputs of different sediment sources. Understanding the sediment fluxes is fundamental to predict the likely effects of future changes of geomorphological activity and landscape development (Slaymaker 2010, Colombera el al. 2013). Proglacial areas exposed thanks to glacier recession are among the most dynamic landscapes in polar and mountainous areas (Hein and Walker 1977, Bennett et al. 2010, Bennett and Evans 2012, Carrivick and Heckmann 2017) and are intensively modified by various geomorphological processes related to the climate change.

In river catchments, hydraulic and sediment characteristics change with downstream distance from the headwaters. As the distance increases downstream, the channel size and discharge increase together with the changes in channel slope and bed material size and roundness (Church 1992). The mechanisms, which contribute to downstream bed material change is abrasion, sorting or transport, and in-situ weathering (Knighton 1998). The downstream trend can be interrupted by the tributaries, channel bars and other lateral sources (*i.e.* lateral erosion of channel banks), which support the main channel flow (Ferguson et al. 2006).

Svalbard is a very dynamically changing area. Proglacial landsystems were studied here by numerous studies (*e.g.* Kostrzewski et al. 1989, Kostrzewski 1989, Ziaja 2004, Lønne and Lyså 2005, Lukas et al. 2005, Ziaja and Pipała 2007, Rachlewicz 2007, Bennett et al. 2000, Zagórski 2011, Zagórski et al. 2012, Malecki 2013, Midgley et al. 2013, Kavan 2017, Ondráčková et al. 2018, Ewertowski et al. 2019, Kociuba et al. 2019, Pleksot 2019, Ondráčková et al. 2020).

Especially the Hørbye River catchment is a well-known area. Many kinds of research studies were published from this area in the late 20th century mainly thanks to the Polish research groups working in this area for a long time. The geomorphology and morphogenesis of the region between Hørbyedalen and Ebbadalen in Petunia Bay region were studied by Stankowski (1989). Another part of the group focused on the chronostratigraphy of glacier deposits in this area (Karczewski and Rygielski 1989), where the lithology of the sediments plays a crucial role like in fluvial deposits. The proglacial zone of Hørbye Glacier is full of small lakes, which was the focus of Wojciechowski (1989), who has studied sedimentation and geomorphology of these lakes located between the braided channels. Generally, the tidal flat plain of Petunia Bay was studied by Borówka (1989). The combination of fluvial, glacial and tidal processes affected also the distant part of the Hørbye River outwash fan, where there is a different degree of degradation during the year (Kostrzewski 1989). The dynamics of the geomorphic processes in the glaciated and non-glaciated catchments were studied by Kostrzewski et al. (1989). The Hørbye River catchment was also studied in the case of flood events (Rachlewicz 2009a) and the changes caused by the river activity. The surficial geology and geomorphology map of the forefield of the Hørbye Glacier were created by Evans et al. (2012). The detailed analysis of the historical landscape change within the foreland of a Hørbye Glacier is described in Ewertowski et al. (2019).

The purpose of this case study is to examine the effects of different material inputs into the Hørbye River fluvial system. It covers also the influence of different sediment sources and fluvial transport through the river catchment. The key question is to recognise the role of the axial sediment transport and the role of the sediment sources within the system. A different role of each sediment source together with its geographical position in the fluvial system was examined. Here, I want to recognise the processes, which influence the changes in roundness and different shares of petrological types in individual sediment sources. The results will help to understand the knowledge about the climatic influence and evolution of the nature of proglacial coarse-grained fluvial sediments in environments affected by glacier and snow melting in the very vulnerable area of the Arctic.

Study Area

This study was undertaken in the Hørbye Valley located in Dickson Land, Spitsbergen, ~ 9.5 km north of Pyramiden town (Fig. 1). The Hørbye River catchment area is ~ 60 km^2. The river originates at the confluence of small streams running from Hørbye Glacier. The polythermal Hørbye and Hoel glacier system is approx. 8 km long and 1 km wide in the proximal part. The extent of ice cover in this catchment from LIA can be seen in Ewertowski et al. (2019 – Fig. 2). The Hørbye river is ~ 10 km long and forms a 2.3 km wide and 4.5 km long braidplain ([2]-TopoSvalbard 2009). At the beginning, the river has a steeper character, but at the distant part it is characterised by many lateral channels and composes a flat braided outwash fan (sensu Hambrey 1994). The Hørbye Glacier forefield is characterized by the presence of eskers, moraines, till plain, lakes and other proglacial landforms (Evans et al. 2012). The river eroded the moraine gradually the second half of 20th century because of the retreat of the glacier. The river network started to spread into the forefield, leaving one of the former corridors between the esker and the moraines on the northeast side. The river network destroyed and moved subglacial sediments and created several lakes, in which there was a mass accumulation of sediments and smaller streams that flew to the south (Hanáček et al. 2013, Ewertowski et al. 2019, [2]-Topo Svalbard 2009).

The climate in the study area is characterized by low precipitation of ~200 mm yr^{-1} and relatively warm winters (Førland et al. 2011, [1]-NPI 2020). The average annual temperature according to Rachlewicz (2003) and NPI 2020 is ~ –5°C. The temperatures in winter (December–February) ranged from –30°C to +3°C, while summer temperatures (June–August) varied from –2°C to +12°C in the nearby Petunia Bay (Láska et al. 2012, Witoszová and Láska 2012). Positive temperatures are important for the water availability of local river systems fed by snow and glacier melting (Rachlewicz 2007). In addition, the study area is influenced by the warm Western Svalbard Current, which contributes to the fact that the local climate is relatively mild (Rachlewicz 2003, Malecki 2016).

