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Bedload transport in Polar gravel-bed rivers

Ph.D. Thesis

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PROHLÁŠENÍ

Prohlašuji, že jsem svoji disertační práci vypracovala samostatně pod vedením doc. Mgr. Daniela Nývlta, Ph.D., s využitím informačních zdrojů, které jsou v práci citovány.

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ABSTRACT

The thesis deals with the transport of sediments in gravel streams in Polar regions. The study of bedload sediments, the transport and changes in their grain size and shape characteristics has a long history, but only recently have they been studied in proglacial rivers of high latitudes. The assigned work aims to study and compare the behaviour of braided gravel-bed rivers and to develop appropriate methods of study and data collection in the Polar regions.

Three catchments of proglacial braided gravel-bed streams were selected for the research. Two river catchments are located on the Svalbard archipelago in northern Billefjorden and one river catchment is located on James Ross Island in Antarctica. These catchments of gravel-bed streams are located in the forefield of glaciers, which has been studied since 2016 during the research expeditions. The Munin River catchment on Svalbard was selected due to the morphology of the whole river catchment, the presence of active sediment sources and the well-developed river bed. The second catchment of the Keller River on James Ross Island was selected as a suitable example for assessing the impact of connectivity in the catchment area on sediment transport. The third catchment of the Hørbye River on Svalbard is characterized by gravel sediments in front of the Hørbye glacier and has been used to study their changes in relation to hydrological activity on the floodplain.

This work brings new results of fluvial geomorphological research of the mentioned Polar braided rivers. It focuses on the transport of sediments in the forefield of glaciers and the development of grain size and shape characteristics. It evaluates the factors influencing the transport of sediments, such as their different sources and their activity and, last but not least, connectivity in the river catchment. This work provides comprehensive information on the functioning of proglacial river systems in selected river catchments with respect to the interaction between river bed morphology, sediments and hydrological activity associated with climate. The location of sediment sources, their activity (main river tributaries) and the length of transport to the main stream from the source to the mouth are taken into account. At the same time, the influence of the connectivity of the slopes to the river bed and the morphology of the braidplain, which has a dominant influence in the upper parts of the river basin, are assessed. Finally, these effects are reflected in the shape characteristics of the transported petrological types, especially in the different degree of roundness of the clasts.

ABSTRAKT

Dizertační práce se zabývá transportem sedimentů ve štěrkonosných tocích v polárních oblastech. Studium dnových splavenin, jejich transportu a změn jejich zrnitostních a tvarových charakteristik má dlouhou historii, avšak teprve v poslední době byly studovány v proglaciálních tocích vysokých zeměpisných šířek. Zadaná práce si klade za cíl studovat a porovnat chování divočících štěrkonosných toků a rozvíjet vhodné metody studia a sběru dat v polárních oblastech.

Pro výzkum byla vybrána tři povodí proglaciálních divočících toků. Dvě povodí, která se nacházejí na souostroví Svalbard v severní části Billefjordu a jedno povodí, které leží na ostrově Jamese Rosse v Antarktidě. Jedná se o povodí štěrkonosných toků v předpolí ledovců, která byla zkoumána od roku 2016 v rámci výzkumných expedic. Povodí toku Muninelva na Svalbardu bylo vybráno z důvodu morfologie celého povodí, přítomnosti aktivních zdrojů sedimentů a vyvinutého říčního koryta. Druhé povodí toku Keller na ostrově Jamese Rosse bylo vybráno jako vhodné pro posouzení vlivu konektivity v povodí na transport sedimentů. Třetí povodí toku Hørbye na Svalbardu je charakteristické štěrkovými sedimenty v předpolí ledovce Hørbyebreen a vhodně posloužilo ke studiu jejich změn ve vztahu k hydrologické aktivitě na výplavové plošině.

Práce přináší nové výsledky fluviálně-geomorfologického výzkumu zmiňovaných polárních toků. Je zaměřena na transport sedimentů v předpolí ledovců a vývoj zrnitostních a tvarových charakteristik. Zhodnocuje faktory ovlivňující transport sedimentů, jako jsou především jejich rozdílné zdroje a jejich aktivita a v neposlední řadě konektivita v povodí. Tato práce přináší komplexní informace o fungování proglaciálních říčních systémů ve vybraných povodích s ohledem na interakci mezi morfologií říčního dna, sedimenty a aktivitou říčního systému spojenou s klimatem. V úvahu je brána poloha zdrojů sedimentů, jejich aktivita (přítoky hlavního toku) a délka transportu do páteřního toku od pramene po ústí. Zároveň je posuzován vliv konektivity svahů ke korytu a morfologie výplavové plošiny, která má dominantní vliv v horních částech povodí. Nakonec se tyto vlivy odráží v tvarových charakteristikách transportovaných horninových typů zejména v rozdílném stupni zaoblení klastů.

CONTENTS

1. PREFACE

This thesis is dealing with the problems of sediment transport in polar rivers. Presented information expand our knowledge about bedload transport characteristics in proglacial gravel-bed rivers based on field mapping and sediment analyses. The sediment transport was studied in the context of the characteristics and activity of sediment sources, morphological changes in braidplain, morphology and connectivity of the stream and catchment taking water availability and climate in account.

The idea is to present the results from the polar field campaigns from Svalbard, the Arctic (with the help of the Czech Arctic Research Station) and from Antarctica (by the cooperation with the researchers from the Johann Gregor Mendel Czech Antarctic Station on James Ross Island (JRI) of the Czech Antarctic Research Programme). The research campaigns took place in summer of 2016 on Svalbard in the Arctic and the one in Antarctica in austral summer of 2018.

This thesis is based on three research papers, which are all about fluvial geomorphological aspects of the sediment transport in polar rivers.

> In the first paper the effect of catchment morphology, axial transport and lateral material sources on the nature of braided river sediments were studied in the Munin Catchment in central Svalbard. This catchment has dominant glacial sources in the upper part and lateral sources of sediment in its middle part, which influenced bedload transport
>
> The second paper originates from Antarctica and the Keller Catchment from James Ross Island and brings the first fluvial geomorphological dataset from this area. The channel morphological changes and downstream changes in the context of material sources and connectivity were observed.
>
> The third paper is based on the dataset from the Svalbard expedition in 2016 from the Hørbye Catchment. In this research several material sources within the Hørbye River braidplain were compared and the longitudinal development of the clasts from the viewpoint of petrological types and roundness were described.

The presented papers bring new information on sediment transport in proglacial fluvial environments from Antarctica and the Arctic. Studied catchments reflects unique characteristics of braidplain morphology, active sediment transport and the presence of diverse sources of sediments connected to the main channel in the changing glacier forefields. It helps us better understand the processes and variables, which influence the braidplain morphology and parameters of sediment transport by the proglacial rivers in the very sensitive Polar areas, which are experiencing essential environmental changes.

PhD Dissertation contains following papers:

Paper 1

Ondráčková, L., Nývlt, D., 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.

LO was responsible for the study design (with a help of MH and DN). LO did the field campaign, processed the data and wrote the manuscript. MH and DN helped with the manuscript writing and interpretation of geological background.

Paper 2

Ondráčková, L., Surian, N., Nývlt, D., Stuchlík, R., (2020). Downstream variability of channel morphology and bed material in the braided Keller River, James Ross Island, Antarctica. Geografia Fisica e Dinamica Quaternaria, 43(2), - *in press*

LO was responsible for the study design (with a help of DN). LO did the field campaign, processed the data and wrote the manuscript. RS helped with the DTM and maps, NS helped with the overall interpretation.

Paper 3

Ondráčková, L., (2020). Longitudinal development of clast shape characteristics from different material sources in Hørbye River, Central Svalbard. Czech Polar Reports, 10(2), 189–202.

LO as the only author prepared the study design (on similar base as in Munindalen study), conducted the field work, processed the data and wrote the manuscript.

2. INTRODUCTION

The proglacial areas are characterized as environments, where large meltwater or multiple streams emanate from the frontal and lateral margins of ice masses and glaciofluvial sediments enter the proglacial zone and bedload competency declines, then characteristically braidplain (Zieliński and Van Loon, 2003) or outwash fans of various dimensions develop (Menzies and Hess, 2013). Due to the high rates of geomorphological activity, they form an ideal location for the application of mapping and measurement methods to document and quantify changes, and to test models, within a comparatively short time period (Carrivick et al., 2013). Glacial forefields, active parts of proglacial braidplain, which are sensitive to water and sediment availability, are object of this research.

The evolution of the braidplain is connected to the glacier melting, meteorological conditions, morphology of the catchment and river-bed and sediment input. The discharge frequency episodes of glacial meltwater dynamics are associated with fluvial dynamics and sediment delivery (Marren, 2005; Rachlewicz, 2007). Geological composition of the catchment with erosion processes influence the amount of material in the catchment. For the sediment transport it is necessary to consider the hydrological and sediment connectivity of the catchment with the role of the sediment delivery and topography (Cavalli et al., 2013; Wohl et al., 2017)

The Munin Catchment (Svalbard), the Keller Catchment (JRI, Antarctica), and the Hørbye Catchment (Svalbard) are ice-free areas. The connection with sediment delivery and activity of local glaciers represent interesting conditions for comparing these polar regions.

Fig. 1 Location of the study area; A – Central Svalbard, B – James Ross Island, 1 – Munin Catchment – paper 1; 2 – Keller Catchment – paper 2; 3 – Hørbye Catchment – paper 3.

2.1 SVALBARD – MUNIN CATCHMENT

The Munin Catchment is located in the central part of Svalbard near the Pyramiden Town. The catchment area is 40.3 km^2. The Munin River is 8 km long and forms a long valley braidplain with a 50–250 m wide channel belt, which is pebble-cobbly along the entire river. The mean annual air temperature of central Svalbard is around –3.7 °C (Ambrožová and Láska, 2017).

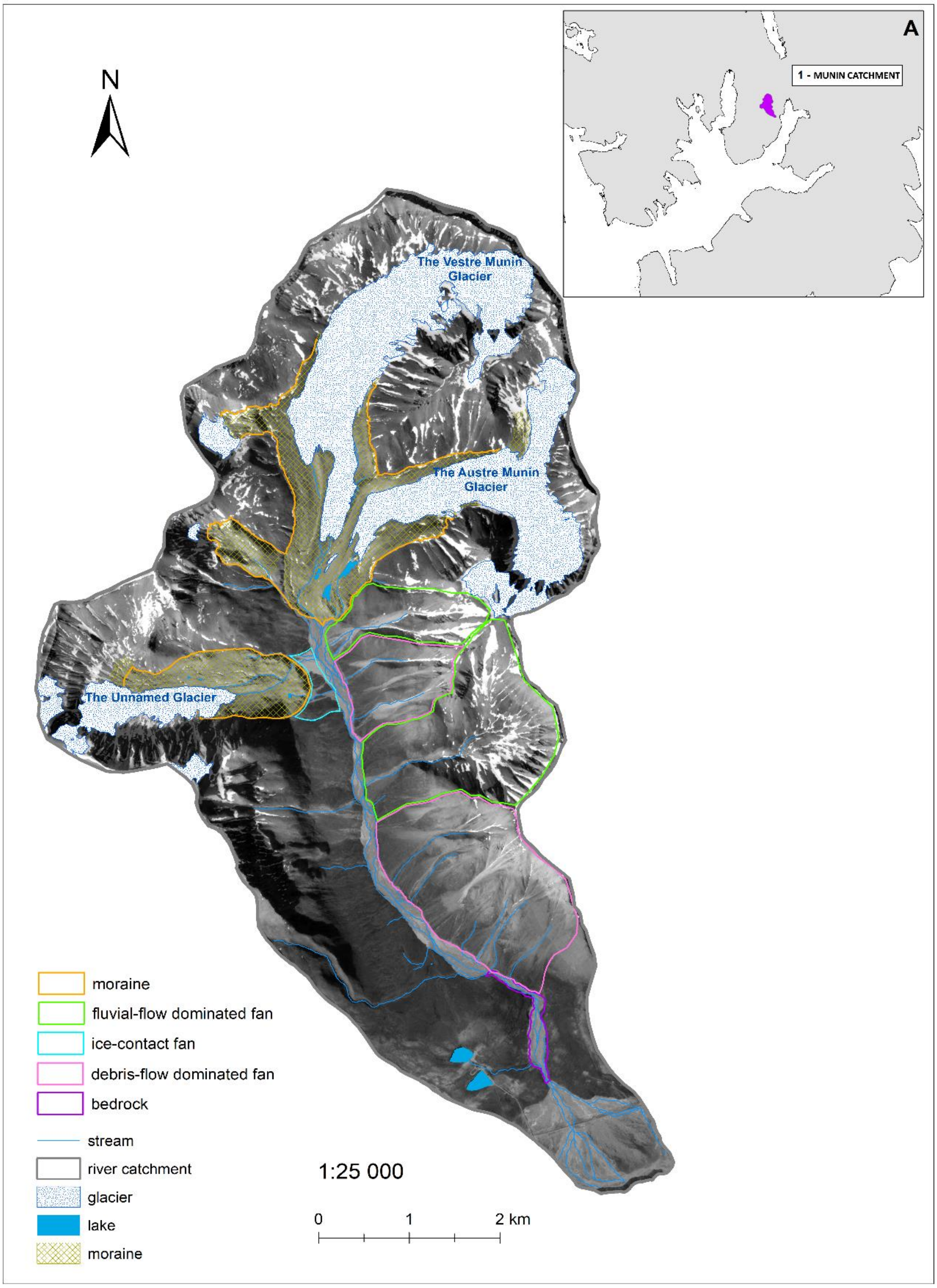

Fig. 2 Ortophotomap with the location of the material sources of the Munin Catchment - Svalbard

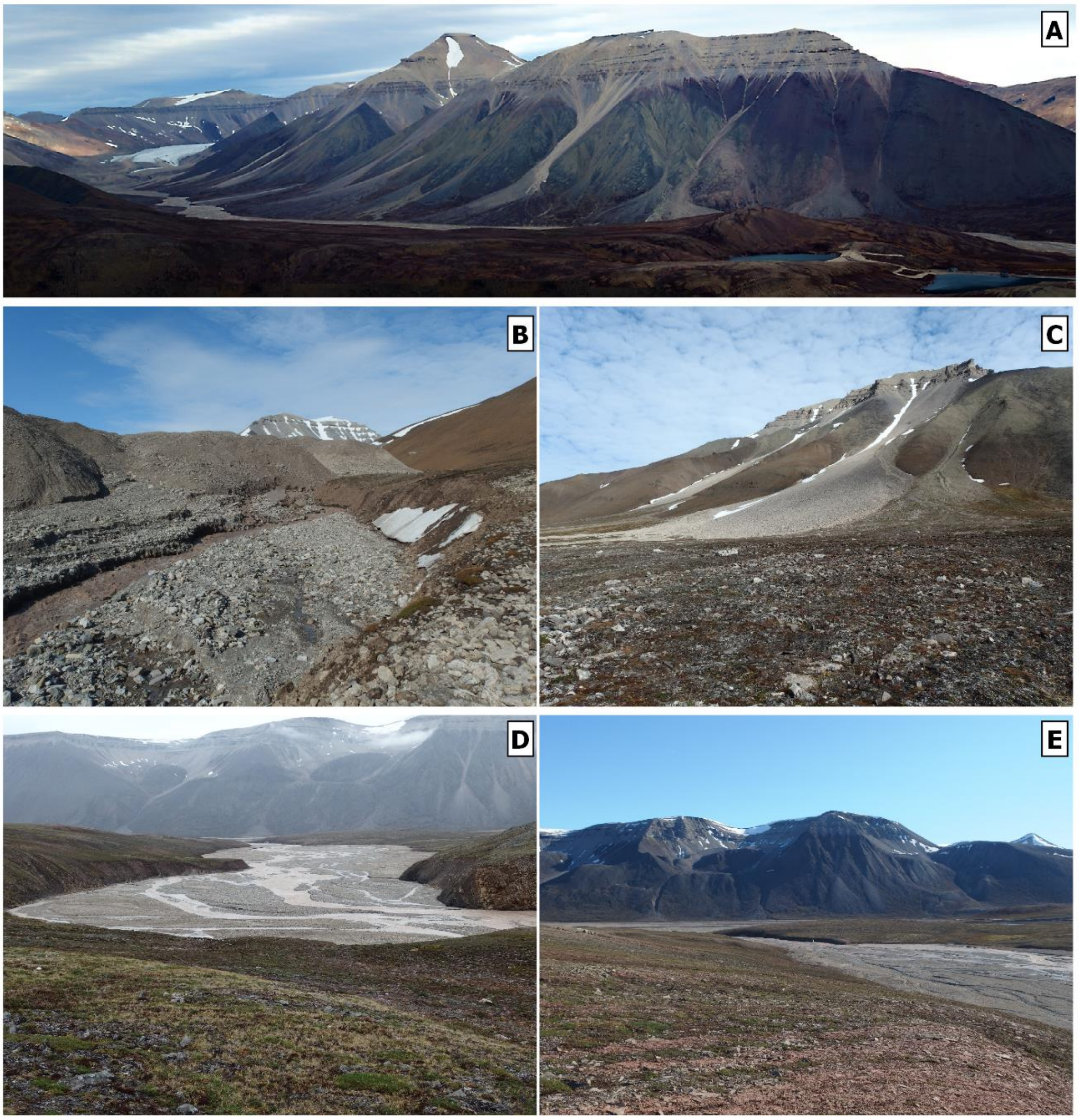

Fig. 3 Photographs of the study areas – Munin Catchment; A - panoramic photo of the Munin Catchment, B – morainic complex, C – lateral debris-flow dominated sources, D – lower part of the river with the widest braidplain during high discharge, E – lower part of the river with the beginning of the gorge during low discharge

There were morainic, ice-contact fan sediment source, fluvial-flow dominated fans and debris-flow dominated fans recognised. The Munin Catchment is built of Devonian Old Red sandstones, Carboniferous-Permian limestones, quarzitic sandstones, conglomerates and mostly shaly siltstones. The topography varies between 1029 and 12 m a.s.l. and sometimes there are steep slopes, from which material into the channel is delivered. The transported material can contain boulder fractions in the upper part during the peak discharges and cobble size fractions in the rest of the longitudinal profile of the stream.