The Hørbye Glacier is the largest in the Petunia Bay area, which is the northern end of Billefjorden. It is a valley glacier filling the extension of the bay. Its marginal zone extends between the slope of Birger Jonsonfjellet in the west and the slope of Gizehfjellet in the east. The Hørbye Glacier is located in the border zone between Dickson Land and Olav V Land. The Hørbye Glacier is up to 170 m thick, with a 40 m thick basal layer under 100–130 m of ice (Malecki 2013). The altitude of the glacier surface ranged from 65 to 665 m. The glacier forefield is located at altitudes from 24 to 111 m, with the highest ridges of the lateral moraine reaching up to 320 m a.s.l. (TopoSvalbard 2009, Evans et al 2012, Ewertowski et al. 2019).

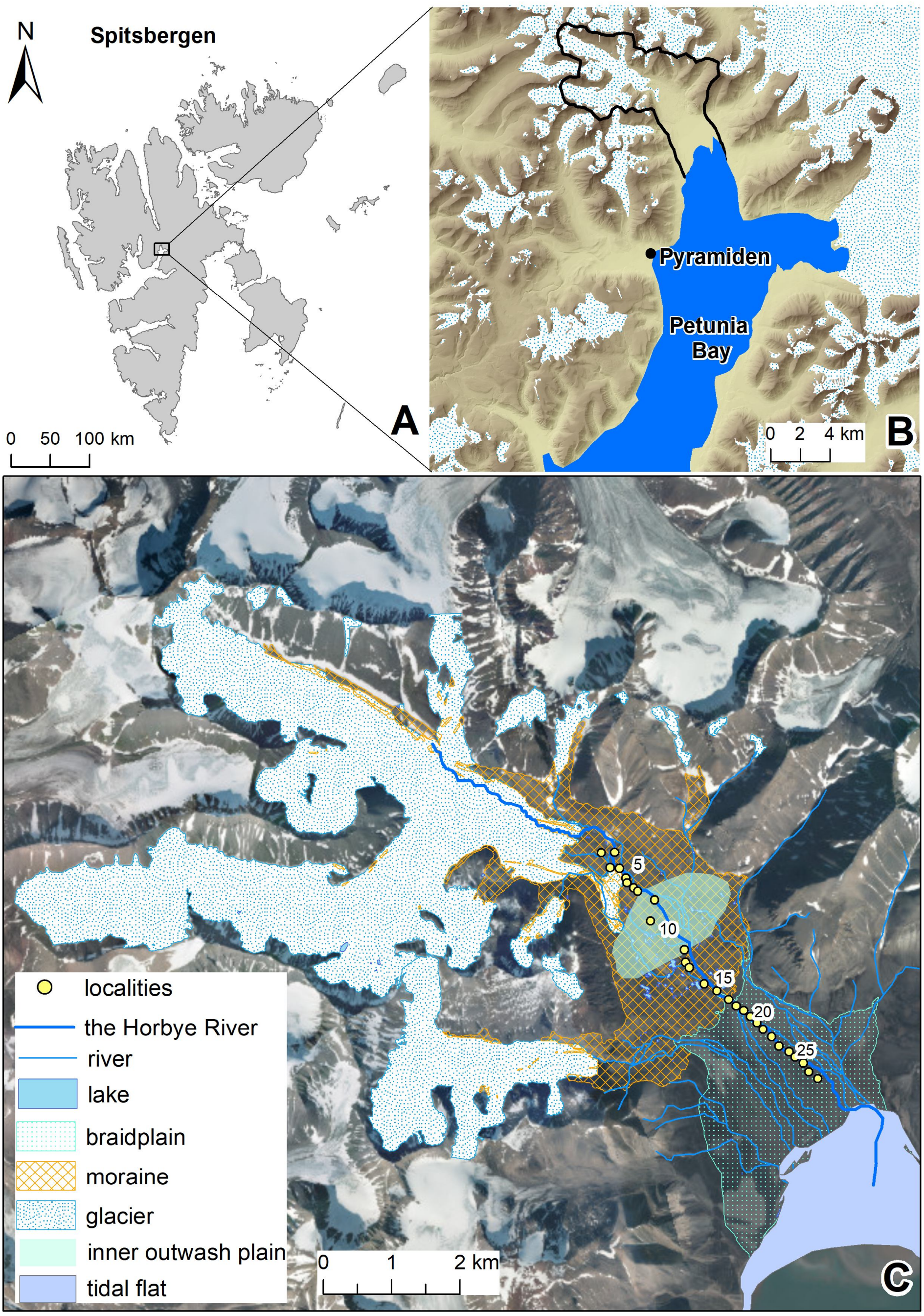

Fig. 1. Location of the study area: A – Spitsbergen, B – Billefjorden, C – The Hørbye River catchment.

Recent moraine-mound complexes of Svalbard glaciers started to develop since the Little Ice Age (LIA) and are still developing with ongoing climate change (Rachlewicz and Styszyńska 2007, Evans et al. 2012). The sediment cover is composed of weathered material originating principally from the Palaeozoic sedimentary rocks and, to a small extent, pre-Devonian metamorphic rocks.

The Hørbye River channel is predominantly pebble-cobbly along the entire stream and different types of channel bars can be found. Braidplain is characterized by the occurrence of active and abandoned channels caused by different fluvial dynamics during the hydrological season. Diverse fractions can be transported within the channel; boulder fractions in the upper part during the peak discharges and cobble and pebble size fractions in the rest of the flow profile. The sedimentation is connected with the weakening transport capacity of the river.

From the geological point of view (*see* Fig. 2), the upper parts of the valley sides consist of Carboniferous sandstone, and siltstone, clastic carbonate rocks and evaporites and the other part of the valley side contains dolomite, sandstone and gypsum (Dallmann et al. 2004). The Carboniferous-Permian limestone build the upper parts of the summits (Dallmann et al. 2004). The middle part of the valley sides consists of Devonian Old Red sandstone and Precambrian orthogneiss and amphibolite (Hanáček et al. 2013). The lowest parts of the valley are filled by glacial, glaciofluvial and marine sediments. The material from individual sediment sources or landforms is transported to the main river channel in different volumes and with diverse temporal supply (Tomczyk and Ewertowski 2017).

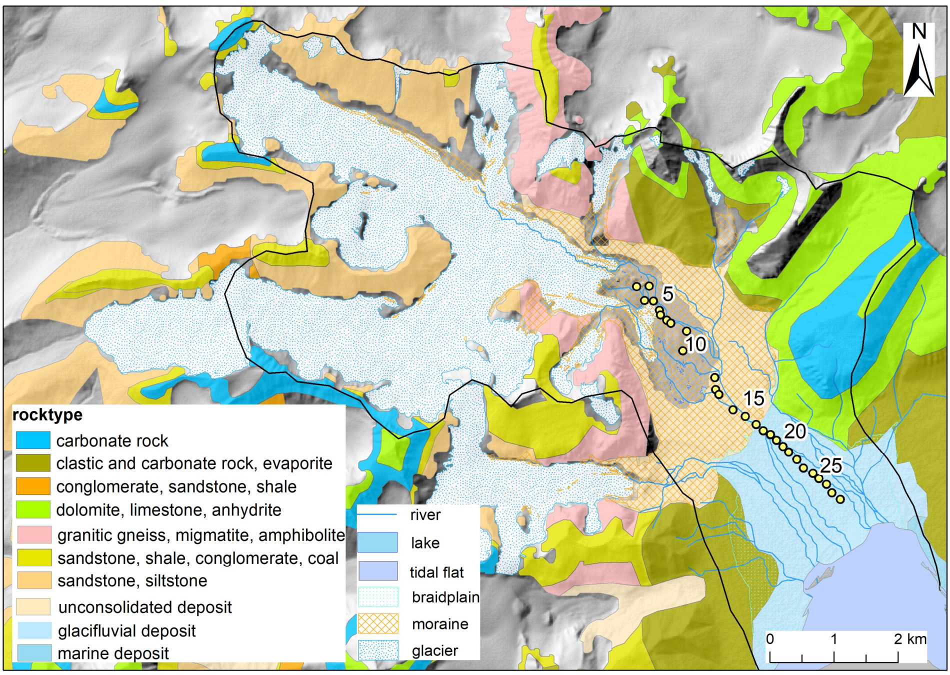

Fig. 2. Geological map of the Hørbye River catchment (based on geological map of Billefjorden by Dallmann et al. (2004)).

Methods

The Hørbye Valley was selected based on aerial images ([2]-TopoSvalbard 2009), because of a well-developed braidplain and well-preserved accumulation landforms. The braidplain character was necessary to study the effect of sediment sources and landforms on the shape properties of fluvial sediments in the dynamic proglacial stream along the 4.5 km long downstream river profile.

The NPI data ([1]-Norsk Polar Institute website) were used in geographical information system environment to pre-select the location of interests. However, the final selection of sediment sampling sites was carried out in Hørbye braidplain during the fieldwork. The selection led to a definition and sampling of major sediment source areas for transported fluvial material. Field geomorphological mapping of the main landforms and sediment sampling along the Hørbye River channel belt were realised at the beginning of August 2016. At the glacier forefield seven sediment sources were recognised representing different sediment-landform assemblages. Seven representative sediment sampling sites from all sediment sources were selected (Fig 3). The following sediment sources were defined: (i) esker complex; (ii) supraglacial debris stripes; (iii) till plain; (iv) hummocky moraine; (v) post-LIA braidplain; (vi) LIA moraine; (vii) LIA braidplain.

Furthermore, 27 sites were selected for sediment sampling and measurements of sediment characteristics along the Hørbye River channel belt for 8–16 mm (b-axis) of the pebble fraction. The fraction was sieved at sampling sites and processed in the laboratory by measurements of clast's axes, identification of clast's roundness and petrography. Each sample contains 100 clasts.