The roundness of gravel clasts is affected by the shape of the channel belt, which is predetermined by the morphology of the catchment's bedrock. The gravel roundness in this fluvial system does not increase gradually downstream, but is importantly influenced by the lateral inputs and channel belt predisposed by the bedrock.

2.2 JAMES ROSS ISLAND – KELLER CATCHMENT

The Keller Catchment is located on JRI, near the Antarctic Peninsula. The river length is 8.6 km. The catchment area is 31 km^2 and catchment elevation ranges from 706 to 0 m a.s.l. The mean annual air temperature of JRI –6.3 °C for the period 2013–2016 (Ambrožová et al., 2018).

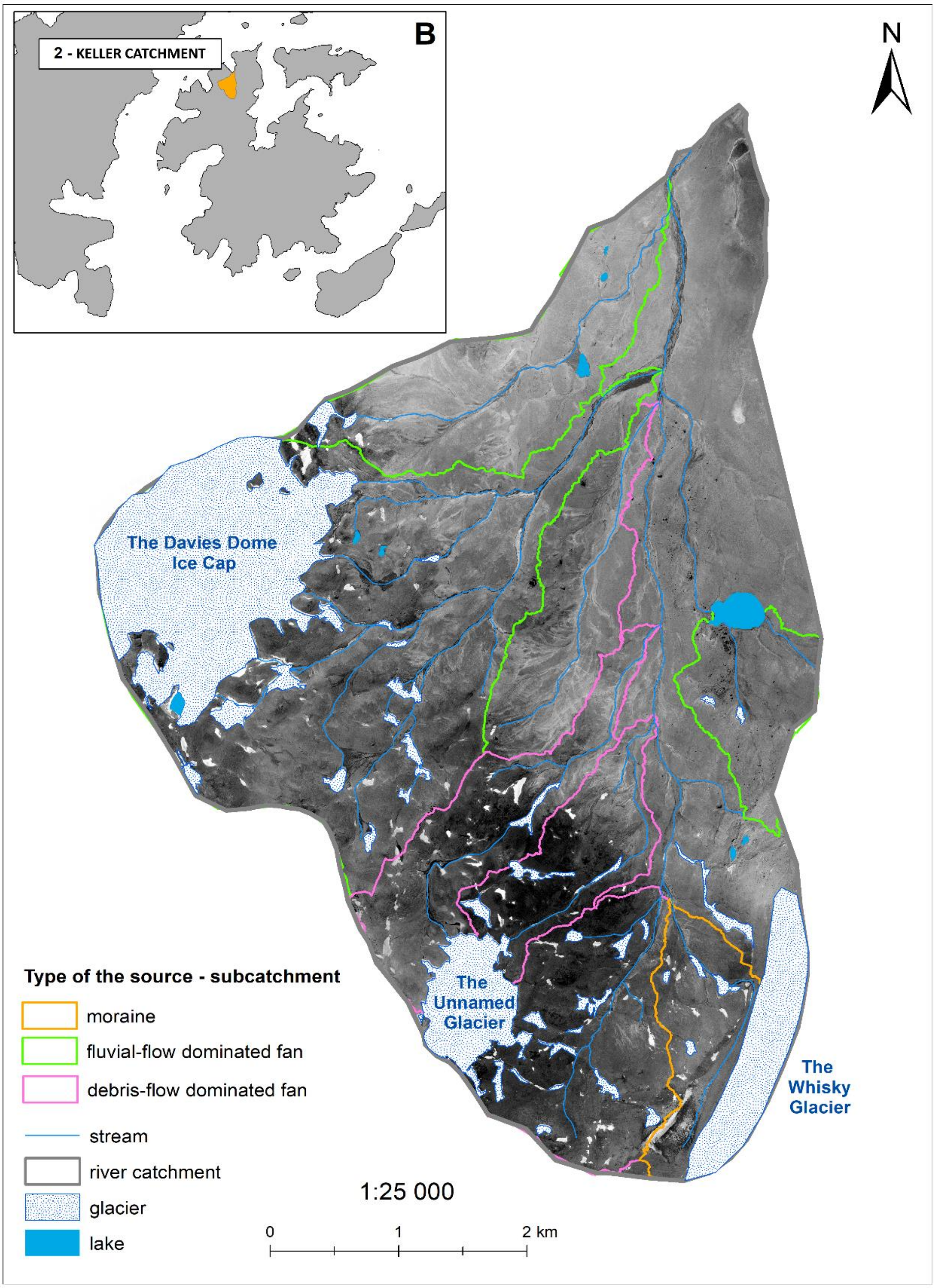

Fig. 4 Ortophotomap with the location of the material sources of the Keller Catchment – James Ross Island, Antarctica

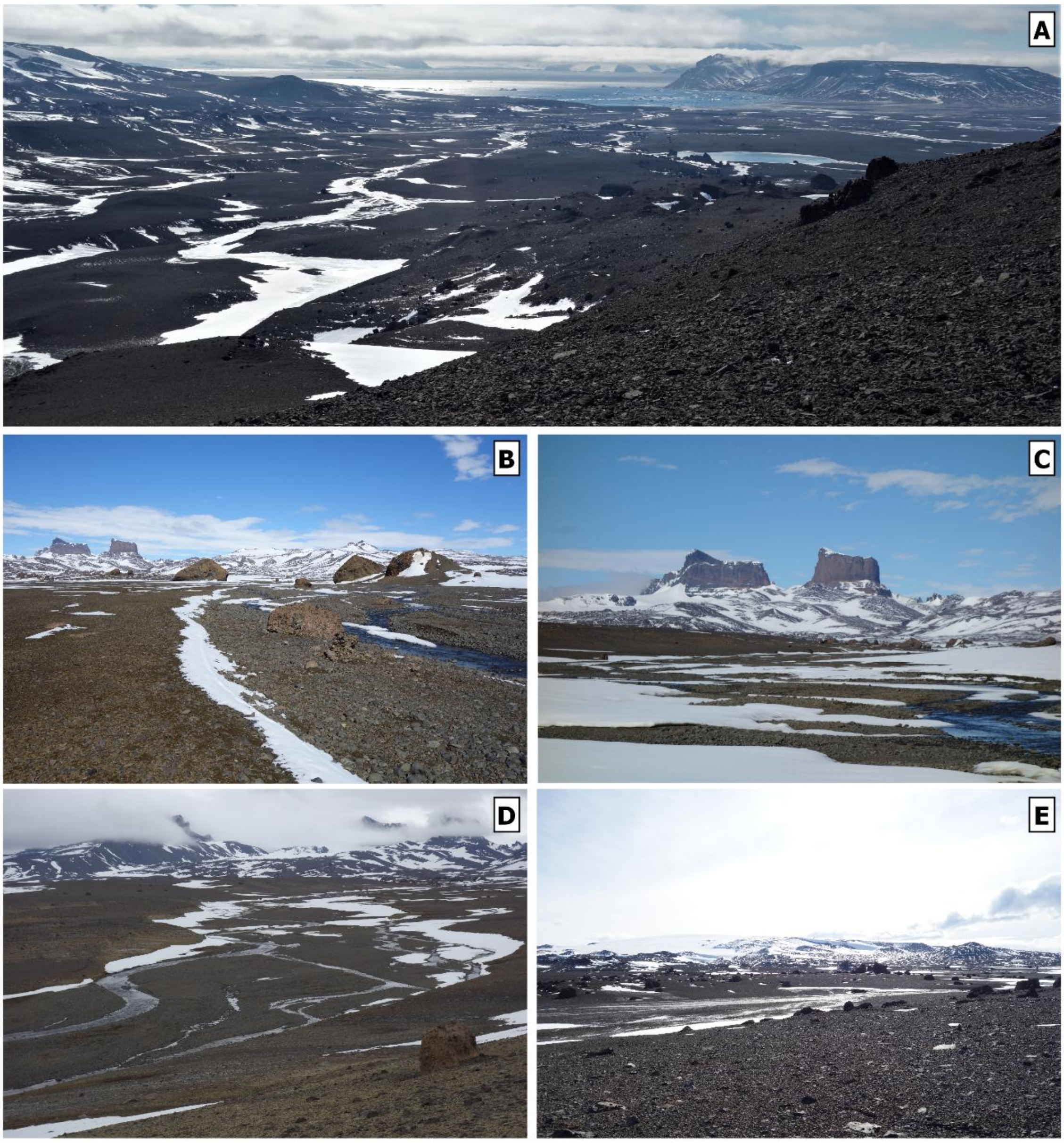

Fig. 5 Photographs of the study areas – Keller Catchment; A - panoramic photo of the Keller Catchment with the Monolith Lake (photo is taken from the Whisky Glacier morainic complex), B – middle reach during the low discharge and hyaloclastite breccia boulders, C – view from the middle part to the upper part of the braidplain with Lookalike Peaks on the horizon, D – lower part of the river with the widest braidplain during high discharge, E – upper reach at the beginning of non-connective part of the braidplain.

In this catchment, the morphology, including river braidplain, sediment sources and connectivity within the catchment were investigated. Eight sediment sources were identified: one morainic sediment source, four debris-flow-dominated sediment sources and three fluvial-flow-dominated sediment sources. Landforms are built by the extensive Cretaceous mudstone and sandstone rocks covered in layers of massive basalts and hyaloclastite breccias from large boulders to sand fraction, braidplain is covered by reworked proglacial sediments at places.

The upper parts are highly connected, and due to the instability of the sediment on the slopes, the debris-flow processes deliver material into the channel together with the fluvial-flow transport by the main tributaries. The channel width and braiding intensity show an increasing downstream trend, sediment sources interrupt the general downstream roundness trend.

2.3 SVALBARD – HØRBYE CATCHMENT

The largest studied catchment described in this thesis is the Horbye catchment. The catchment area is 60 km^2. Is about twice the size of the Keller Catchment on James Ross Island, Antarctica. The glaciated area in Hørbye Catchment is also the biggest - the polythermal Hørbye and Hoel glacier system is approx. 8 km long and 1 km wide in the proximal part. The glacierized area is approx. 15.9 km^2 (Malecki et al., 2013).

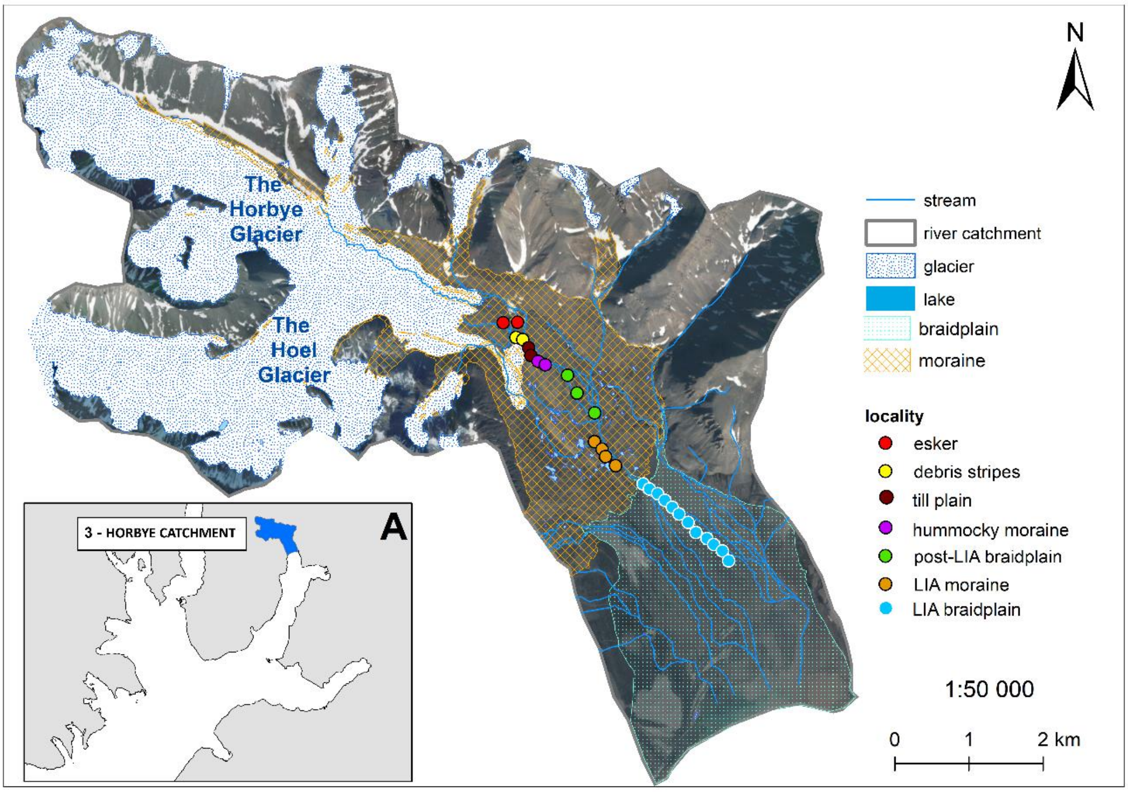

Fig. 6 **Ortophotomap with the location of the material sources of the Hørbye Catchment – James Ross Island, Antarctica**

The area of interest is located along the 10 km long Hørbye River. The Hørbye River channel is predominantly pebble-cobbly along the entire stream and has different types of channel bars. The braidplain is 2.3 km wide and 4.5 km long and is characterized by the presence of eskers, moraines, till plain, lakes and other proglacial landforms (Evans et al., 2012). The average annual temperature according to (NPI, 2020) is –5 °C.

The topography varies between 1028 – 0 m a.s.l. The braidplain is located at altitudes to 111 m, with the higher ridges of the lateral moraine reaching up to 320 m a.s.l. The upper parts are made of sandstone, siltstone, clastic carbonate rocks and evaporates. The other part of the valley side contains dolomite, sandstone and gypsum. The main influence on sediment transport in this area has a glacial retreat and reworking of the sediments within the braidplain by current fluvial processes.

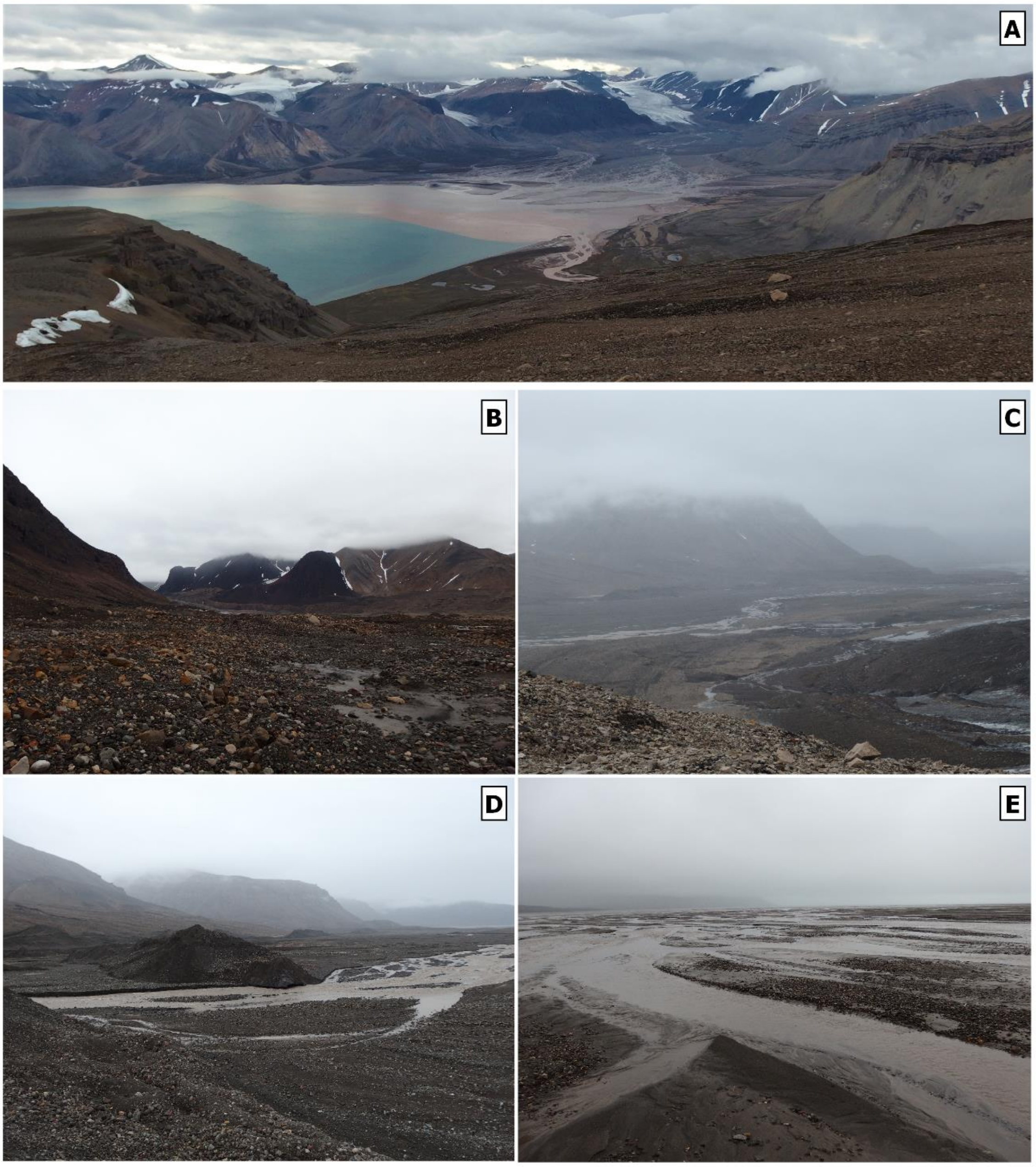

Fig. 7 Photographs of the study sites – **Hørbye** Catchment; A - panoramic photo of the **Hørbye** Catchment with the end of the Petunia Bay (photo is taken from the hill Lovehovden – 608 m a.s.l.), B – upper reach during the low discharge with the presence of reworked till, C – view from the frontal moraine of the **Hørbye glacier** on the entire braidplain, D – middle part of the river with the sediment input to the channel, E – lower part of the braidplain during high discharge.