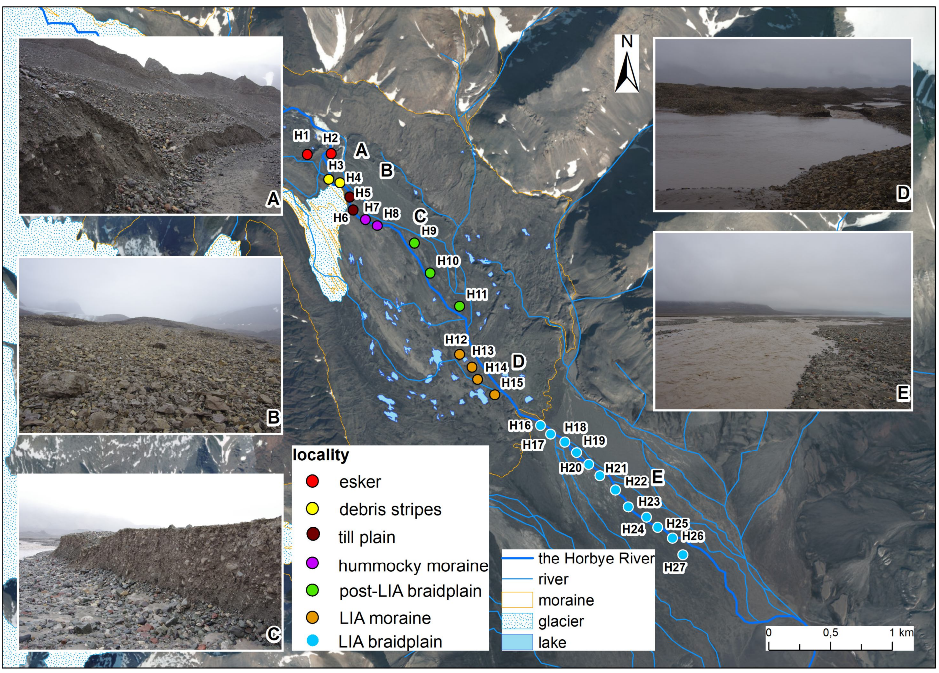

Fig. 3. Topographic map of the Hørbye River braidplain with location of the material sources and the sediment sampling localities.

The sampling was supplemented by GPS position, site description and photo documentation of the site and the close surroundings. It should be noted that all samples were taken from first-order bars, as second-order bars were flooded during the high summer research season (Folk and Ward 1957, Lunt and Bridge 2004, Lunt et al. 2004).

In the case of this study, I decided to use the length of the Hørbye River from the Hørbye Glacier (determined by current ice position) with the start of the river mileage determined from the Digital Elevation Model to an average sea level corresponding to the end of the river mileage.

Petrological analyses of sampled clasts consist of the following steps: (I) identification of petrology according to units from a geological map of Billefjorden (SVP – sandstone, VAP – limestone, ORT – orthogneiss; Dallmann et al. 2004); (II) measurements of a, b and c axes; and (III) roundness assessment using the roundness classes of Powers (1953). The roundness is presented in Fig. 5 together with 2 examples (sediment sites H4 and H8). The main petrological types are plotted in Fig. 4 with a photo documentation taken originally in the Hørbye Glacier forefield.

Together with the field work, several underlying maps (slope, aspect, hillshade) were produced using DEM, datasets from NPI and geological map. The NPI Topo Svalbard[2] source were used for shapefiles together with GPS positions of each sediment sampling locality (Fig. 3). For the geological map of the Hørbye River catchment, the geological map of Billefjorden (Dallmann et al. 2004) was adopted (Fig. 2).

Results

The Hørbye River catchment is affected by the presence of glaciers and very variable topography (the highest point is above 1000 a. s. l.). It is oriented in west-east direction at the head, and north-south at the mouth of the catchment located in Petunia Bay. Half of the area is very hilly with steep slopes and on the other hand the glacier forefield represents lower positions with mild decrease in altitude to the sea level (Fig. 1). The origin of the sediment is different. Some of them are transported from hillslopes by gravitational processes. Another group is affected by the combination of glacial and fluvial processes during the glacier ablation period (subglacial, supraglacial and englacial sediments).

The dominant landforms with sediment sources localities in the Hørbye Glacier forefield are represented by eskers, debris stripes, morainic complex, till plain and post-LIA braidplain and in distal part LIA braidplain (Fig. 3). The landform position is determined by the hydraulic system of the glacier, its thermal regime, position of the supraglacial and englacial stripes and geological composition within the braided outwash fan. The presented graphs (Fig. 4 and Fig. 5) do not strictly show the downstream trend with respect to the position of landforms, but the differences in the petrological type and in the roundness.

The esker sediment source represents samples from localities H1 and H2. In debris stripes landform were sampled at two localities (H3 and H4). Another two localities are within the till plain (samples H5 and H6) and in hummocky moraine (samples H7 and H8). Localities with samples H9 to H11 belongs to post-LIA braidplain. Next four samples (H12, H13, H14 and H15) are located in the LIA moraine area. Last 13 samples (from H16 to H27 localities) represent LIA braidplain. The different sediment sampling localities are also visible on photographs (Fig. 3). The accumulation of sediments is necessary for the future sediment transport behaviour especially during the ablation period. The studied clastic material at all 27 sediment sampling localities show a different proportion of petrological types, and also diverse degree of clast roundness. Only before the LIA period could the downstream trend develop. Even so, the similarity of the first approximately 1.5 km long section with various landforms and in front of the LIA outwash fan and the difference of these sections from the post LIA braidplain is clear from the line. You should also note that the whole area was glacially sculpted.

From the lithological point of view (*see* Fig. 4), the dominance of sandstone is evident in 25 out of 27 samples. It makes more than 60% (Fig. 4), limestones covers around 20% and orthogneiss is supplementary within studied samples. The esker landform sediment samples is dominantly formed by sandstones (74% and 62%) – one of the highest portions of this petrological type within the whole samples. On the other hand, sandstone is missing in the sample H3, where limestone is dominating (90%). Only the samples from localities H3 and H4 from debris stripes are special for the dominance of limestone. The sample H3 have 90% of limestones and 10% of orthogneiss. The sample from other locality made of limestone debris stripes (H4) has 70% of limestones, 20% of sandstones and small proportion of orthogneiss. The highest portion of orthogneiss is evident from the sample H5 belonging to till plain. Another fluctuation is in till plain and hummocky moraine samples. Here sandstone covers 60 – 70% and the rest is divided between limestone and orthogneiss. The dominance of sandstone is unchanging in the rest of samples and there are some small fluctuations between limestones and orthogneiss (*e.g.* in LIA moraine, LIA braidplain). Fig. 4 is showing the evolution of the samples of petrological types at every locality and the graph is supplemented by the photos from the Hørbye River catchment.

Another important characteristic of clasts is their roundness. How the clast changes, among the different sediment sampling localities of the Hørbye River braidplain is presented in Fig. 5. The graph symbology is similar as before (Fig. 4), but there are 4 important lines, which represent degree of roundness (data come from 27 samples within 7 sediment sources). There are SA (sub-angular, green line) and SR (sub-rounded, blue line), the extreme categories in angularity (VA+A, black line) and in rounded clasts (R+WR, orange line) are complementary here. There are two extreme diverse samples (H3 and H4), which contain 92% and 77% of angular and very angular clasts, respectively. This degree of roundness is connected with petrological type, which has not a long transport by the river. This character of angular clasts is typical for limestone debris stripes located in the studied catchment. At the next sediment sources, there are recognizable fluctuation between rounded and angular clasts. Compared to the samples from debris stripes, the sample from the locality H8 (hummocky moraine) contains a higher portion of well-rounded and rounded clasts (48%). Moreover, in this graph (Fig. 5) there are 2 small histograms, which describes two important sediment source samples with the largest deviations in angularity (sample H3 – debris stripes sediment source; sample H8 – hummocky moraine sediment source). Because of the combination of glacial and fluvial processes influenced sediments in braidplain, there are almost no significant trends in increasing sediment roundness as is usual in axial transport with the increasing transport distance. Even before the frontal moraine, braiplain develops after LIA, just as in the struggle for a frontal moraine.

For example the highest portion of rounded clasts was in sample H2 (from esker – 40%), sample H5 (from till plain – 47%) and in two samples from LIA braidplain (H17 and H18 – 41%, 40%).

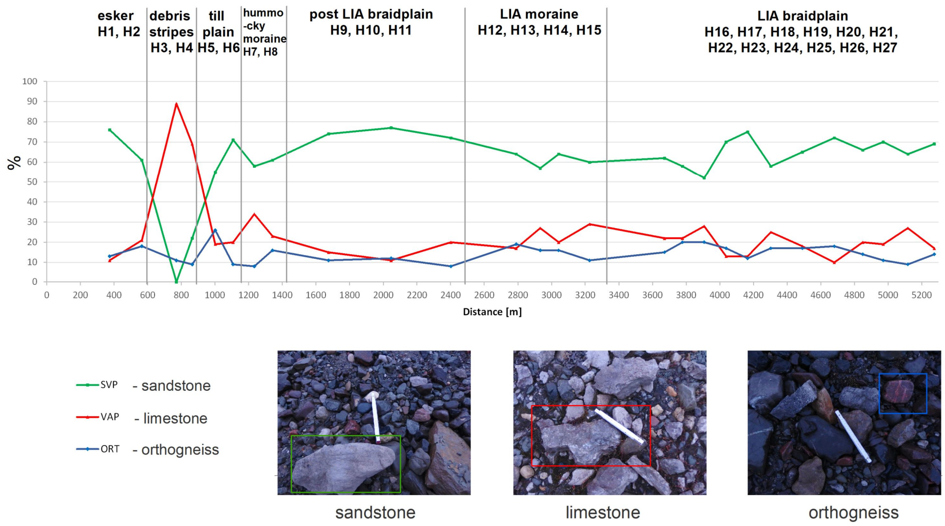

Fig. 4. Downstream change of the main petrological types of sediments in the Hørbye River braidplain.

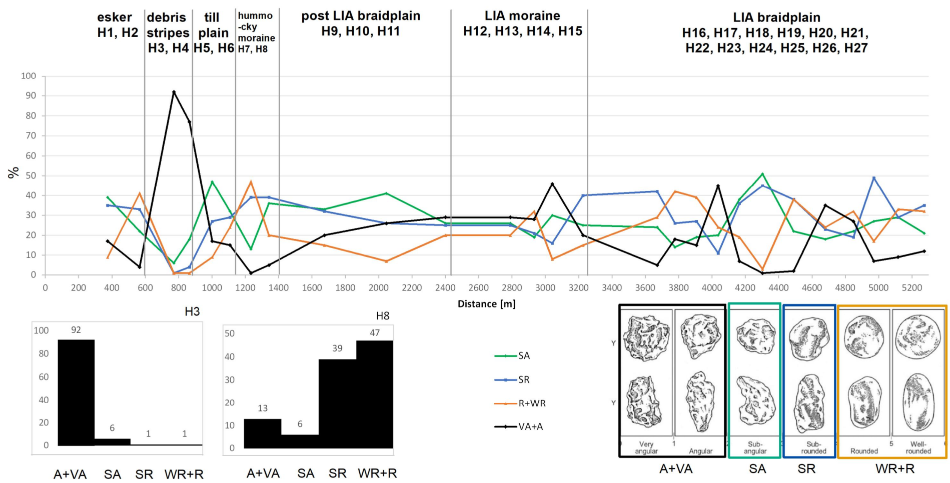

Fig. 5. Downstream change of sediment roundness in the Hørbye River braidplain.

From the graph in the Fig. 5, the fluctuation from the first samples to approx. 1 400 m (till plain) is evident. Then continues stable part until the 2 800 m in the section of hummocky moraine and post-LIA braidplain. Last part from LIA moraine (2 800 m) till the end of LIA braidplain (5 300 m) is very dynamic in the case of roundness again.