3. MATERIAL AND METHODS

During the preparation of the study design for each study, there was an effort to maintain rather similar methods. The reason for that was to find the comparable proglacial environments (catchments). The methods applied focused on sediment transport in catchments under study and are briefly described below. Availability of material sources and individual data differ between the localities (Svalbard and James Ross Island).

3.1 DATASETS, HISTORICAL PHOTOGRAPHS, MAPS

There is higher amount of historic materials from the Arctic (Svalbard). Historic photographs, maps and information are available via NPI (Norsk Polar Institute), which provides individual datasets (for example .shp layers). The preliminary view everyone can have via TopoSvalbard – online web server with topographic map, orthophoto map and 3D model. Geological maps are on Norsk Polarinstitut WebGIS (SvalbardKartet), here you also can use WMS servers for any geographical information environment. Svalbard Museum and UNIS (University Centre on Svalbard) provide further information.

Old photographs (since 1930) from Svalbard and the new photos or 3D models helped to observe changes in this very sensitive Arctic landscape. The important role is also the transport accessibility to the field, possibility of cooperation with scientists from UNIS or Norway and presence of many Arctic stations on Svalbard.

The more complicated situation is on the opposite polar region, in Antarctica. For preliminary analyses, an aerial orthophoto Image (Czech Geological Survey, 2009), REMA model (Howat et al., 2019) and geological (example .shp layers) and topographical map from the Czech Geological Survey (2009 and 2020) were used. Field activities on JRI are closely linked with the opening of the Johann Gregor Mendel Czech Antarctic Station in 2007 and subsequent observations and measurements.

3.2 PREPARATION OF THE STUDY DESIGN

According to the available sources of information, the selection of catchment was processed. The final validation of localities was carried out during the field campaigns. The preparation phase always included map analysis, DEM processing and preselection of landforms and sediment sampling localities for each scientific study. Also, the sediment sources were pre-defined.

3.3 FIELD WORK

During the research campaign, the detailed geomorphological mapping of each catchment was completed. The final selection of sediment sources was defined during the field work. The sediment sources outside of the braidplain were defined as ice-contact fans, debris-flow-dominated fans, fluvial-flow-dominated fans and morainic sources (De Haas et al., 2015; Tomczyk and Ewertowski, 2017) within the catchments (paper 1 and paper 2). Sediment sources within the braidplain were i) esker complex; (ii) supraglacial debris stripes; (iii) till plain; (iv) hummocky moraine; (v) post-LIA braidplain; (vi) LIA moraine; (vii) LIA braidplain (paper 3). The activity of channel in braidplain and also of the sediment sources were observed during different meteorological conditions (Ondráčková et al., 2017).

3.4 SEDIMENT CHARACTERISTICS

For each catchment, sediment sampling localities were selected in the flow profile and from every sediment source. Some of the samples were analysed directly in the field, but the rest were sieved at sampling sites and processed in the laboratory by measurements of clast axes, identification of their roundness and petrography. Each sample contained 100 clasts. The sampling was supplemented by GPS position, site description and photo documentation of the site and the close surroundings. This method was similar for all studied catchments.

Sedimentary petrological analyses of sampled clasts consist of the following steps: (i) identification of petrology; (ii) measurements of a, b and c axes; and (iii) roundness assessment using the roundness classes of Powers (1953). For clast shape, ternary diagrams of Sneed and Folk (1958) were plotted using the Triplot Excel macro of Graham and Midgley (2000). For further analyses of the material sources and transport history of fluvial sediments, the covariate plot of C40 and RA indexes (Benn and Ballantyne, 1994) were used. Besides, the covariant plot of the transport distance and the degree of roundness (Hanáček et al., 2013) was used in paper 1. The results are visualized in graphs with position of the sediment sampling localities and percentage of roundness type, or petrological type for individual localities.

3.5 CHANNEL MORPHOLOGY

In paper 2, segmentation of the river into similar reaches was applied. This study contained more geospatial analyses and map developing with several topics for a better understanding of the processes and parameters influencing the sediment transport. The detailed morphology, slope profile, confinement index, valley morphology, braiding index and channel width were obtained according to the Guidebook for the evaluation of stream morphological conditions (Rinaldi et al., 2011).

3.6 SEDIMENT SOURCES AND CONNECTIVITY

Connectivity can be interpreted as a limiting factor for the relationships between sediment supply and transport (Fryirs, 2013). However, if it is not in this almost ideal state, there will be violations and discontinuities (disconnections). Connectivity, defined as the transfer of energy and mass between two landscape units within the system as a whole (Chorley and Kennedy, 1971), must be maintained on the basis of inputs in the source zone and outputs at the mouths of rivers.

If this connectivity is disrupted, disconnection occurs, which depends on the position of the blockers (Fryirs et al., 2017). Disconnectivity within and between landscape units affects the extent and speed of energy and mass transfer in the river basin. Different forms of relief can hinder the contribution of sediments to the river system (Brunsden and Thornes, 1979) and it is necessary to identify the dominant processes.

Paper 2 also brings information about connectivity of material sources to the channel. SedInConnect 2.3 software (Crema and Cavalli, 2018) is a freeware tool that implements Cavalli et al. (2013) approach with further improvements used for the Keller Catchment. An index of connectivity evaluates the potential connection between hillslopes and features acting as targets, or 167 storage areas for transported sediment (Cavalli et al., 2013).

4. SUMMARY OF RESULTS

Presented papers give us the information about the functioning of the sediment transport in proglacial fluvial systems within the two areas of interests, i.e. on Svalbard, the High Artic, and on James Ross Island, the marginal Antarctica. The polar regions are highly exposed to undergoing climate change. The High Arctic region, especially Svalbard is the unique place to study the environment evolution according to the availability of historical data since the end of the Little Ice Age (LIA). On the opposite side of the globe, the James Ross Island (JRI) bear the largest ice-free area in the Antarctic Peninsula region with an unglaciated area of 552 km^2 and 12.5% of it are located on the Ulu Peninsula, where the Keller Catchment occurs. The current conditions in the Keller Catchment foresee the understanding of local and regional specifics of sediment dynamics of the proglacial landscape evolution in other Antarctic regions, which are expected to become ice-free in the next decades and/or centuries.

The resulting sedimentary processes are representative of the Polar proglacial landsystem, in many places and their dynamic provides the ideal opportunity to study changes in glacial and fluvial sediment budget in response to changes in meteorological conditions and geomorphological processes.

4.1 THE EFFECT OF BEDROCK MORPHOLOGY, AXIAL TRANSPORT AND LATERAL MATERIAL SOURCES

In the Paper 1, which presents results from well-developed valley train of the Munin River, were described the main controlling factors on sediment transport. After a detailed field work, eight sediment sources were determined. Starting from the upper part of the valley, it is the morainic complex and ice-contact fan, with a high portion of angular clasts. The sediment sources on western part of the valley, the debris-flow dominated fans were observed with the dominance of slope and gravitational activity. Furthermore, the fluvial-flow dominated fans on the tributaries were mapped.

The influence of the sediment sources on each segment is presented in Paper 1 together with the petrological types proportions and degree of roundness change. The Munin River was divided into four segments based on the importance of the following factors: a) bedrock morphology, i.e. surface topography of pre-Holocene geological units in individual parts of the catchment; b) water availability of material sources, including seasonal or temporary ablation of snow patches and glaciers' ablation; c) axial transport, i.e. downstream movement of material in the Munin River channel belt.

Generally, the proportion of angular clasts is higher in the cobble fraction compared to the pebble fraction. Particles are influenced by fluvial transport; however, the effect of sediment sources can be recognised. The downstream roundness in cobbles is very variable, while in pebbles it decreases towards the end of the entire river. The morphological changes of the channel belt are controlled by the bedrock morphology of the catchment, which is the main factor affecting the clast roundness in the Munin River (especially in the segment 3 – the gorge). The axial transport is dominant in the case of cobbles. The fluvial transport is more effective than debris-flows for the transport of cobbles.

The Hørbye River is specific from the viewpoint of the sediment sources. Glacial landforms appearing directly in the braidplain served directly as sediment sources: i) esker complex; (ii) supraglacial debris stripes; (iii) till plain; (iv) hummocky moraine; (v) post-LIA braidplain; (vi) LIA moraine; (vii) LIA braidplain, which are all characterized in detail in Paper 3.

4.2 RIVER SEGMENTATION AND CHANNEL MORPHOLOGY

River segmentation was used primarily in Paper 1 (Munin Catchment, Svalbard) and Paper 2 (Keller Catchment, JRI). The first approach - segmentation of the channel belt based on the influence of several factors on sediment transport in Munin River was used in Paper 1. Whereas, the segmentation of the Keller River reflects the confinement index variability (from a single-thread channel in a confined V-shaped valley at the source reach to the unconfined valley with the multiple channels). Together with a confinement index, the braiding index was assessed in Paper 2.

With braiding index and the size of braidplain, the channel width (the width of the active zone) is connected. In the Munin River, the channel was segmented when a change in parameters has been detected after an entire analysis to the final 4 reaches (Paper 1). The Keller River segmentation was delimited every 25 m at the beginning of the work and the parameters described in Paper 2 provide the background for splitting into the final 7 reaches. The trend shows increased braiding intensity when moving downstream together with the general widening of the active zone. This results correspond with the catchment morphology, where the V-shaped valleys occur in the upper parts.

4.3 DOWNSTREAM CHANGES IN BEDLOAD MATERIAL CHARACTERISTICS

In all three papers, the dominant parameters of lithological composition/petrological type and the degree of roundness were examined. For the Munin Catchment, the most dominant petrological types in the studied samples within the Munin River catchment are Devonian Old Red sandstone (65%) and Carboniferous to Permian limestone (30%). Less common accessory petrotypes (<5%) are represented mostly by quartzite and shale (Paper 1). Within the Hørbye River, the most common petrological types among the clasts were sandstone, limestone and orthogneiss. The dominance of sandstone clasts is evident. At many sediment sampling localities, the proportion of sandstone clasts was more than 60%. The second most common type – limestone clasts – covers around 20% and they are sourced from the upper part of the catchment. An appreciable increase in the amount of limestone proportions is evident in the debris stripes sediment source. Orthogneiss and additional lithologies are only accessory (Paper 3).

The Keller Catchment basement is made of Cretaceous sandstones, and Neogene basalts and palagonites (from the hyaloclastite breccias). The downstream change of each dominant petrological type is presented in Paper 2. Among studied samples, the most dominant types were sandstone (usually more than 50%) and basalt (approximately 30%), with the remainder being palagonites. Overall, sandstone and basalt clasts show a slight decreasing trend along the longitudinal flow profile of the river, while palagonite shares increased especially in the middle part of the braidplain due to the presence of hyaloclastite breccia boulders and their in situ weathering.

In the case of roundness, the common feature is the presence of the more angular particles in the upper part of the valleys, where the traction of the clast in the flow is minimal. The high heterogeneity in sediment compounds and high glacial reworking in the past changed the variability of the degree of roundness within the longitudinal flow profile. Downstream roundness trend is disturbed at places, where the lateral material sources are connected and changes of material contribution are evident. The downstream changes in shares of very angular and angular (RA), sub-angular and sub-rounded (RS), and rounded and well-rounded (RR) clasts were studied.

Within the Munin River, the downstream changes of RA shares demonstrate the influence of morainic and ice-contact fan sources, which bring a higher amount of angular clasts to the fluvial system in the uppermost reach. The general decrease of the shares of RA clasts is caused in the downstream direction for the pebble fraction by fluvial abrasion and sediment rounding. Downstream changes of RS shares show an increasing trend of sandstone and limestone clasts. The amount of rounded clasts is rather unstable and depends on the presence of material input, but the pronounced increase in roundness in the lowermost 2 km of the Munin River were highlighted in Paper 1.

Generally, for the Keller River, the increasing downstream roundness can be observed alongside the decreasing angularity. Moreover, the two important sediment sources: morainic and fluvial-flow are described to interrupt this trend. The effects of the tributaries are clearly visible too, especially the increased amount of angular material caused by the input from morainic sediment sources (Paper 2). For the Hørbye River, the degree of roundness is also connected with the petrological type, and the length of a fluvial transport. The character of angular clasts is typical for limestone debris stripes located in the studied catchment. Fluctuation between rounded and angular clasts are found for the other sediment sources. Compared to the samples from debris stripes, the sample from the hummocky moraine contains a higher portion of well-rounded and rounded clasts. Because of the combination of glacial and fluvial processes influencing sediments in braidplain, there are almost no significant trends in increasing sediment roundness as is usual in axial transport with the increasing transport distance (Paper 3).

4.4 CONNECTIVITY OF THE LATERAL SEDIMENT SOURCES IN THE CATCHMENT

For a better understanding of how such sediment sources affect channel morphology and processes and bed material characteristics, the index of connectivity was determined for the whole Keller Catchment in Paper 2. It is necessary to know the position of the sediment source and its activity. Some areas indicate places with a low index of connectivity (e.g., areas around the Monolith Lake and in the middle part of the active zone). Another highlights the areas with a high index of connectivity (e.g., first sediment source – the steepest debris-flow dominated fan, moraine of the Whisky Glacier, upper parts of the tributaries and the left-side slope of the last left-side tributary – the fluvial-flow dominated fan).

Some of the sources are well-connected and on the other hand some are disconnected (the fluvial-flow dominated fan from Monolith lake). Well-connected are upper parts of slopes, V-shaped valleys, confined parts of the valleys, where the gravitational processes helped to donate sediments directly to the tributaries (in the vicinity of Lookalike Peaks, the Whisky Glacier moraine). On the contrary, there are areas, which create a natural barrier in the continuous sediment transport (decrease of slope - plains).

5. SUMMARY AND CONCLUSION

In this Ph.D. thesis, the bedload sediment transport studies from the various Polar catchments in the period 2016–2018 on Svalbard and James Ross Island are presented. The results are important from the perspective that this thesis brings the first comparison between the Svalbard catchments (Munin Catchment and Hørbye Catchment) and the very first study from the James Ross Island (Keller Catchment). Moreover, the Ulu Peninsula is the largest ice-free area in the whole Antarctic Peninsula region, which offers a unique opportunity to study the fluvial geomorphological processes in contrast to climate, water availability, catchment topography or connectivity and represents thus an excellent playground to study processes, which will become more frequent in other parts of marginal Antarctica due to ongoing climate change. The assessment of sediment transport in proglacial channels has been a primary source for estimations of sediment budgets in Polar environments. This approach is very important for the future not only for uninhabited Polar areas, but also for the mountain regions, where there are remnants of glaciers that will be subject to changing climate. The focus in this work goes from the parameters of the whole catchment, through the river system, to landforms, sediment sources and finally to sedimentary particle parameters. The overview of braidplain characteristics help us to understand the processes in very sensitive Arctic and Antarctic catchments.

For all presented studies, the basic pillar was the robust field work, which contained the fluvial geomorphological mapping and sediment sampling respecting the braidplain morphology and catchment parameters. Thus, in the particular studies, the effect of five important factors (bedrock morphology, axial transport, lateral sediment sources, channel/braidplain topography and connectivity) was examined and the data are also discussed within the context of the Polar Regions. The intense morphodynamics of Polar proglacial streams allow research of different fluvial processes within short periods of time that lead to the wider awareness in gravel-bed river behaviour. The results of this work enable a better understanding of channel morphology, sediment characteristics and factors controlling their variability along the selected Polar rivers. The focus was on the material transported within the braidplain, through channel morphology, sediment sources, axial transport variability towards the disruptions and sediment connectivity.

For all studied catchments, the presence of a glacier as a source of meltwater suggesting a high variability of river discharge was intended. Seasonal and daily periodicity is complemented by floods caused by meteorological conditions and glacier dynamics, which influenced the parameters of sediment transport in all proglacial streams. The character of the bedload sediments is controlled principally by the shape of the channel belt (channel width, longitudinal slope, braiding intensity). The roundness degree increases in river segments with a small channel belt width and with low sinuosity of channels. The transport energy of flowing water increases in segments with narrow channel belt and straight channels. The shape of the channel belt is predetermined by the morphology of the catchment’s bedrock as the primary factor affecting the roundness of the particles.

Another factor, the connectivity plays a prevailing role in sediment transport from slopes to channels. The upper parts of the catchment are highly connected, and due to the instability of the material covering on the slopes, the activity of the sediment sources, the debris-flow processes (or other gravitational processes) donates material into the channel. This approach can be used in all three catchments. Debris-flow processes and fluvial-flow transport are supported by melting of snow, ice and active layer. The Keller Catchment has a different shape, with highly connective upper parts, which controls the axial sediment transport. Opposite to the Keller Catchment, Munin Catchment has between the active sources (upper parts) and the active braidplain a stable part of the valley, which is stabilized by the vegetation cover. The last catchment of the Hørbye River is the largest and quite specific (the studied sediment sources in Paper 3 are located at landforms directly in the braidplain). The sediment sources here were studied directly in the active part of the braidplain and their characteristics resemble their source origin from various glacial landforms reflecting thus different previous transport in glacial system.