Discussion

Proglacial rivers are very dynamic systems influenced by glacier melting. On Svalbard we can see increasing temperatures, but there are differences between meltwater discharges between small valley glacier rivers (the Elsa River, the Ferdinand River) and the Hørbye River. It depends on the areaof the glacier, which melted and fed the proglacial river. Together with discharge it fluctuates sediment transport and deposition. Clasts are modified by an active traction processes in subglacial environments and deposited during the Little Ice Age (LIA) in forms of subglacial tills and frontal moraine diamictites and remained partly in forms of moraine hummocks and ice-cored moraine ridges. Sandstone clasts are recently reworked by glaciofluvial processes and modified by fluvial transport on braided outwash fans, which evolved in the forefield of the LIA moraines (Karczewski and Rygielski 1989). Some of clasts from the Pleistocene to early Holocene sediments within tidal plain of Hørbye Glacier could be resedimented. According to Karczewski and Rygielski (1989) here lies a fragment of a raised marine terrace of an altitude of 45 m above sea-level. It is undercut by a proglacial river constituting an exposure with a series of marine, fluvio-glacial and moraine deposits. Subsequently, the sediments were eroded by proglacial river system within the braided outwash fan.

The proximal part and pre-LIA outwash fan show similarity in fluctuations of roundness with a diverse portions of rounded clasts. There is evident short transport distance from the glacier because the transport energy of flowing water decreases on a wider braidplain. In the Bertil braided outwash fan, the clasts were seen rather rounded, which was caused by a very short material transport (Hanáček et al. 2011). The post-LIA braidplain sediment source has a relatively stable portion of petrological types (dominance of sandstone) together with the degree of roundness (SA and SR types). There can be recognized slight trend in increasing angularity of clasts between 1 200 m to 3 000 m. On the other hand in the LIA moraine, the high portion of angular clast is expected compared to the Muninelva River (Ondráčková et al. 2020), where the morainic sediment source was dominant at the beginning of the profile.

In Billefjorden area in Central Svalbard we can recognize proglacial fluvial systems comparable to the Hørbye River braidplain (Rachlewicz 2007, Marciniak and Dragon 2010, Hanáček et. al. 2011, Ondráčková et al. 2020; [2]-Topo Svalbard 2009). From the morphological point of view, the Hørbye River braidplain is well-developed in comparison to others. The position of landforms in braidplain, which forms a sediment sources is affected by the morphology of the catchment. Bertil braided outwash fan is smaller and narrower with fewer active braided channels. This is due to a more gradual transition from the deeply incised gorge to the outwash fan at its confluence with the main Mimer River. Sven River braidplain next to Hørbye catchment is, on the contrary, shorter with the sediment source localities lying in the first half of the length, but the area of the outwash fan is of slightly higher altitude. Munin River outwash fan is longer and narrower than that in Hørbye Valley due to different catchment topography (side sediment sources, influence of the slope processes and gorge in the last part of the river).

The proglacial stream in Hørbye Valley flows from the terminal moraine of Hørbye Glacier along the axis of a wide valley and the material transport is more axial-like when compared to the Munin River. The braided outwash fan of which is much shorter and relatively wider due to an active braiding. Hydrological regime of the material sources, especially the lateral fans, is crucial for the delivery of coarse-grained material into the main river. Therefore, in the Hørbye River braidplain the effect of side material sources is not so evident as the position of landforms directly in the braidplain.

The hydrological regime is crucial for the evolution of the sediment transport. The hydrological regime of the Hørbye River is similar to the Munin River and Ebba River in Petunia Bay, which has a typical diurnal hydrological regime with highest daily discharges between 12–16 PM during the highest summer temperatures of the hydrological season between mid-June and early September (Rachlewicz 2007, 2009b; Szpikowski et al. 2014). Because of the glacier retreat and melting of accumulated snow I assume the main hydrological activity of the Hørbye River is at the end of spring and in early summer season (Rachlewicz 2007, 2009b; Bernhardt et al. 2017). The grain-size of bedload material in both rivers (Ebbaelva and Muninelva) compared to Hørbye River varies from sand to gravel; channel bars are present from the glacier snout to the middle-section of the Ebbaelva River, but in the case of sediment sources there is a big difference – Ebbaelva is supplied by an important right-side lateral sediment source, which is, however, composed by much finer material when compared with the axial-transported material. In the Hørbye River system I studied primarily the proglacial outwash fan, where the geological composition plays the biggest role. Lateral sediment sources have smaller influence following the geology and water availability. We need to have in mind that the Hørbye outwash fan sediments were glacially reworked and then occasionally modified by the fluvial processes in this braided river system.

Conclusions

The results of this case study show differences between sediment sources in braidplain located in the Hørbye Glacier forefield. The main sediment sources were defined: (i) esker complex; (ii) debris stripes; (iii) till plain; (iv) hummocky moraine; (v) post-LIA braidplain; (vi) LIA moraine; (vii) LIA braidplain within the 27 localities. The overview of this braidplain characteristics helps us to understand the processes in this very sensitive Arctic catchment. Our focus goes from the parameters of the whole catchment, through the river-system, to landforms, sediment sources and finally to sediment parameters. For this catchment 7 sediment sources were defined along the entire river. The biggest difference can be seen in the localities H3 and H4, which are composed of limestone debris stripes. Here, big changes in the case of petrological type and also in roundness are observed. In the rest of the localities, there is a smaller and different role of each source in sediment input into the main channel. The main influence has a glacial retreat and reworking the sediments within braidplain by the fluvial processes.

References

BENNETT, G. L., EVANS, D. J. (2012): Glacier retreat and landform production on an overdeepened glacier foreland: the debris‐charged glacial landsystem at Kvíárjökull, Iceland. *Earth Surface Processes and Landforms*, 37(15): 1584-1602.

BENNETT, G. L., EVANS, D. J., CARBONNEAU, P. and TWIGG, D. R. (2010): Evolution of a debris-charged glacier landsystem, Kvíárjökull, Iceland. *Journal of Maps*, 6(1): 40-67.

BERNHARDT, H., REISS, D., HIESINGER, H., HAUBER, E. and JOHNSSON, A. (2017): Debris flow recurrence periods and multi-temporal observations of colluvial fan evolution in central Spitsbergen (Svalbard). *Geomorphology*, 296: 132-141.

BORÓWKA, M. (1989): The development and relief of the Petuniabukta tidal flat, central Spitsbergen. *Polish Polar Research*, 10: 379-384.

CARRIVICK, J. L., HECKMANN, T. (2017): Short-term geomorphological evolution of proglacial systems. *Geomorphology*, 287: 3-28.

CHURCH, M. (1992): Channel morphology and typology. *In*: P. Calow, G. E. Petts (eds.): The Rivers Handbook. Blackwell: Oxford, pp. 126–143.

COLOMBERA, L., MOUNTNEY, N. P. and MCCAFFREY, W. D. (2013): A quantitative approach to fluvial facies models: methods and example results. *Sedimentology*, 60: 1526-1558.

DALLMANN, W. K., PIEPJOHN, K. and BLOMEIER, D. (2004): Billefjorden, Svalbard 1:50,000. Geological map with excursion guide. Norsk Polar Institute. Tromsø.

EVANS, D. J., STRZELECKI, M., MILLEDGE, D. G. and ORTON, C. (2012): Hørbyebreen polythermal glacial landsystem, Svalbard. *Journal of Maps*, 8(2): 146-156.

EWERTOWSKI, M. W., EVANS, D. J., ROBERTS, D. H., TOMCZYK, A. M., EWERTOWSKI. W. and PLEKSOT, K. (2019): Quantification of historical landscape change on the foreland of a receding polythermal glacier, Hørbyebreen, Svalbard. *Geomorphology*, 325: 40-54.

FERGUSON, R. I., CUDDEN, J. R., HOEY, T. B. and RICE, S. P. (2006): River system discontinuities due to lateral inputs: generic styles and controls. *Earth Surface Processes and Landforms*, 31(9): 1149-1166.

FOLK, R. L., WARD, W. C. (1957): Brazos River bar [Texas]; A study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, 27(1): 3-26.

FØRLAND, E. J., BENESTAD, R., HANSSEN-BAUER, I., HAUGEN, J. E. and SKAUGEN, T. E. (2011): Temperature and precipitation development at Svalbard 1900–2100. *Advances in Meteorology*, 2011: 1-14. doi: 10.1155/2011/893790

HAMBREY, M. J. (1994): Glacial environments. UCL Press, London: 296 p.

HANÁČEK, M., FLAŠAR, J. and NÝVLT, D. (2011). Sedimentary petrological characteristics of lateral and frontal moraine and proglacial glaciofluvial sediments of Bertilbreen, Central Svalbard. *Czech Polar Reports*, 1(1): 11-33.

HANÁČEK, M., NÝVLT, D., FLAŠAR, J., STACKE, V., MIDA, P., LEHEJČEK, J. and KŘENOVSKÁ, I. (2013): 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. *Czech Polar Reports*, 3(2): 107-129.

HEIN, F. J., WALKER, R. G. (1977): Bar evolution and development of stratification in the gravelly, braided, Kicking Horse River, British Columbia. *Canadian Journal of Earth Sciences*, 14(4): 562-570.

KARCZEWSKI, A., RYGIELSKI, W. (1989): The profile of glacial deposits in the Hörbyedalen and an attempt at their chronostratigraphy, central Spitsbergen. *Polish Polar Research*, 10: 401-409.

KAVAN, J. (2017): Water temperature and runoff dynamics in two high Arctic streams. *In*: *Proceedings: Students in Polar and Alpine Research Conference 2017,* 20-22 April Brno, Czech Republic, pp. 26.

KNIGHTON, D. (1998): Fluvial forms and processes: A new perspective. London: Arnold. 383 p.

KOCIUBA, W., JANICKI, G. and DYER, J. L. (2019): Contemporary changes of the channel pattern and braided gravel-bed floodplain under rapid small valley glacier recession (Scott River catchment, Spitsbergen). *Geomorphology*, 328: 79-92.

KOSTRZEWSKI, A. (1989): The development of the marginal zone of the Hörbyebreen and the share of proglacial water in the formation of the Petuniabukta tidal flat, central Spitsbergen. *Polish Polar Research*, 10: 369-370.

KOSTRZEWSKI, A., KANIECKI, A., KAPUŚCIŃSKI, J., KLIMCZAK, R., STACH, A. and ZWOLIŃSKI, Z. (1989): The dynamics and rate of denudation of glaciated and non-glaciated catchments, central Spitsbergen. *Polish Polar Research*, 10: 317-367.

LÁSKA, K., WITOSZOVÁ, D. and PROŠEK, P. (2012): Weather patterns of the coastal zone of Petuniabukta, central Spitsbergen in the period 2008–2010. *Polish Polar Research*, 33: 297-318.

LØNNE, I. and LYSÅ, A. (2005): Deglaciation dynamics following the Little Ice Age on Svalbard: Implications for shaping of landscapes at high latitudes. *Geomorphology*, 72(1-4): 300-319.

LUKAS, S., NICHOLSON, L. I., ROSS, F. H. and HUMLUM, O. (2005): Formation, meltout processes and landscape alteration of high-Arctic ice-cored moraines–Examples from Nordenskiold Land, central Spitsbergen. *Polar Geography*, 29(3): 157-187.

LUNT, I. A., BRIDGE, J. S. (2004): Evolution and deposits of a gravelly braid bar, Sagavanirktok River, Alaska. *Sedimentology*, 51: 415-432.