The sediment input also affects channel morphology (channel width and braiding intensity) and bed material characteristics. The sediment sources in all catchments have notable role on clast roundness with the effect of different petrological types being smaller. The downstream clast roundness trend is interrupted by the input of new angular clasts from the sources – this effect was noted in some cases at all rivers. The roundness in proglacial fluvial system does not increase gradually in the downstream direction, but it changes abruptly depending on the changes of the channel belt controlled by the bedrock.

The effect of lithology has a notable role. Dominantly sandstone and limestone clasts were investigated in all catchments. The influence was higher in the gorge segment (the Munin Catchment – paper 1) and also by the limestone debris stripes (the Hørbye Catchment – paper 3). For 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 on sediment transport has the glacial retreat and reworking of the sediments within the braidplain by fluvial processes.

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HydroDívka

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Paper 1

Ondráčková, L., Nývlt, D., 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.

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Effect of bedrock morphology, axial transport and lateral material sources on braided river sediments: A case study from Munin Valley, central Spitsbergen

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Abstract: The Munin River (Svalbard) is a mountainous braided proglacial river. It drains from two valley glaciers developing an elongated channel belt and turning into a wide braided outwash fan before entering the main river. The Munin River is in its axial head supplied by the material from glaciers, and along the stream by material from lateral sources, *i.e.* braided outwash fan, debris-flow and fluvial-flow dominated fans. Detailed analyses of clast roundness showed that roundness suddenly changes to higher degrees in negative correlation with channel belt width and sinuosity of the channels. The roundness increases rapidly in sections with small channel belt width and low sinuosity, which can be seen in the bedrock gorge. On the contrary, the roundness does not change much in sections with large channel belt width and high sinuosity. The morphological changes of the channel belt are controlled by the bedrock morphology of the catchment, which is the main factor affecting the clast roundness in the Munin River. The nature of the lateral material sources and the downstream traction affect rather the individual gravel fractions.

Key words: Arctic, Svalbard, sedimentology, proglacial stream, bedload sediment.

Introduction

The importance of bedload studies in mountain and proglacial environments has grown within last decades due to the significant world-wide shrinkage of glaciers (Heckmann *et al.* 2016). We need to know how river change due to global climate change and its consequences (Kammerlander *et al.* 2017). To achieve this, various research methods have been applied by sedimentologists, geomorphologists and environmental scientists. Shape characteristics, *i.e.* size and roundness of clastic material, indicate transport processes driving the general river morphology (Heckmann *et al.* 2016). One of the features to identify these changes is clast roundness. Sub-angular to sub-rounded forms with increasing roundness intensity downstream predominate in alluvial streams (Gustavson 1974). Present-day fluvial sediment, in many formerly glacierized drainage basins, are still predominantly influenced by transport of reworked glacigenic sediment rather than by ‘primary’ erosion of the land surface (Church and Ryder 1972; Ballantyne 2002). The combination of the laboratory analyses and field observations leads to a consistent conceptual model, where increased fine particle loading occurs when the discharge initiates bedload transport (Park and Hunt 2017).

The streams between the glacier snout across the valley floor to the river delta, fed mainly by glacial melt water and snow, are recognized as proglacial rivers (Hambrey 1994; Carrivick and Heckmann 2017). Proglacial braided river systems are characterized by numerous channels in different stages of discharge activity depending on the actual hydrological cycle (Marren 2005; Slaymaker 2011). The type of glacier, wheather it is cirque glacier, valley glacier, ice cap, or ice sheet, and the morphology of the proglacial zone control the main topography of a sandur or braidplain (Marren 2005). Examples may be found in recently and previously glacierized areas like Alaska, Canada, Spitsbergen, the Alps, the Himalayas, New Zealand, Antarctica and many others (Hambrey 1994). The external factors controlling the behaviour of proglacial streams are: (i) climate; (ii) water availability predominantly in peak discharge; (iii) basin morphology; (iv) sediment transport and availability and (v) vegetation cover and soils. On the other hand, the internal factors are: (i) channel gradient; (ii) its floodplain geometry (iii) and morphology as well as (iv) bank cohesion (Kochel 1988).

Meltwater streams are powerful agents of erosional and transporting processes in the proglacial environment. For proglacial valleys, the valley train (Benn and Evans 2010) and braided outwash fan type of depositional landforms dominate. Braided outwash fans develop, where the river systems are limited by valleys, like lowland plains between two parallel ridges (Hambrey 1994). Channel bars with generally coarser material at the upstream ends of the bars (Lunt and Bridge 2004) occur in such an environment. They are developed in response to marked fluctuations in discharge, sediment supply and seasonal variations in water inflow from glaciers. In winter, glacier discharge is nearly none, but in early summer, when ice melt combines with the snow melt, the entire valley floor can be washed by the flood and much debris is transported (Hambrey 1994).

The newly developed proglacial environments linked to decreasing ice cover are also called paraglacial (Ballantyne 2002; Slaymaker 2009), or generally cold environments (Tricart 1970; Beylich and Warburton 2007). Studies in recently deglaciated areas have focused on hillslope processes, as glacial retreat also exposes unvegetated valley-floor deposits that may show various forms of modification by mass-movement, freeze-thaw, running water and wind action (Ballantyne 2002; Beylich *et al.* 2017; Ewertowski and Tomczyk 2019). Redeposited unconsolidated valley-fill deposits are exhibited as alluvial fans, proglacial sandurs (Benn and Evans 2010), terraces or deltaic and lake sediments (Ballantyne 2002). The glacier foreland (proglacial) land system is characterized by the wide range of processes operating on recently exposed, unvegetated glacigenic deposits (Gurnell *et al.* 2000; Ballantyne 2002). In active landscapes, proglacial rivers in very similar settings can have dramatically different morphologies (Davies 2013). Glacier retreat opens large areas for newly developed channel patterns in proglacial river systems and changes water availability and sediment supply to the channels (Marren and Toomath 2014).

Benn *et al.* (2003) conceptualized how topography, sediment supply to a glacier surface and the efficiency of sediment transport affect the material transport from a glacier to its forefield. The general forces in sediment cascade are gravity and water availability. The changes in the sediment cascade could be presented by the transported volumes, sediment weight, denudation in the catchment with retreat of glaciers (Krautblatter *et al.* 2012). Due to expected changes due to climate change in high-latitude environments, the water availability, sediment transport and geomorphic processes will shift irreversibly (Beylich *et al.* 2006). Sediment sources in proglacial environments are divided into three groups: (i) resulting from glacial erosion, (ii) weathering and slope processes and (iii) sediments remobilized from the previously created landforms, such as moraines, channel bars, *etc.* (Carrivick and Heckmann 2017).

The aim of this study is to present the characteristics of transported and deposited material to reveal the influence of different sediment sources and fluvial transport through the river catchment. The main goal is to recognize the role of sediment transport and the role of the axial *vs.* lateral sediment delivery at present and in the past. Our question is whether clast shapes at any part of the braidplain channel belt are affected by the fluvial traction only, or whether an important effect of lateral material sources is to be found. To ascertain this, we studied pebble and cobble fractions in the lateral sediment sources and the river channel bars of the Munin River catchment in central Spitsbergen. The results will help to further build up the general knowledge about the climatic influence and evolution of the nature of piedmont coarse-grained fluvial sediments in proglacial environments. Furthermore, the often reported hypothesis of downstream trend in increased roundness is tested in this catchment. Our results could thus improve the palaeogeographical interpretation of past proglacial sediments.

Study area

This study was undertaken in the Munin Valley located in Dickson Land, Spitsbergen, ~ 4 km west of Pyramiden town (Fig. 1). The Munin River catchment area is 40.3 km^2. The river originates at the confluence of three small streams running from two connected glacier tongues (Vestre and Austre Munin Glaciers) in the NNW part of the valley and flows southwards along the valley axis to its mouth in Mimer Valley, where it joins the Mimer River. The river is ~8 km long and forms a long valley braidplain with a 50–250 m wide channel belt. The climate in the study area is characterized by low precipitation of ~200 mm yr^{-1} and relatively warm winters (Førland *et al.* 2011). The temperatures in winter (December–February) ranged from +3 °C to –30 °C , while summer temperatures (June–August) varied from –2 °C to +12 °C in 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).

The Munin River channel is predominantly pebble-cobbly along the entire stream. In the Munin River braidplain, different types of channel bars can be found. The character of the river bed is described by the occurrence of active and abandoned channels caused by diverse channel activity and dynamics (Colombera *et al.* 2013) with a presence of channel bars (Lunt and Bridge 2004; Lunt *et al.* 2004) together with many channels. The transported material can contain boulder fractions in the upper part during the peak discharges and cobble size fractions in the rest of the flow profile. The pebble to boulder fraction in the river has a different origin.

At the upper part, near the glacier snout, morainic and ice-contact fan sediment sources were recognized. In contrast, fluvial-flow dominated fans and debris-flow dominated fans (Tomczyk and Ewertowski 2017) represent lateral sources in the middle and lower reaches of the river. Material from individual sediment sources is transported to the main river channel in different volumes and with diverse temporal supply (Carrivick and Heckmann 2017).

Devonian Old Red rocks crop out at the eastern valley side as variously coloured sandstones, conglomerates and shales below the Carboniferous-Permian limestones, which build the upper parts of the summits (Dallmann *et al.* 2004). Devonian sandstones cropping out in the catchment could be divided into two groups. The first group is characterized by grey colour and is positioned closer to the main river. The second group is more coloured. Green, red or multi-coloured sandstones are present in this group and they crop out mainly at the lower part of the valley close to the Munin River mouth and also on the eastern slope of the valley (Fig. 1). This group comprises quarzitic sandstones, conglomerates and mostly shaly siltstones. Layers of conglomerate up to 2 m in thickness are associated with grey and multi-coloured sandstones. They are massive, light grey, yellow and black and are poorly sorted, matrix-supported and poorly stratified

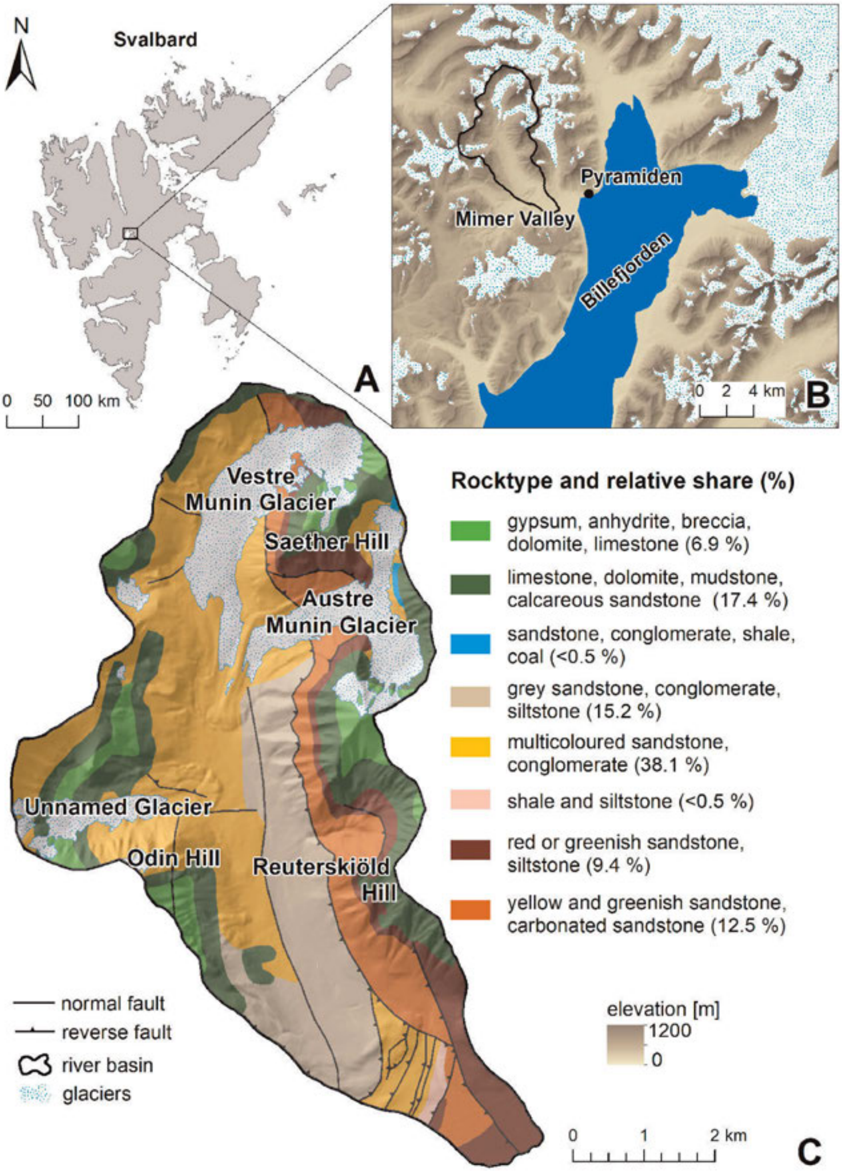

Fig. 1. Location of the study area: **A** - the archipelago of Svalbard with the largest island of Spitsbergen, **B** - the area of Billefjorden, **C** - geological map of the Munin Valley, based on geological map of Billefjorden by Dallmann *et al.* (2004).

(Piepjohn and Dallmann 2014). The grain size of conglomerate clasts is medium to coarse-grained pebbles and they are variably coloured (Dallmann *et al.* 2004), but boulders up to 40 cm could also be found. Conglomerates contain rounded to well-rounded pebbles and cobbles encrusted by Fe-Mn oxides. However, most common are green, grey to dark grey subangular siltstone and mudstone clasts (Piepjohn and Dallmann 2014). Clasts of metamorphic quarzitic rocks and white rounded quartzite clasts up to 4 cm in diameter could also be found in conglomerates (Brinkmann 1997; Dißmann 1997 in Piepjohn and Dallmann 2014).

Horizontally deposited Carboniferous to Permian limestones are located in altitudes >500 m a.s.l. They build upper parts of the catchment near watersheds like Odin, Reuterskiöld and Saether hills at the western, eastern and northern side of the valley (Fig. 1). Carboniferous to Permian anhydrites crop out together with limestones and dolomites in the highest parts of watershed ridges such as in Odin and Reuterskiöld hills (Dallmann *et al.* 2004).

Glaciers in this area are covered by angular supraglacial debris especially in their frontal parts. Medial moraine formed by connected adjacent lateral moraine tongues constitutes mound piled clasts and rugged glacier-covered debris composed mainly of limestones. Frontal moraine is composed of angular clasts of both sandstones and limestones. According to De Haas *et al.* (2015) and Tomczyk and Ewertowski (2017), we define the lateral sources as ice-contact fan source locality, debris-flow dominated fan source locality and fluvial-flow dominated fan source locality. Ice-contact fan is located below the east-side glacier with frontal and lateral moraine complex. Well-developed debris-flow dominated fans are present on the lower slope part of the eastern valley side. They are mostly built of grey, yellow and greenish sandstones. Fluvial-flow dominated fans, located on the eastern valley side, are of the same lithology. Western side slopes of the Munin Valley are less active in the sediment supply to the active channels in the Munin Braidplain. At the beginning, the Munin River has a steeper character, but at the mouth, after leaving the gorge, it is characterized by many lateral channels and composes a flat braided outwash fan (*sensu* Hambrey 1994) in the main Mimer Valley. Based on the landforms and associated sediments, individual main sediment source types were recognized in the Munin River catchment.

Methods

The Munin Valley was selected basing on aerial images (TopoSvalbard), because a presence of a well-developed braidplain and well-preserved accumulation landforms. These prerequisites were necessary to study the effect of sediment sources on the properties of fluvial sediments in the dynamic proglacial stream along the 8 km long downstream river profile.

The NPI data (Norsk Polar Institute website) were used in geographical information system environment to pre-select our location of interests. However, the final selection of sediment sampling sites was carried out in Munin Valley during the fieldwork. The selection led to a definition and sampling of major sediment source areas for fluvial material transported.

Field geomorphological mapping of the main landforms and sediment sampling along the Munin River channel belt were realized at the beginning of July 2016. The following sediment sources were defined: (i) terminal moraine-mound complex; (ii) ice-contact fan, (iii) debris-flow dominated fan and (iv) fluvial-flow dominated fan. Eight representative sediment sampling sites from all sediment sources were selected (Figs 2 and 3).

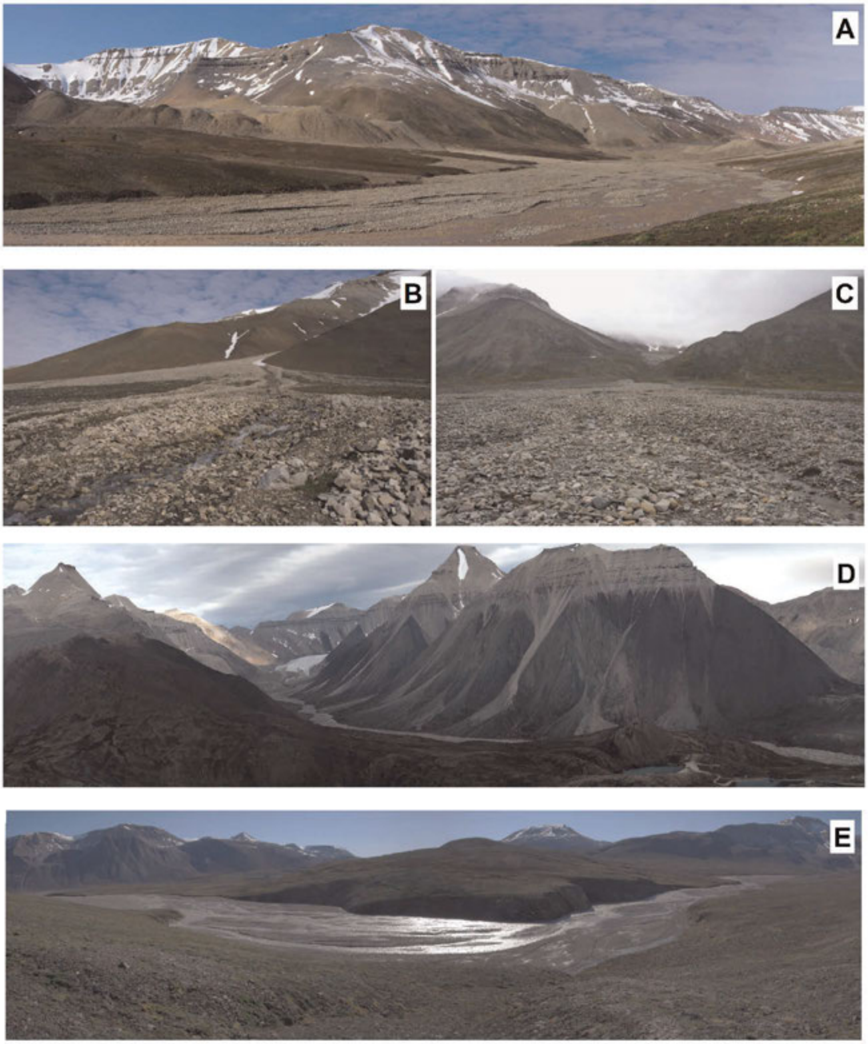

Fig. 2. Examples of the material sources in the Munin Valley: **A** - Morainic sources, **B** and **C** - Fluvial-flow dominated sources, **D** - Debris-flow dominated sources, **E** - Gorge at the lower part of the Munin River.