LUNT, I. A., BRIDGE, J. S. and TYE, R. S. (2004): A quantitative, three – dimensional depositional model of gravelly braided rivers. *Sedimentology*, 51: 377-414.

MAŁECKI, J. (2013): Elevation and volume changes of seven Dickson Land glaciers, Svalbard, 1960–1990–2009. *Polar Research*, 32(1): 18400. doi: 10.3402/polar.v32i0.18400

MAŁECKI, J. (2016): Accelerating retreat and high-elevation thinning of glaciers in central Spitsbergen. *The Cryosphere*, 10: 1317-1329.

MARCINIAK, M. A., DRAGON, K. (2010): The influence of groundwater discharge on the runoff of an Arctic stream (Ebba River, central Spitsbergen). *Biuletyn Państwowego Instytutu Geologicznego*, 441 (Hydrogeologia z. 10): 93-100.

MIDGLEY, N. G., COOK, S. J., GRAHAM, D. J. and TONKIN, T. N. (2013): Origin, evolution and dynamic context of a Neoglacial lateral–frontal moraine at Austre Lovénbreen, Svalbard. *Geomorphology*, 198: 96-106.

ONDRÁČKOVÁ, L., HANÁČEK, M. and NÝVLT, D. (2018): Axial transport and sources of fluvial gravel in Munindalen, Svalbard. *In*: *Proceedings: Students in Polar and Alpine Research Conference 2018*. Brno, Czech Republic, pp. 30–31.

ONDRÁČKOVÁ, L., NÝVLT, D. and HANÁČEK, M. (2020): Effect of bedrock morphology, axial transport and lateral material sources on braided river sediments: A case study from Munin Valley, central Spitsbergen. *Polish Polar Research*, 41(3): 213-235.

POWERS, M. C. (1953): A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology*, 23: 117-119.

RACHLEWICZ, G. (2003): Warunki meteorologiczne w zatoce Petunia (Spitsbergen środkowy) w sezonach letnich 2000 i 2001. *Problemy Klimatologii Polarnej*, 13: 127-138.

RACHLEWICZ, G. (2007): Floods in high Arctic valley systems and their geomorphologic effects (examples from Billefjorden, Central Spitsbergen). *Landform Analysis*, 5: 66-70.

RACHLEWICZ, G. (2009a): River floods in glacier-covered catchments of the high Arctic: Billefjorden-Wijdefjorden, Svalbard. Norsk Geografisk Tidskrift, 63: 115-122.

RACHLEWICZ, G. (2009b): Contemporary sediment fluxes and relief changes in high Arctic glacierized valley systems (Billefjorden, Central Spitsbergen). Wyd. Nauk. UAM Poznań, seria Geografia, nr 87: 204.

RACHLEWICZ, G., STYSZYŃSKA, A. (2007): Comparison of the course of air temperature in Petuniabukta and Svalbard-Lufthavn (Isfjord, Spitsbergen) in the years 2001–2003. *Problemy Klimatologii Polarnej*, 17: 121-134.

SLAYMAKER, O. (2010): Drivers of mountain landscape change during the twenty-first century. *Journal of Soils and Sediments*, 10: 597-610.

STANKOWSKI, W. (1989): Geomorphology of the north-eastern area adjacent to Petuniabukta and the northern shores of Adolfbukta, central Spitsbergen. *Polish Polar Research*, 10: 265-266.

SZPIKOWSKI, J., SZPIKOWSKA, G., ZWOLINSKI, Z., RACHLEWICZ, G., KOSTRZEWSKI, A., MARCINIAK, M. and DRAGON, K., (2014): Character and rate of denudation in a High Arctic glacierized catchment (Ebbaelva, Central Spitsbergen). *Geomorphology*, 218: 52-62.

TOMCZYK, A. M., EWERTOWSKI, M. W. (2017): Surface morphological types and spatial distribution of fan-shaped landforms in the periglacial high-Arctic environment of central Spitsbergen, Svalbard. *Journal of Maps*, 13(2): 239-251.

WITOSZOVÁ, D., LÁSKA, K. (2012): Spatial distribution of air temperature in central part of Svalbard in the period 2008–2010. *Czech Polar Reports*, 2: 117-122.

WOJCIECHOWSKI, A. (1989): Sedimentation in small proglacial lakes in the Hörbyebreen marginal zone, central Spitsbergen. *Polish Polar Research*, 10: 385-399.
ZAGÓRSKI, P. (2011): Shoreline dynamics of Calypsostranda (NW Wedel Jarlsberg Land, Svalbard) during the last century. *Polish Polar Research*, 32(1): 67-99.
ZAGÓRSKI, P., GAJEK, G. and DEMCZUK, P. (2012): The influence of glacier systems of polar catchments on the functioning of the coastal zone (Recherchefjorden, Svalbard). *Zeitschrift für Geomorphologie, Supplementary Issues*, 56(1): 101-121.
ZIAJA, W. (2004): Mountain landscape structure and dynamics under the 20th century climate warming in central Nordenskiöldland, Spitsbergen. *Ekológia*, 23: 374.
ZIAJA, W., PIPAŁA, R. (2007): Glacial recession 2001-2006 and its landscape effects in the Lindströmfjellet-Håbergnuten mountain ridge, Nordenskiöld Land, Spitsbergen. *Polish Polar Research*, 28(4): 237-247.

Web sources / Other sources

[1] Norsk Polar Institute (NPI) website. Tromsø. 2020. [accessed 2020 July 10] https://data.npolar.no/dataset/

[2] TopoSvalbard. Norsk Polar Institute. Tromsø. 2009. [accessed 2020 July 20] http://toposvalbard.npolar.no/