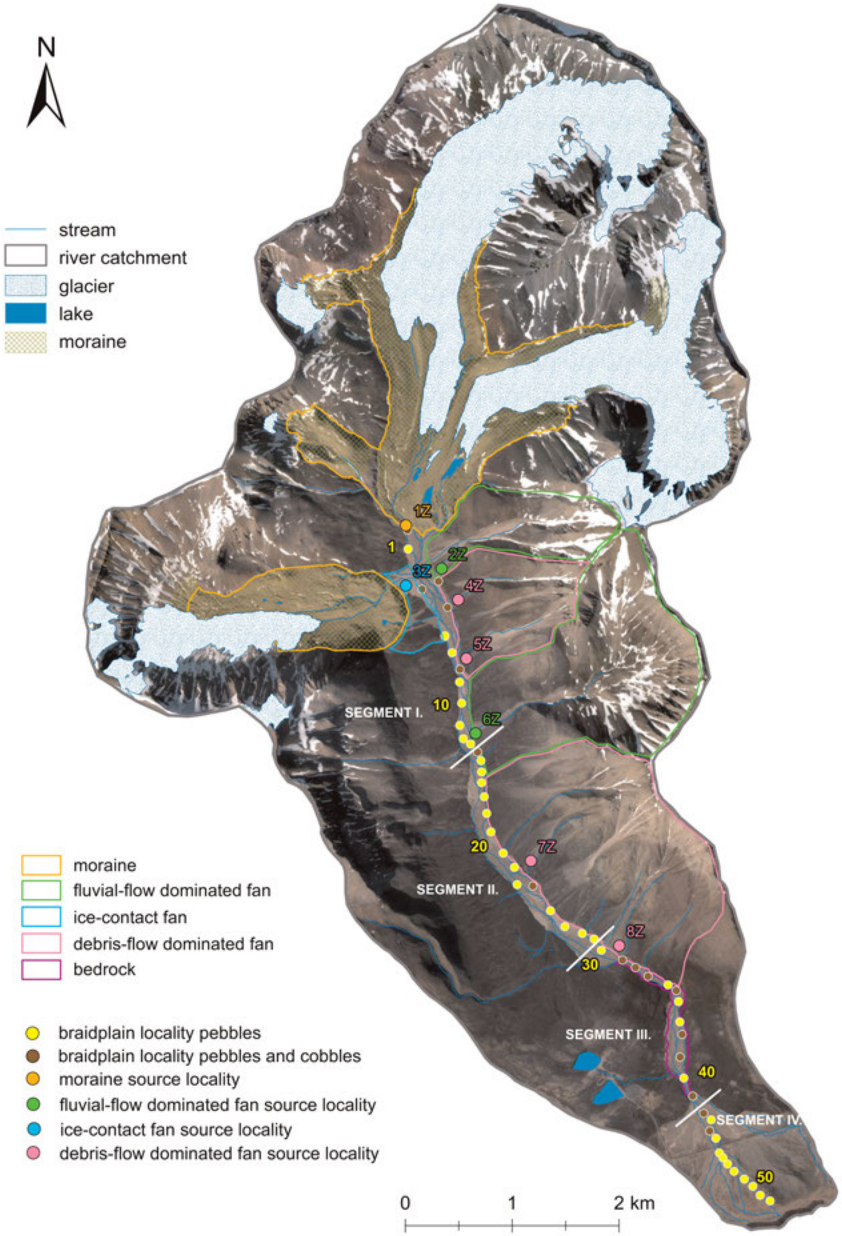

Fig. 3. Topographic map of the Munin Valley with location of the material sources and the sediment sampling localities.

Furthermore, we selected 16 sites for sediment sampling and measurements along the Munin River channel belt for 64–256 mm (b-axis) in cobble fraction and 52 sediment sampling sites for 8–16 mm (b-axis) in pebble fraction. The larger clast fraction was analysed directly in the field. The finer fraction was sieved at sampling sites and processed in the laboratory by measurements of axes, identification of the roundness and petrography. Each sample contained 100 clasts. 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.

In the case of this study, we decided to use the length of the Munin River from the Munin Glaciers morainic complex, the start of the river mileage determined from the Digital Elevation Model, to the confluence of the Munin and the Mimer River corresponding to the end of the river mileage. Petrological analyses of sampled clasts consist of the following steps: (i) identification of petrology using a geological map of Billefjorden (Dallmann *et al.* 2004); (ii) measurements of a, b and c axes; and (iii) roundness assessment using the roundness classes of Powers (1953).

For clast shape, ternary diagrams of Sneed and Folk (1958) were plotted using the Triplot macro of Graham and Midgley (2000). For further analyses of the material sources and transport history of fluvial sediments, we used covariate plot of C_{40} and RA indexes (Benn and Ballantyne 1994). The C_{40} index is the amount of clasts with a c/a ratio <0.4. The RA index is the share of very angular and angular clasts based on Powers' (1953) roundness classes. Our plots were modified from their original version by amplification to the range of values in our study maintaining covariant shape (Hanáček *et al.* 2013). Downstream roundness changes of individual clast petrological types are presented in the following covariant plots: distance *vs.* RA index (RA index indicating share of very angular and angular clasts), distance *vs.* RS index (RS index indicating share of sub--angular and sub-rounded clasts; Hanáček *et al.* 2013) and distance *vs.* RR index (RR index indicating share of rounded and well-rounded clasts).

Results

The source areas for the bedload material in the Munin River braidplain are moraine complexes of the Austre and Vestre Munin glaciers and an unnamed glacier ice-contact fan in the upper part of the river basin. The western-side slopes of the Munin Valley represent debris-flow sources of sediments. As a debris-flow dominated fans sediment source, we assumed the western side slopes of the Munin Valley. The fourth sediment sources were fluvial-flow dominated fans demonstrating the lateral sediment source from the Munin River tributaries. The Munin River tributaries were determined as the fluvial-flow dominated fans (Fig. 2). At the last segment of the Munin River, we also expect material entering the fluvial system directly from the bedrock.

The most dominant petrological types in the studied samples within the Munin River catchment are Devonian Old Red sandstone (65%) and

Carboniferous to Permian limestone (30%). Less common accessory petrotypes (< 5%) are represented mostly by quartzite and shale in pebble and cobble fractions, respectively (Figs 4 and 5).

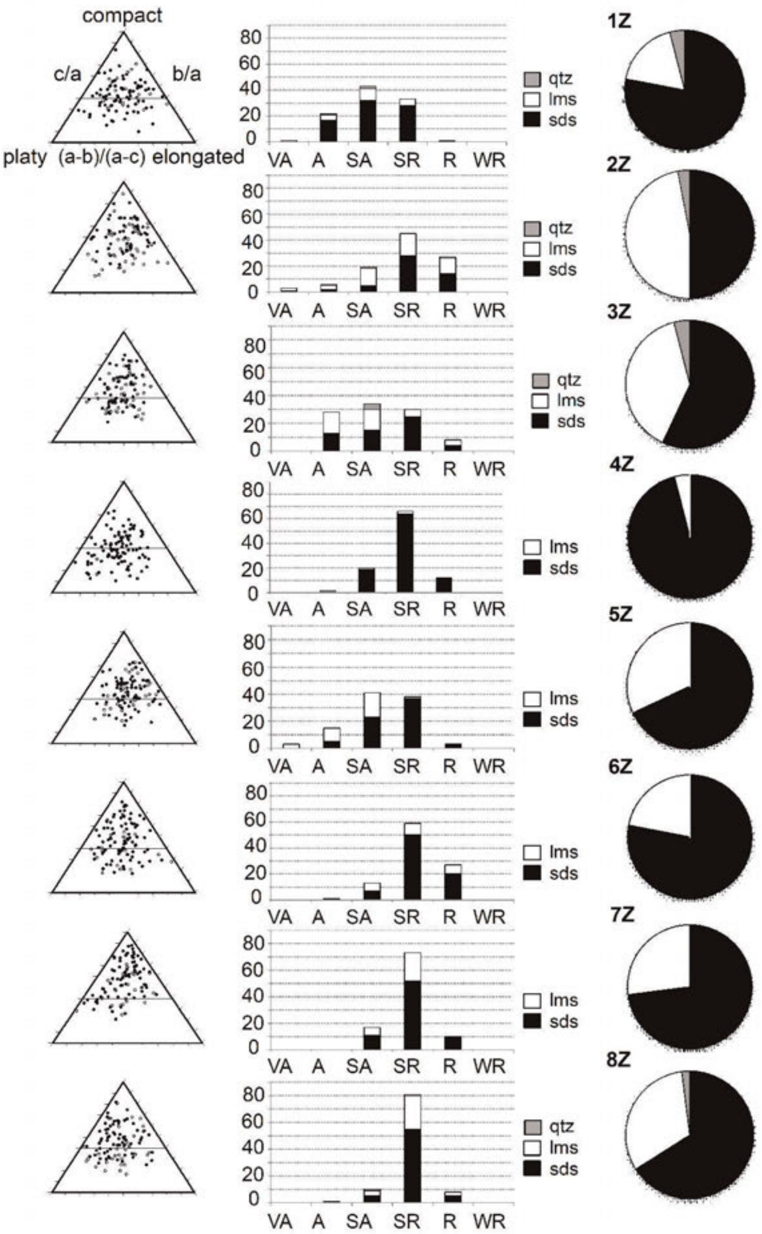

Fig. 4. Triplot graphs from sediment sampling localities at material sources for the pebble fraction 8–16 mm along the b-axis. Abbreviations: VA - very angular, A - angular, SA - subangular, SR - subrounded, R - rounded, WR - well-rounded; qtz - quartzite, lms - limestone, sds - sandstone.

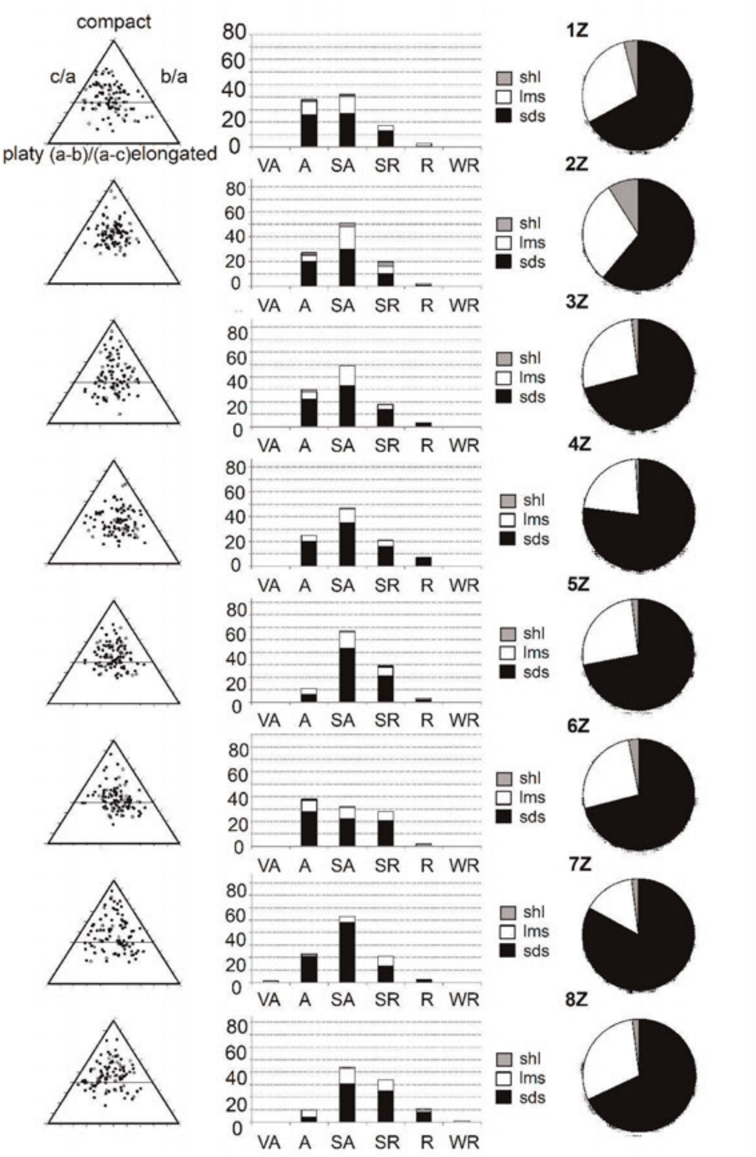

Fig. 5. Triplot graphs from sediment sampling localities at material sources for the cobble fraction 64–256 mm along the b-axis. Abbreviations: VA - very angular, A - angular, SA - subangular, SR - subrounded, R - rounded, WR - well-rounded; shl - shale, lms - limestone, sds - sandstone.

Downstream roundness changes, together with the effect of lateral material sources on both pebble and cobble fractions are presented in Figs 6 and 7. It comprises downstream changes in shares of very angular and angular (RA), sub-angular and sub-rounded (RS), and rounded and well-rounded (RR) clasts for fluvial sediments and material from moraines, ice-contact, fluvial-flow dominated and debris-flow dominated fans.

Downstream changes of RA shares demonstrate the influence of morainic and ice-contact fan sources, which bring a higher amount of angular clasts to the fluvial system in the uppermost reach. The general decrease of the shares of RA clasts is caused in the downstream direction for the pebble fraction by fluvial abrasion and sediment rounding. Morainic, ice-contact and debris-flow dominated fan sources supply a significant proportion, generally up to 50% of RA clasts. They always have higher shares of RA clasts when compared to the fluvial material for the pebble fraction. This is different for the fluvial-flow dominated fan, which does not contribute RA clasts into the fluvial system. The contribution of RA cobble clasts from lateral sources to the overall share of RA material in the fluvial system is insignificant. Only few lateral sources contribute importantly with RA clasts to the fluvial system in the pebble fraction (Figs 6–8). However, the high shares of RA cobble clasts in the upper reaches of Munin Valley are affected by morainic and ice-contact fan material sources. The significant rounding trend of both petrological types examined could be seen in the important reduction of RA clasts from 20–30% to <10% after 3 km of fluvial transport of pebble material. Such change appears after only 1 km for the cobble material (Figs 6 and 7). The covariant plots for C_{40} ratio and RA share (Fig. 8) shows the mutual relation between clast shape and roundness for both fractions. The sediment sources in the case of sandstones have higher portion of RA clasts in comparison with limestones.

Downstream changes of RS shares show an increasing trend of both petrological types in the pebble fraction with an important increase after 3.5 km. In the cobble fraction, a downstream decrease of the shares of RS clasts from 5th km of the river mileage to the Munin River mouth is evident (Figs 6 and 7). The percentage of RS shares in source localities and the fluvial system is analogous in the pebble fraction, but percentages are generally higher in the cobble fraction of the fluvial localities. All types of material sources supply a significant portion, generally 60 to 90% of RS clasts in the pebble fraction, which is a similar proportion as in the fluvial system. For the cobble fraction, the importance of lateral sources is very similar (60–80%). In the lower reach, in the braided outwash fan, RS shares of cobble clasts are <60%.

The downstream trend of RR shares in the pebble fraction is rather unstable. For sandstone and limestone clasts, an increasing share is typical for the 0–3.5 km of the river mileage and then a decreasing share between 3.5th and 5th km of the river is visible. In the lower reach from 5th km to the river mouth, the RR share slowly increases for Old Red sandstone clasts, but is highly variable for limestone clasts. For the cobble fraction, we observe increasing shares of RR clasts in both petrological types. There is a pronounced increase in the lowermost 2 km of the Munin River, which correlated negatively with a decrease of RS shares for both petrological types (Figs 6 and 7).

All material from the sources tends to be generally subangular to subrounded and angular to subangular for pebble and cobble fractions, respectively

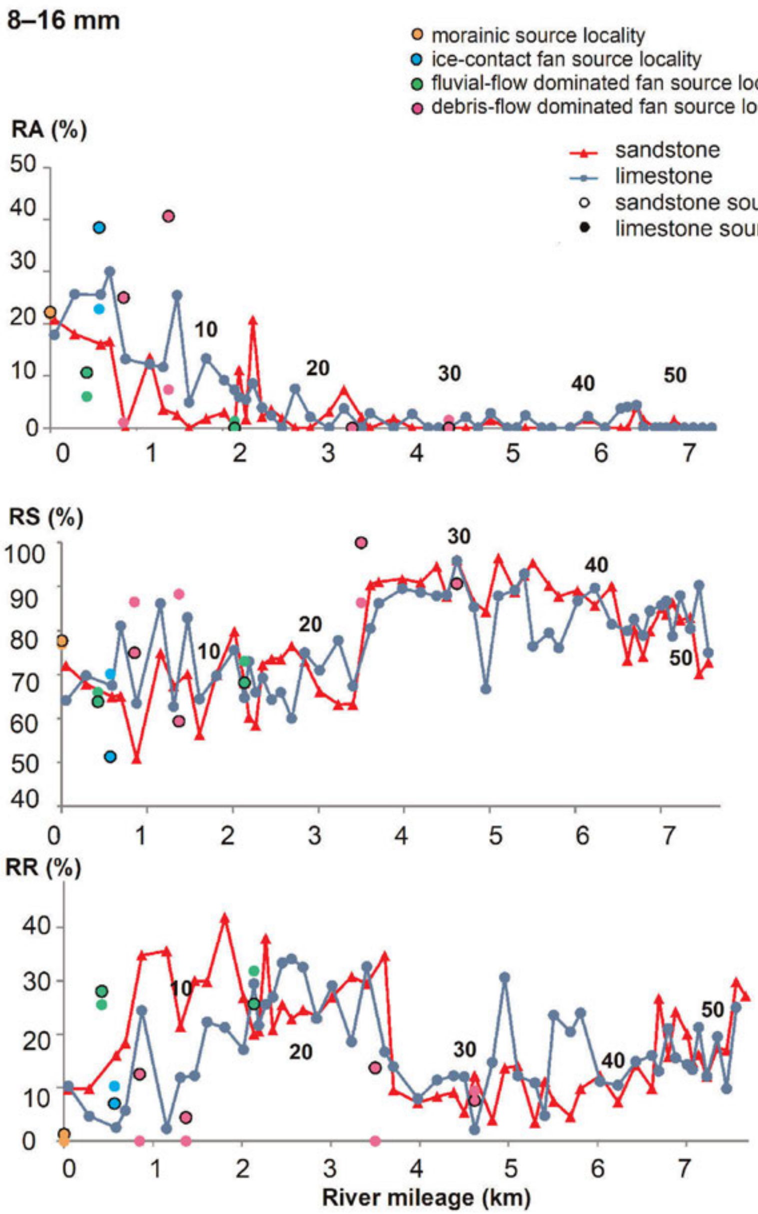

Fig. 6. The covariant plot of the transport distance and degree of roundness (RA, RS and RR shares) comparing sediment sampling localities from material sources and the Munin River channel belt for the fraction 8–16 mm and both petrological types.

(Figs 4 and 5). The pebble fraction is characterized by the presence of quartzite of up to 4%, which appears at the 1Z and 3Z sampling sites representing morainic and ice-contact fan source material. The amount of angular clasts is higher at 1Z and 3Z sampling sites, where the RA index reaches 21.7% and 22.8%,

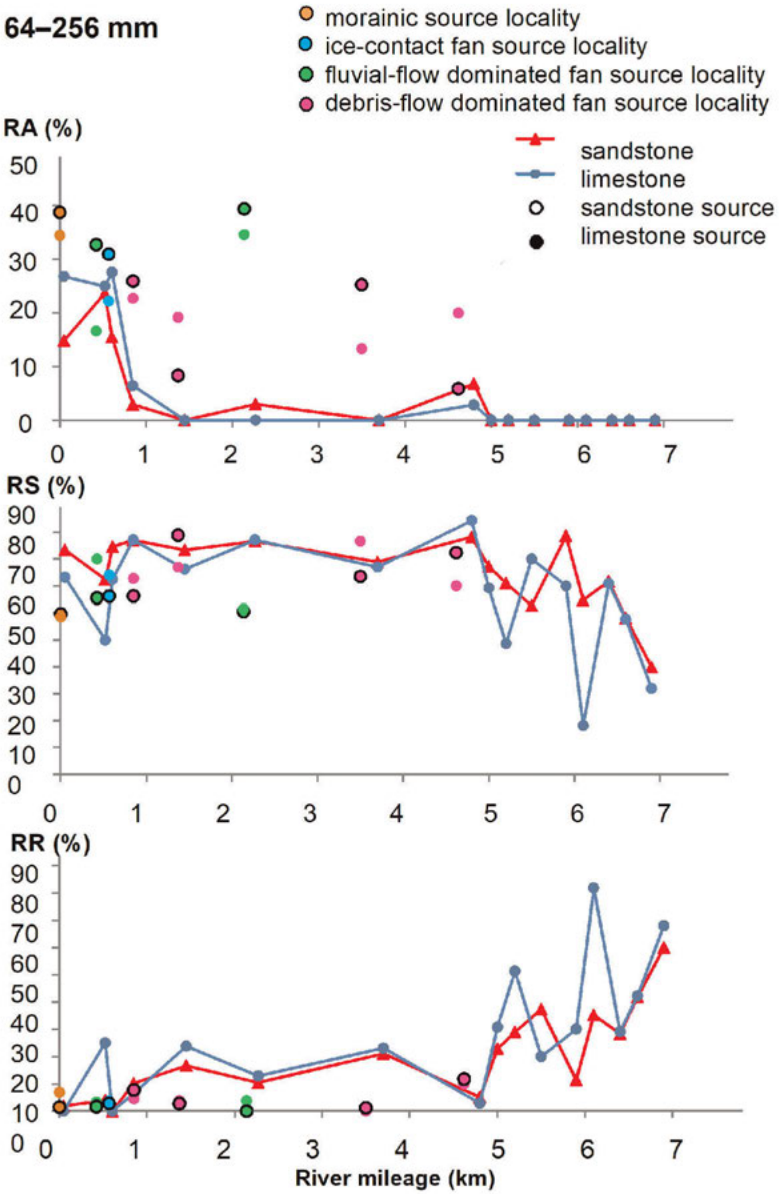

Fig. 7. The covariant plot of the transport distance and degree of roundness (RA, RS and RR shares) comparing sediment sampling localities from material sources and the Munin River channel belt for the fraction 64–256 mm and both petrological types.

respectively. Angular clasts are higher at the 5Z sampling site, especially in limestone clasts. Sub-rounded clasts are dominant at the 4Z, 6Z, 7Z and 8Z, mostly in sandstone clasts (Fig. 4). Fluvial-flow dominated fan material sources (2Z and 6Z) bear the highest shares of rounded clasts in the pebble fraction

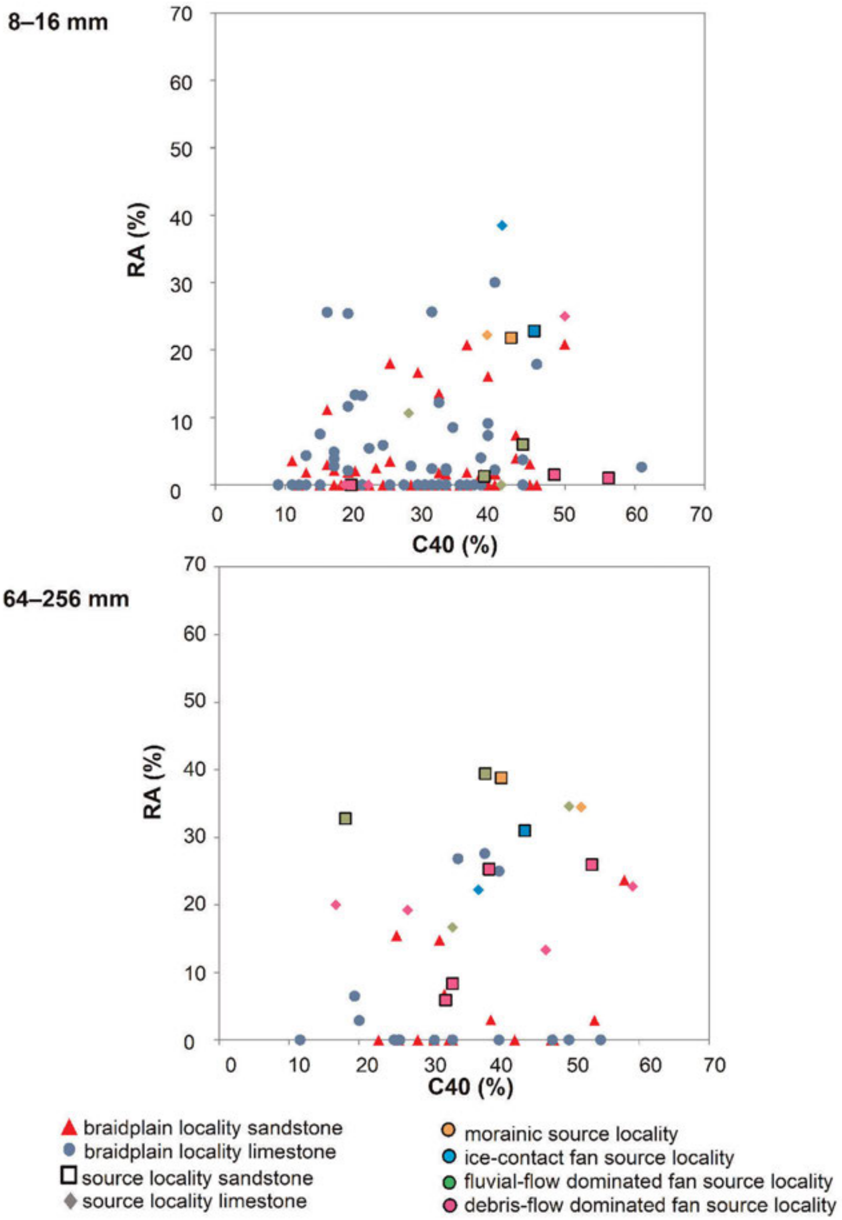

Fig. 8. The covariant plots for C40 ratio and RA share for both studied fractions 8–16 mm and 64–256 mm.

(Fig. 4). The cobble fraction is different in accessory petrological type. Shale clasts occur and the highest amount of 9% at the 2Z sediment source locality, which is a left-side fluvial-dominated fan. Furthermore, sites Z1–Z3 and Z6 have high shares of angular clasts. The Z6 sampling site has 38% of angular clasts, similar to the morainic source Z1. Generally, the total amount of angular clasts is higher in the cobble fraction compared to the pebble fraction. But shares of rounded clasts are generally rather low. Clasts are influenced by their fluvial transport, however the effect of sediment sources can be recognized. The trend of RS clasts in cobbles is very variable, while in pebbles it decreases towards the end of the entire river. The triplots of source localities are presented in Figs 4 and 5.

Interpretation

The three main factors controlling the shape characteristics of material in the Munin River could be defined according to the Munin Valley land system features. These are: (i) bedrock morphology, *i.e.* surface topography of pre-Holocene geological units in individual parts of the catchment, (ii) water availability of material sources, including seasonal or temporary ablation of snow patches and glaciers' ablation and (iii) axial transport, *i.e.* downstream traction of material in the Munin channel belt. The Munin River could be split in the proximo-distal direction in four segments according to the comparison of the material clast roundness in its channel belt and different effect of the main above-mentioned controlling factors (Fig. 3). The importance of these controlling factors is highlighted for individual segments.

Segment 1; from the Munin Glaciers' morainic complex to 2.5 km of the river mileage. — This segment represents the narrowest uppermost part of the Munin Valley, which is surrounded by steep slopes with summits above 800 m a. s.l. with glaciers and perennial snow patches. Segment 1 is characterized by the most varied source variability, including morainic, glaciofluvial ice-contact fan, fluvial-flow and debris-flow dominated fan sources. Both the area and volume of the source clastic material clearly outweigh the area and volume of the material in the Munin River channel belt. Channelized water flow dominates within the material sources. The sources are highly energetic with dominant coarse-grained material traction and they thus locally provide high shares of RS and RR clasts. It is possible that some moraines may be locally rich in rounded cobbles due to the effect of subglacially, or englacially transported material like rounded and well-rounded egg gravel (Bennett *et al.* 1997; Huddart *et al.* 1998, 1999). Some intramarginal outwash plain may also occur there. However, the moraines of local glaciers (Hanáček *et al.* 2011; Ewertowski *et al.* 2012, 2019) are generally rich in angular clasts. The sedimentary nature of the sources is affected by the bedrock morphology of these lateral catchment parts, because both fan types have a very high gradient due to steep mountain slopes (2Z = 26.3°; 4Z = 25.7°; 5Z = 25.0°; 6Z = 20.4°). The intensity of the clast modification increases by traction in the fans. Therefore even debris-flow dominated fans hold high shares of RS and RR clasts. The shape variability of the source material explains the variable shares of roundness classes in this segment, which is flat (3.1°) compared to lateral fans. The material in Segment 1 inherits the shape properties of the source sediments, because the axial transport is incompetent to modify them. Clast roundness in the channel belt of Segment 1 is therefore highly variable from place to place and dependent on the adjacent input source.

Segment 2; between 2.5 and 5.0 km of river mileage. — The effect of axial river transport on clast roundness increases in this segment by the progressivity of the RS share and rapid decline in the RA share. This trend has been described from proglacial streams in numerous studies (Gustavson 1974; Huddart 1994; Bennett *et al.* 1999; Hambrey and Ehrmann 2004; Hambrey and Glasser 2012; Hanáček *et al.* 2013). The dominance of axial transport is allowed by a stable channel belt with unchanging and flat (2.6°) morphology of the river floor. The valley is widest, relatively open and clearly asymmetrical in this segment. The valley asymmetry causes the material sources to prograde to Segment 2 only from the east. These are represented by low-energetic debris-flow dominated fans originating from intermittent snow patches, which melt down only during the peak summer period. Snow patches are located on a mountain ridge with summits up to 800 m a.s.l. Slope gradients in Segment 2 (24.9° for 7Z and 22.9° for 8Z) are mostly smaller than for the lateral fans in Segment 1.

Segment 3; between 5.0 and 6.5 km of river mileage. — The channel belt in this segment is tight in a gorge deeply eroded into the solid Old Red rocks with slightly higher dip. No lateral sources prograde into the channel belt for morphological reasons. The steep gorge walls limit the lateral extension of the channel belt, thereby enhancing axial transport and facilitating clast rounding. In Segment 3, the downstream trend of roundness is amplified by a massive and sudden increase in the share of RR cobbles accompanied by an equally noticeable drop in the share of RS cobbles, and almost a disappearance of RA clasts in both cobbles and pebbles. The disappearance of RA clasts demonstrates minimal delivery of the mechanically weathered debris from the gorge walls into the river. Angular debris accumulates just along the gorge walls and does not extend into the channel belt.

Segment 4; between 6.5 and 7.0 km of river mileage and further down to the confluence with Mimer River. — This segment represents a braided outwash fan, which is characterized by a flat (1.2°) and wide fan-shaped branching of river channels just after the Munin River enters from the gorge into the Mimer Valley, based on the 1961 aerial image and TopoSvalbard. No lateral material sources prograde onto the fan. The loss of transport energy by the sudden change from a channel belt into the braided outwash fan and the lack of lateral material sources cause Segment 4 to inherit the trend of material roundness from Segment 3. The effect of axial transport exists due to the actual material traction on the fan surface, but this is so weak that it does not appear in the downstream trend (Figs 6 and 7).

Comparison between segments. — The factors as bedrock morphology, axial transport and water availability of material sources are reflected in a different roundness of the two studied fractions. The effect of the presented factors are apparent when comparing the two fractions in the fluvial sediments of Segments 1 and 2 and in material sources, *i.e.*, a high variability of shares in Segment 1 *vs*, constant shares in Segment 2. However, the following trends could be found in Segment 2: (i) RA cobbles almost disappear in the river while attaining shares of up to 30% in the sources; (ii) an abundant share of RR cobbles (up to ~ 30%) is present in the river, while they are almost absent in the sources; (iii) the share of RR pebbles generally decreases downstream while the share of RR cobbles fluctuates irregularly; and (iv) the share of RS pebbles grows steadily, whereas the share of RS cobbles fluctuates irregularly.

The primary factor explaining these trends is the bedrock morphology, i.e. material sources prograde into the channel belt only from one side in Segment 2. A smaller gradient of fans slows down the transport power of debris flows (Tomczyk and Ewertowski 2017). The secondary factor is the effect of the water availability of material sources, *i.e.* sources are subsidized by water from temporary snow patches, so debris flows are active only for a part of the ablation season. However, the sources deliver a number of pebbles into the river of Segment 2. This is the reason why the share of RS pebbles increases and the share of RR pebbles decreases in Segment 2. If the pebble roundness were caused only by the axial transport, the share of RR pebbles would grow as well. Thus, the supply of RS pebbles by lateral sources partially wipes out the progressive downstream increase in roundness.

Sediment transport. — The axial transport is dominant in the case of cobbles. The fluvial transport is more effective than debris-flows for the transport of cobbles. It is indicated by the relatively high share of RR cobbles in the river and small share of RR cobbles in material sources in Segment 2. The progressive downstream rounding of cobbles in Segment 2 increases, *i.e.* the RA cobbles move to the RS category and part of the subrounded cobbles moves to the RR category due to the progressive downstream rounding. The stronger effect of axial transport in cobbles is caused by the nature of the sources. Energetically weaker sources seem to transport pebbles more easily than cobbles. Therefore, most cobbles were transported to Segment 2 by downstream traction from Segment 1 and less by lateral sources directly within Segment 2.

Main factors controlling the clast shape characteristics. — It seems clear that the bedrock morphology has a fundamental effect on the shape development of transported material in the Munin River. Other factors have hierarchically lesser effect, because they are predisposed by the morphology of the bedrock and its individual parts. The second most important effect is the water availability in material sources, which is caused by snow and ice melting or by flood events in Munin Valley. Although, the area is believed to be dry, heavy rain events are appearing more and more frequently. The higher temperature periods strongly influencing discharge during early snowmelt and foehn phenomena (Rachlewicz 2007, 2009) occur more often. The position of glaciers and perennial and temporary snow patches is predisposed by altitude, hence the morphology of a given part of the catchment. Melting factor is therefore subordinated to the morphological factor. The rather non-dynamic bedrock morphology of the Munin River floor gives rise to conditions typical for proglacial braided streams as can be seen in Segment 2. In contrast, the dynamic bedrock morphology of the gorge in Segment 3 reinforces the axial transport, which is then almost eliminated in the entry into the flat Mimer Valley floor in Segment 4. The morphologically-climatically driven weak activity of material sources in Segment 2 allows the dominance of axial transport of cobbles in the channel belt. Thus, the effect of fluvial traction changes passively in connection with the effect of bedrock morphology and the activity of material sources.

Comparison of the Munin River system with other fluvial systems in the area. — The Munin River is the mountainous glaciofluvial system, in which a slight degree of shape modification of clastic material is generally assumed (Bennett *et al.* 1997). For a modern braided river, Gustavson (1974) described an increase of clasts' roundness in the downstream direction. Hambrey and Ehrmann (2004) and Hambrey and Glasser (2012) also noted the dominance of grain roundness of modern proglacial streams. Thus, the existing literature has generalised the properties of transported material of the mountainous proglacial braided river environment to the trend of the gradual roundness increase or its overall dominance.

The Munin River is the second longest proglacial stream in the northern Billefjorden area, with the widest braided outwash fan (>1000 m) at its confluence with the main Mimer River (Hasenöhrlová 2018). It could be expected based on the length of the Munin River that a clear downstream trend of roundness increase is to be present here. Detailed analysis from the Munin River shows that the behaviour of proglacial braided rivers is much more complicated. The proximal section may contain completely chaotic nature of material shapes with a high proportion of well-rounded clasts at places despite its ice proximal position. A sudden increase in the proportion of well-rounded material could be found in the section where the river flows through the bedrock gorge. The effect of axial transport increases in the gorge because of its concentration to only one main channel, which leads to a rapid increase of the roundness degree. The prominent increase of well-rounded material in the gorge is not related with the outcrops of Devonian conglomerates with rounded sandstone clasts just above the gorge, as the trend toward well-rounded clasts is also found among limestone clasts. The roundness does not change much in the subsequent section of the outwash fan. The considerable width of the fan and the high sinuosity of channels (Hasenöhrlová 2018) enable lateral dispersion of water and its transport energy. Therefore, the outwash fan does not change or only an increase the roundness of the clasts originating from the upstream-located gorge is observed.

Only a minor effect of downstream traction on the clast roundness was also found on the proglacial fans of Bertilbreen and Hørbyebreen, where the input of lateral inflows was proved to be more effective (Hanáček *et al.* 2013). Thus, the downstream trend of the clast roundness of mountainous proglacial rivers is fundamentally influenced by sudden changes in channel belt width and by the sinuosity of the channels. These changes are controlled by bedrock morphology. The proximal section of the stream is affected by the variability of material sources like moraines, and different types of lateral alluvial fans.

The Munin River sediment sources can be compared with those presented in Tomczyk and Ewertowski (2017) from the nearby Petunia Bay region, where the sediment delivery depends on the fan's shape, its area, slope and flow activity. The upper parts of slopes are the steepest and the transport activity is reduced further downstream both for the fans in the Munin Valley as well as from those in Petunia Bay described by Tomczyk and Ewertowski (2017). On the contrary, their lowest parts are the flattest, so the delivery of material into the main axial valley is not so active (Tomczyk and Ewertowski 2017). These factors mainly affect segments 1 and 2 in the Munin River.

Clasts' shape trends were also investigated in sediments of the Pleistocene continental glaciation. The downstream trend of roundness increase, *i.e.* progressivity of the subrounded degree, was described from proglacial glaciofluvial sediments (Nývlt and Hoare 2011) and subaqueous debris flows (Elwirski and Woźniak 2019). In the terminoglacial braided outwash fan, the clasts were very slightly rounded, which was caused by a very short material transport (Hanáček 2011). The downstream evolution of clast roundness in the Munin River shows that especially for fossil glaciofluvial sediments, in which only relics of the original accumulations without preserved landsystem relationships are known, the original position of these sediments cannot be interpreted basing on the material roundness exclusively. Detailed research on selected mountainous glaciofluvial and fluvial river systems with rather diverse catchment topography could bring important information about the links of the clastic material character and the topography of source areas.

Conclusions

The roundness of gravel clasts in the Munin River is controlled principally by the shape of the channel belt. The roundness degree increases in river segments with a small channel belt width and with low sinuosity of channels. On the other hand, the roundness does not change in segments with a large channel belt width and high sinuosity of channels. The transport energy of flowing water increases in segments with narrow channel belt and straight channels. Conversely, the transport energy of flowing water decreases on a wide channel belt with branching channels. The shape of the channel belt is predetermined by the morphology of the catchment's bedrock. Therefore, the morphology of the bedrock is the primary factor affecting the development of the roundness of the clastic material in the downstream direction. This case study from the Munin River has shown that the roundness in proglacial fluvial system does not increase gradually in the downstream direction, but that it changes abruptly depending on the changes of the channel belt predisposed by the bedrock.

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Paper 2

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DOWNSTREAM VARIABILITY OF CHANNEL MORPHOLOGY AND BED MATERIAL IN THE BRAIDED KELLER RIVER, JAMES ROSS ISLAND, ANTARCTICA

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ABSTRACT

Changes in sediment supply and water availability in rivers are associated with ongoing climate change and glacier melting. The processes connected with increasing temperatures largely determine braidplain activity within glacier forefields. This work focuses on downstream changes in channel morphology (i.e. channel width and braiding intensity) and bed material (i.e. petrological types and clast roundness), as well as possible controlling factors (i.e. sediment sources and sediment connectivity). The study area is the Keller River catchment located on the James Ross Island (JRI), Antarctica. This paper describes the 8.6 km-long Keller River in terms of morphology, including river braidplains, sediment sources and connectivity within the catchment. Eight sediment sources and three types were identified: one moraine sediment source, four debris-flow-dominated sediment sources and three fluvial-flow-dominated sediment sources. Along with high sediment connectivity, the occurrence of lateral sediment sources from tributaries significantly impacted downstream changes in channel morphology and processes. Channel width and braiding intensity showed an increasing downstream trend, although the channel width trend was irregular. As for bed material, sediment sources markedly control clast roundness with little effect of petrological properties.

KEYWORDS

proglacial stream, channel width, clast roundness, sediment sources, sediment connectivity, Antarctica

INTRODUCTION

It is well known that river morphology and processes are closely connected to catchment characteristics (e.g. lithology, tectonics and vegetation cover) and processes (e.g. slope instability and sediment connectivity) (Fryirs & *alii*, 2007; Cavalli & *alii*, 2013). Increasing our understanding of such relationships requires investigating appropriate fluvial systems, chiefly those where human impact is low or absent. Proglacial rivers are often ideal for such investigations (Carrivick & *alii*, 2013). The transport of bed material in proglacial rivers has been analysed in several studies (Ashworth & Ferguson, 1986; Ferguson & *alii,* 1992; Wathen & *alii*, 1995; Knighton, 1998; Beylich & *alii,* 2017; Carrivick & Heckmann, 2017; Kammerlander & *alii*, 2017; Ondráčková & *alii*, 2018; Ondráčková & *alii*, 2020), but few studies have compared channel and catchment processes (e.g. Ashmore & Day, 1988; Rachlewicz, 2007; Bartsch & *alii*, 2009; Carrivick & *alii*, 2013; Kidová & *alii*, 2016).

Sediment transport in various localities and previously glacierised areas has been described by many researchers (Hambrey, 1994; Maizels, 1997; Hodson & *alii*, 1998; Bhutyiani, 2000; Bogen & Bønsnes, 2003; Marren, 2005; Rachlewicz, 2007; Slaymaker, 2011; Marren & Toomath, 2014; Carrivick & Heckmann, 2017; Park & Hunt, 2017; Weckwerth & *alii*, 2019; Mancini & Lane, 2020), but few such studies pertain to Antarctica (Carrivick & *alii*, 2012; Davies & *alii*, 2013; Kavan & *alii*, 2017; Kavan & Nývlt, 2018; Ondráčková & *alii*, 2018; Sroková, 2019). Antarctica is a special and vulnerable region that deserves our attention. It is almost entirely without vegetation cover and save for some terrestrial algae, cyanobacteria, lichens and mosses, which stabilise catchment surfaces little and affect only areas with sufficient nutrients (Navas & *alii,* 2008, Barták & *alii*, 2015; Marečková & Barták, 2016; Nývlt & *alii*, 2016; Chattová, 2018; Ruiz-Fernández & *alii*, 2019; Hrbáček & *alii*, 2020) and therefore in some other Antarctic areas can have a quite important effect. The proglacial areas are affected by the harsh climatic conditions (van Lipzig & *alii*, 2004; Láska & *alii*, 2010; Láska & *alii*, 2011; Glasser & *alii*, 2012) with a combination of the influence of glaciers, snow cover and permafrost degradation (Smellie & *alii*, 2008; Baewert & Morche, 2014; Nývlt & *alii*, 2014; Oliva & Ruiz-Fernández, 2015; Hrbáček & *alii*, 2016).The morphological and sedimentary conditions of glacier outwash plains depend on several other factors: the geomorphic and tectonic history of the river catchment, ongoing climate change and base level variations (Lane & *alii*, 1997; Baewert & Morche, 2014; Knight & Harrison, 2014; Kociuba, 2017, Strzelecki & *alii*, 2018; Weckwerth, 2018).

Several works from many regions worldwide have pointed out the longitudinal trend of reduced bed material size, i.e. “downstream fining” (e.g. Ferguson & *alii*, 1996; Rice & Church, 1998; Surian, 2002; Gasparini & *alii*, 2004; Piégay & *alii*, 2006; Rice & Church, 2010; Weckwerth & *alii*, 2018; Sklar & *alii*, 2020). Three mechanisms contribute to downstream fining: abrasion, hydraulic sorting or transport and in-situ weathering (Knighton, 1998). Tributaries and other lateral sources, such as banks, can introduce sediment to the main stream causing discontinuities in the downstream fining process (Ferguson & *alii*, 1996). Tributary size, as well as the size of sediments carried by the tributary, are two factors that determine whether a tributary will change bed material characteristics (Knighton, 1998).

Sediment sources and connectivity are key aspects controlling downstream changes in bed material. Sediment connectivity refers to the relationship between components in a geomorphic system and plays a crucial role in sediment transport (Baartman & *alii*, 2013; Geilhausen & *alii*, 2013; Heckmann & *alii*, 2018). As particles are transported downslope and delivered to channels, the size of sediments produced on hillslopes evolves (Sklar & *alii*, 2020). Sediments produced in the uplands, where hillslopes and channels are closely connected, can influence downstream fining trends in a channel (Ferguson & *alii*, 1996; Sklar & *alii*, 2020).

In this paper, we present the findings of a study investigating the role of sediment sources in channel morphology and bed material characteristics in the Keller Catchment (James Ross Island [JRI], East Antarctic Peninsula). The Keller Catchment was selected for its position in a changing polar environment and its proximity to the Czech Antarctic station. There is no existing fluvial geomorphological study from this sector of Antarctica. The aims of this study are (a) to analyse the downstream changes of channel morphology and bed material in the Keller River and (b) to explore the controlling factors of such downstream changes in a braided river under natural conditions.

STUDY AREA

The Keller Catchment is located on the JRI (64°10'S; 57°45'W), the JRI's total surface area is 2.450 km^2 and is located in the north-western Weddell Sea behind the Antarctic Peninsula (Fig. 1), which acts as an orographic barrier. Its northernmost part, the Trinity Peninsula, is separated from the JRI by the 6–24 km-wide and 450–1.600 m-deep Prince Gustav Channel (Camerlenghi & *alii*, 2001).

The study area is approximately 15 km away from the Johann Gregor Mendel Czech Antarctic Station. The mean elevation of the Keller River catchment is roughly 370 m a.s.l., and its 31 km^2 catchment area is bounded by the periphery of the Davies Dome Glacier, Medina Peak (199 m), Sekyra Peak (553 m), Lookalike Peaks (706 m) and the lateral moraine of the Whisky Glacier (Nelson & *alii*, 1975; Czech

Geological Survey, 2009). The most important glaciers here are Davies Dome, Whisky Glacier and Unnamed Glacier in the upper part of the catchment (Engel & *alii*, 2012).

The mean annual air temperature in the vicinity of Johann Gregor Mendel station at 10 m a.s.l. was −6.9 °C from 2006–2014 (Hrbáček & *alii*, 2016), with January being the warmest month (+ 8.0 °C) and July and August (−30.0 °C) being the coldest months (Láska & *alii*, 2010; 2011). The region sees over 200 positive degree days and 100 freeze-thaw days (days in which there are both negative and positive temperatures with at least one value greater than ± 0.5 °C; cf. Michel & *alii,* 2014) per year, which vary highly year by year. Precipitation in this area mostly consists of snow (about 450 mm/year), mainly from March to November (van Lipzig & *alii*, 2004; Hrbáček & *alii*, 2016). Because of the area's topography, most snow cover is blown away during windstorms.

Landforms within braidplain are created by the extensive Cretaceous mudstone and sandstone rocks covered in layers of massive basalts and hyaloclastite breccia boulders (Kňažková & *alii*, 2020; Mlčoch & *alii*, 2020). The catchment can be separated into three parts based on geology. The upper part, which is made up of Neogene hyaloclastite breccias and basalts. The middle part, which is composed of Cretaceous sandstones and siltstones (Santa Marta Formation). The lower part and surrounding areas, which are covered by Holocene periglacially reworked subglacial till (Mlčoch & *alii*, 2020). Geological map of the Keller Catchment is presented in Fig. 2. The entire catchment is underlain by permafrost with seasonal thawing of the active layer usually 0.5–0.6 m thick (Hrbáček & *alii*, 2017).

This part of the JRI is one of the largest deglaciated areas in Antarctica with small remaining glaciers (Engel & *alii*, 2012). Regarding the deglaciation of this area, altitudes between 20–50 m have been ice-free since 12.9±1.2 ka (Nývlt & *alii*, 2014). According to Nývlt & *alii* (2014) and Glasser & *alii* (2014), most of the Keller Catchment has been ice-free since 6.7 ± 0.3 ka.

The length of the Keller River is 8.6 km. Its starting position was delimited from a Digital Elevation Model (DEM) and verified in the field, but it should be noted that during the ablation period of the glaciers and snowfield, this position can differ with each season. The stream ends at an inlet of Brandy Bay. The Keller River is a confluence of small streams in the uppermost parts of the catchment under Lookalike Peaks that stem from the melting Unnamed Glacier. The most important tributary is the Monolith River running out of Monolith Lake, which is filled by two unnamed streams and melting snowfields. The Keller River ends in Brandy Bay following its confluence with the Monolith River. Both rivers are characterised by braided patterns, the presence of channel bars and many confluences with side-channels. Other tributaries also act as important sediment sources (see Fig. 4).

MATERIAL AND METHODS

Preliminary analysis and field work design

Pre-selection of the studied catchment together with the sediment sampling sites was done before the Czech Antarctic Expedition in austral summer 2018 (January-March 2018). For preliminary analyses, an aerial Orthophoto Image (2006), REMA (The Reference Elevation Model of Antarctica) model (Howat & *alii*, 2019) and geological and topographical map from the Czech Geological Survey (2009) and Mlčoch & *alii*, 2020) were used (Fig. 1 and Fig. 2). This dataset was pre-analysed in Geographic Information System (GIS) environments, namely ArcGIS and QGIS. The slope raster, aspect raster and flow accumulation raster were derived from the DEM and then combined with the glacier locations and stream network to pre-select sediment source localities (Fig. 3 and Fig. 4). A plan for field work and sediment sampling was designed before the expedition.

During the austral summer research campaign, a detailed geomorphological mapping of the Keller Catchment was completed. However, the final selection of sediment sources occurred during field work. The sediment source type were debris-flow-dominated fans, fluvial-flow-dominated fans and moraine source (De Haas & *alii*, 2015; Tomczyk & Ewertowski, 2017). In total eight representative sediment sampling sites in each of the eight defined sediment sources were selected (Fig. 4). For sediment sampling in the active part of the channel, 31 sampling sites were chosen (Fig. 4).

Channel morphology

After geomorphological mapping, the active zone of the Keller River was analysed in ArcGIS and QGIS. The active zone surrounds the 7 km of the length of the river, because the first 1.6 km flows within a very narrow valley (Fig. 5). We then focused on segmentation to obtain a detailed assessment of channel morphology. Along the whole length of the Keller River, seven reaches were defined according to their differences in longitudinal slope profile, valley morphology, confinement and connection to sediment sources and important tributaries (see Fig. 5). After that, channel width was measured perpendicularly to the centreline of the active zone at every 25 m. Along with channel width, the braiding index was counted in the number of active flowing channels (Rinaldi & *alii*, 2011).

Bed material characteristics

Sediment sampling and measuring was carried out at selected areas of each sediment source locality (eight sites) and along the Keller River (31 sites). Sediments were sampled using a sieving method (Bunte & Abt, 2001) (fraction 8–16 mm) and processed in a laboratory to define their petrography, shape and roundness. Each sample from the sediment sources (8 localities) and from the active channel (31 localities) contained 100 clasts and was collected from channel bars. The field sample data were accompanied by their respective GPS positions, site descriptions and photo documentation of sites and their surroundings (see Fig. 4).

Laboratory and petrological analyses of clasts entailed (i) identifying petrology using a geological map of the northern part of the JRI (Mlčoch & *alii*, 2020), (ii) measuring the a, b and c axes (Wadell, 1932) and (iii) assessing roundness using the roundness scale by Powers (1953). For clast characteristics, the Triplot macro by Graham & Midgley (2000) was used.

Sediment sources and connectivity

To assess sediment supply, it was necessary to analyse sediment connectivity. To do this, a raster (Fig. 8) was used in Cavalli & *alii's* (2013) model. SedInConnect 2.3 software (Crema & Cavalli, 2018) is a freeware tool that implements Cavalli & *alii's* (2013) approach with further improvements. An index of connectivity evaluates the potential connection between hillslopes and features acting as targets or storage areas for transported sediment (Cavalli & *alii*, 2013). The method used in this software for the computation of the contributing area, a roughness index as the weighting factor for transport sediments. It has been implemented to adapt the model to sediment transfer processes within the catchment, which are characterized by contrasting morphology and affected by hillslope sediment transfer of different type and intensity of the source. The connectivity index focuses on the influence of topography on sediment connectivity, whereas other aspects such as vegetation cover and type, the effect of different active layer depths on various lithologies (Hrbáček & *alii*, 2017) are not taken into account (Cavalli & *alii*, 2013). This model clearly shows the index of connectivity in the whole Keller Catchment, especially in sediment source subcatchments. We used the DEM for delimiting the subcatchments. Selected subcatchments with each sediment source were defined previously (Fig. 4). The index of connectivity in the whole catchment, selected subcatchments and the whole Keller River is shown in Fig. 8. This analysis helps to verify the importance of slope processes as potential sediment sources and highlights their influence on channel morphology and processes.

RESULTS

River segmentation and channel morphology

Segmentation was carried out taking into account similar stream properties, active zones and valleys in the surroundings (Fig. 3). The Keller River was divided into seven reaches (R1 at the spring, R7 at the bay). Reach 1 is located in the source area starting at 369 m a.s.l., which consists of a single-thread channel in a confined V-shaped valley. The first reach, which is 1.550 m long with a longitudinal slope of 10.5%, yielded the debris-flow-dominated sediment at the beginning of the river. Reach 2 begins at the active zone of the Keller River. At this reach, there is a U-shaped valley and confluence with the right-side morainic sediment source. This reach is the longest (2.150 m) and its longitudinal slope is 4.1%. At the beginning of Reach 3, a left-side debris-flow-dominated sediment source lies, which is very close to the river channel. This reach is 775 m long with a longitudinal slope of 2.4%. Reach 4 contains another left-side debris-flow-dominated sediment source, which is also located at the beginning of the reach, and is characterized by a wide active zone with several channels. Its length is 1.075 m and its longitudinal slope is 2.2%. At the end of Reach 5, which is flat and consists of a wide active zone, there is a confluence with a left-side debris-flow-dominated sediment source. This reach is 825 m long with a longitudinal slope of 1.8%. Reach 6 is the shortest (750 m) with a longitudinal slope of 1.7%. At the beginning of Reach 6 is the Monolith fluvial-flow sediment source tributary on the right; on the left lies another large fluvial-flow tributary from the Davies Dome Glacier. Here is a wide active zone, several channels and well-developed channel bars. The last left-side fluvial-flow-dominated sediment source lies at the final reach, Reach 7. Its right slope is roughly 3–4 meters high and is 1.350 m long with a longitudinal slope of 1.6%. It has a wide active zone, several channels and bars and braided morphology. Reaches 1 and 2 are confined, Reaches 3 and 4 are partly confined and Reaches 5, 6 and 7 are unconfined.

Figure 5a shows channel width and corresponding longitudinal variability. The active zone starts after 1.550 m from the spring. At every 25 m following the start of the active zone, the channel width was measured with an orthophoto image and also verified using the DEM. The most important tributaries (sediment sources) are indicated using black arrows. For clarity, a scale of confinement and a line identifying reaches are also presented. The trend shows an increase in channel width moving downstream (the maximum width of 108 m is reached 7.8 km away from the spring), but also demonstrates significant variability. Figure 5b outlines the braiding index and longitudinal variability. The symbology for tributaries, confinement and reaches is the same as in the case of channel width.

The trend shows increased braiding intensity moving downstream. The maximum braiding index was 8 located at 7.8 km away from the start of the active zone, which corresponds to the maximum channel width in the relative flat area at the beginning of the last reach.

Downstream changes in bed material characteristics: lithological composition and roundness

The geological map of the Keller Catchment (Fig. 2) shows some differences in the lithological composition of the area. We should note that while the whole area was glacially reworked, the main petrological types among the clasts are Cretaceous sandstones, and Neogene basalts and palagonites (from the hyaloclastite breccias). The downstream change of each dominant petrological type is presented in Fig. 6. Among 31 sampling sites in the active channel, the most dominant types were sandstone (usually more than 50%) and basalt (approximately 30%), with the remainder being palagonites. Overall, sandstones and basalts showed a slight decreasing trend along the flow of the river, while palagonite rates increased.

Another important clast characteristic is roundness. Clast changes, along with the longitudinal profile of the Keller River, are presented in Fig. 7. The most important degrees of roundness are sub-angular (SA, denoted in green) and sub-rounded (SR, denoted in red), while the more extreme categories of angular (VA+A, denoted in black) and rounded (R+WR, denoted in grey) are complementary here to other categories. Generally, increasing downstream clast's roundness can be observed alongside their decreasing angularity. Moreover, there are two small histograms in this graph that describe two important sediment sources: moraine and fluvial-flow fan. The effects of these tributaries are clearly visible in the graph, especially the increased amount of angular material derived from moraine sediment sources. A significant portion of angular clasts (VA+A, 22%) and sub-angular clasts (SA, 65%) can be observed.

Sediment sources and connectivity

To explain the effects of sediment source subcatchments (Fig. 4), it is necessary to know the type, position and activity of each source.. Source 1 is at the upper part of the Keller River and is a debris-flow-dominated fan with an area of 1.9 km^2 and a highest slope greater than 87%. The moraine sediment source (Source 2) is right-side with a highest slope greater than 88% and an area of 1.2 km^2. Other left-side debris-flow-dominated fans are sources 3, 4 and 5, which are similar in area and activity. Sediment source 6 encompasses the Monolith fluvial-flow sediment source, which flows from the Monolith Lake and is a flat area with braided morphology. With an area of 8.5 km^2, debris-flow-dominated fan source 7 is the largest, which can be owed to the Davies Dome Glacier in the upper parts of this tributary. The eighth and last sediment source is fluvial-flow-dominated and close to the Brandy Bay with an area of 2.4 km^2. Clast analysis and geomorphological mapping was carried out at each sediment source.

For a better understanding of how such sediment sources affect channel morphology and processes and bed material characteristics, the index of connectivity was determined for the whole Keller Catchment (Fig. 8). Using Cavalli & *alii*'s (2013) index, this analysis is accompanied by some documentary photographs. Blue areas indicate places with a low index of connectivity (e.g. areas around the Monolith Lake and in the middle part of the active zone), while red colour highlights the areas with a high index of connectivity (e.g. first sedimentary source, moraine of the Whisky Glacier, upper parts of the tributaries and the left-side slope of the last tributary). This analysis allowed for the identification of different degrees of connectivity—that is, sources that are more connected (Source 1) and those that are almost disconnected (Source 6). The studied catchment area, which is devoid of human activity, is a good reference for fluvial systems characterised by high sediment connectivity and high sediment supply.

DISCUSSION

Downstream changes in the sediment characteristics

Small petrological differences were observed in sediments, but it is unclear if these were influenced by tributaries. Notwithstanding this, the catchment was influenced by glacier retreat, which reworked sediments and caused sandstone to be the dominant type, whereas basalt was decreased and palagonite was increased along the river from the spring to the mouth. The only notable change in sediment characteristic trend was observed in reach 5 at locality 10, where the confluence with left-side tributary from Monolith Lake is located. The Monolith Lake area is known for the presence of large hyaloclastite breccia boulders (Kňažková & *alii*, 2020), from which palagonites originated due to weathering.

Factors controlling downstream changes in channel morphology and clast roundness

From a channel morphology point of view, tributaries (sediment sources) impact the widening of channels, in contrast with the findings of Ondráčková & *alii* (2020). Significant disruptions can be explained by natural factors, such as sediment input into the main channel and changes in valley morphology (e.g. confinement, confluences and flat areas). Braiding indices are closely linked with channel width, and unconfined conditions make more space for braiding to develop. It is worth noting that under the conditions in this region (no vegetation cover and high sediment supply), braiding intensity increases remarkably, especially in the last reach after significant confluence with other important tributary sources 5, 6 and 7.

The association between discontinuities in roundness and tributaries has shown that some tributaries disrupt downstream roundness processes. The moraine sediment source (2) adds a significant portion of very angular, angular and sub-angular clasts into the main Keller River. It is a frontal to lateral moraine with traces of push processes. There is a 25% decrease in sub-rounded clasts, which is the most significant longitudinal trend change along the river. Afterward, the number of angular clasts transported by the stream decreases and is accompanied by a significant increase in clast roundness. This trend is amplified in the last two reaches (R6 and R7). The effects of axial river transport on clast roundness also increases in these two areas; this type of trend has been expressed in several proglacial streams (Gustavson, 1974; Huddart, 1994; Bennett & *alii*, 1997; Hambrey & Ehrmann, 2004; Hambrey & Glasser, 2012; Hanáček & *alii*, 2013). The dominance of axial transport is enabled by a stable channel belt. In a modern braided river, Gustavson (1974) described an increase in clast roundness in the downstream direction. Hambrey and Ehrmann (2004) and Hambrey and Glasser (2012) also noted the dominance of rounded grains in modern proglacial streams. In other words, the existing literature has noted that in general, transported material in mountainous proglacial braided rivers exhibit trends in gradual roundness increases or in dominance of rounded classes.

CONCLUSIONS

The results of this work enable a better understanding of channel morphology, bed sediment characteristics and factors controlling their variability along the Keller River on James Ross Island, Antarctic Peninsula. The focus shifts from the scale of the sediments transported in the Keller River to channel morphology, sediment sources and sediment connectivity.

The connectivity within the Keller Catchment plays a prevailing role in sediment transport from slopes to channels. The upper parts of the catchment are highly connected, and due to the instability of the material cover on the slopes, the debris-flow processes (or other gravitational processes) transport material into the channel. Fluvial-flow transport by tributaries was also found to be important in Keller Catchment. Both debris-flow processes and fluvial-flow transport are supported by melting of snow, active layer and glaciers.

Overall, the Keller Catchment is characterised by high sediment connectivity and high sediment supply, which clearly affect channel morphology and bed material characteristics. As for channel morphology, both channel width and braiding intensity show an increasing downstream trend, although its channel width is quite irregular. As for bed material, sediment sources have notable control of clast roundness with little effects on petrological characteristics.

This work presents the first fluvial geomorphological dataset from this region. The catchment area, which is devoid of human activity, is a good reference for studying braided river systems under natural conditions. Our study gives insights for understanding of channel morphology, bed material characteristics and factors controlling their variability at a local scale – or typical for proglacial rivers in polar regions. On the other hand, such insights about fluvial processes coupled to sediment connectivity can be used in another catchments in different climatic conditions.

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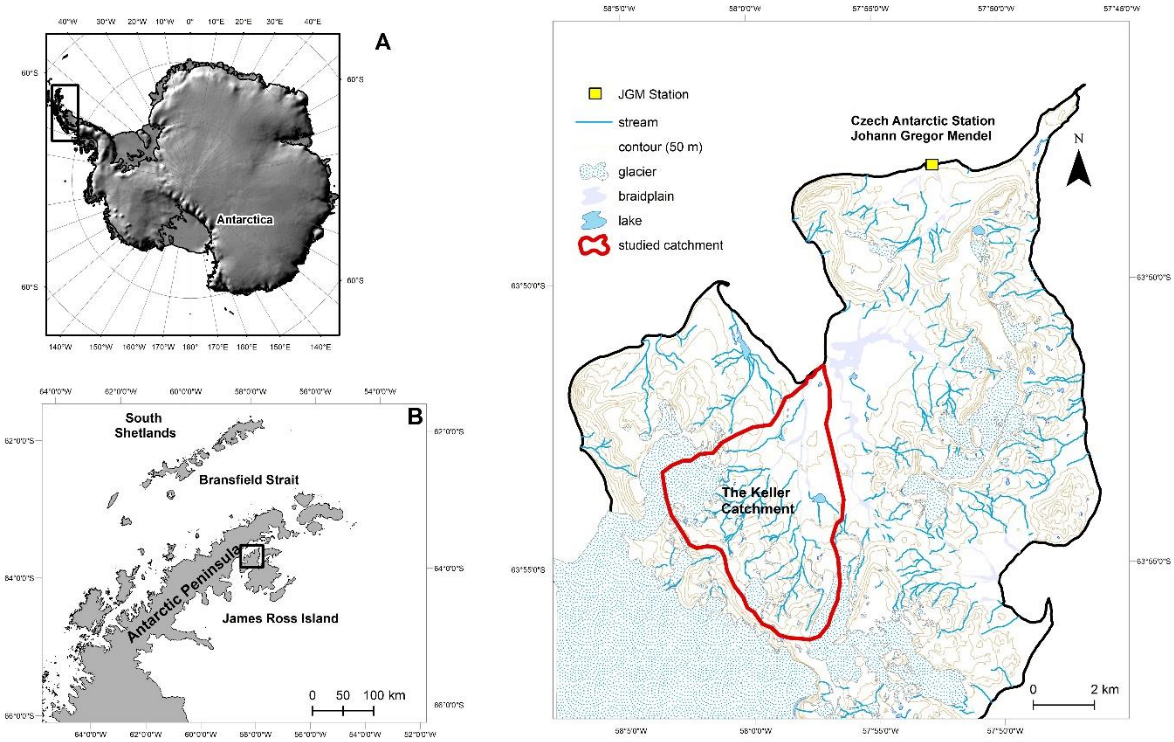


FIG. 1 Location of the Keller Catchment (A – Antarctic Peninsula; B – James Ross Island; C – Ulu Peninsula and the Keller Catchment)

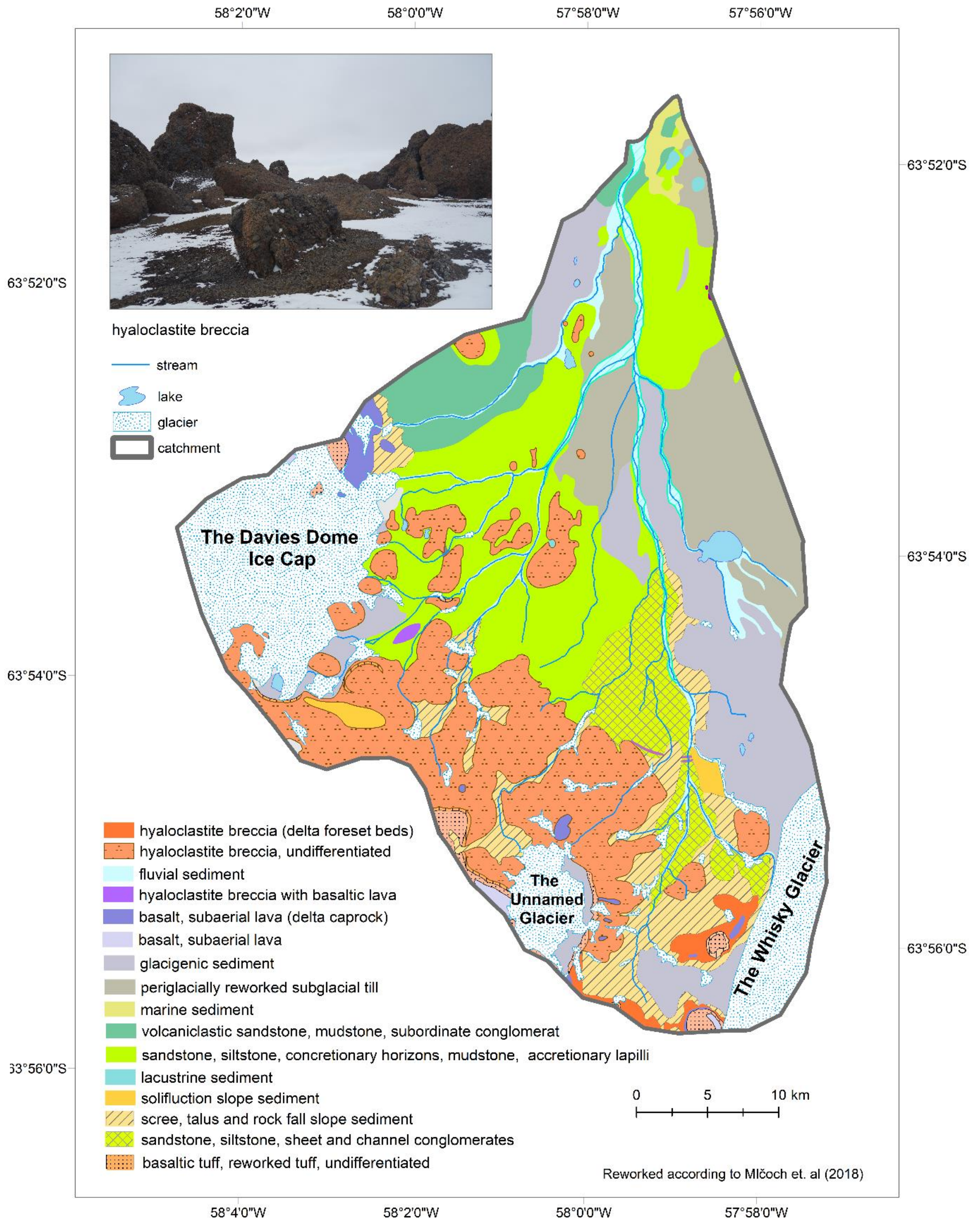


FIG. 2 Geological map of the Keller Catchment (based on Mlčoch *& alli*, 2018)

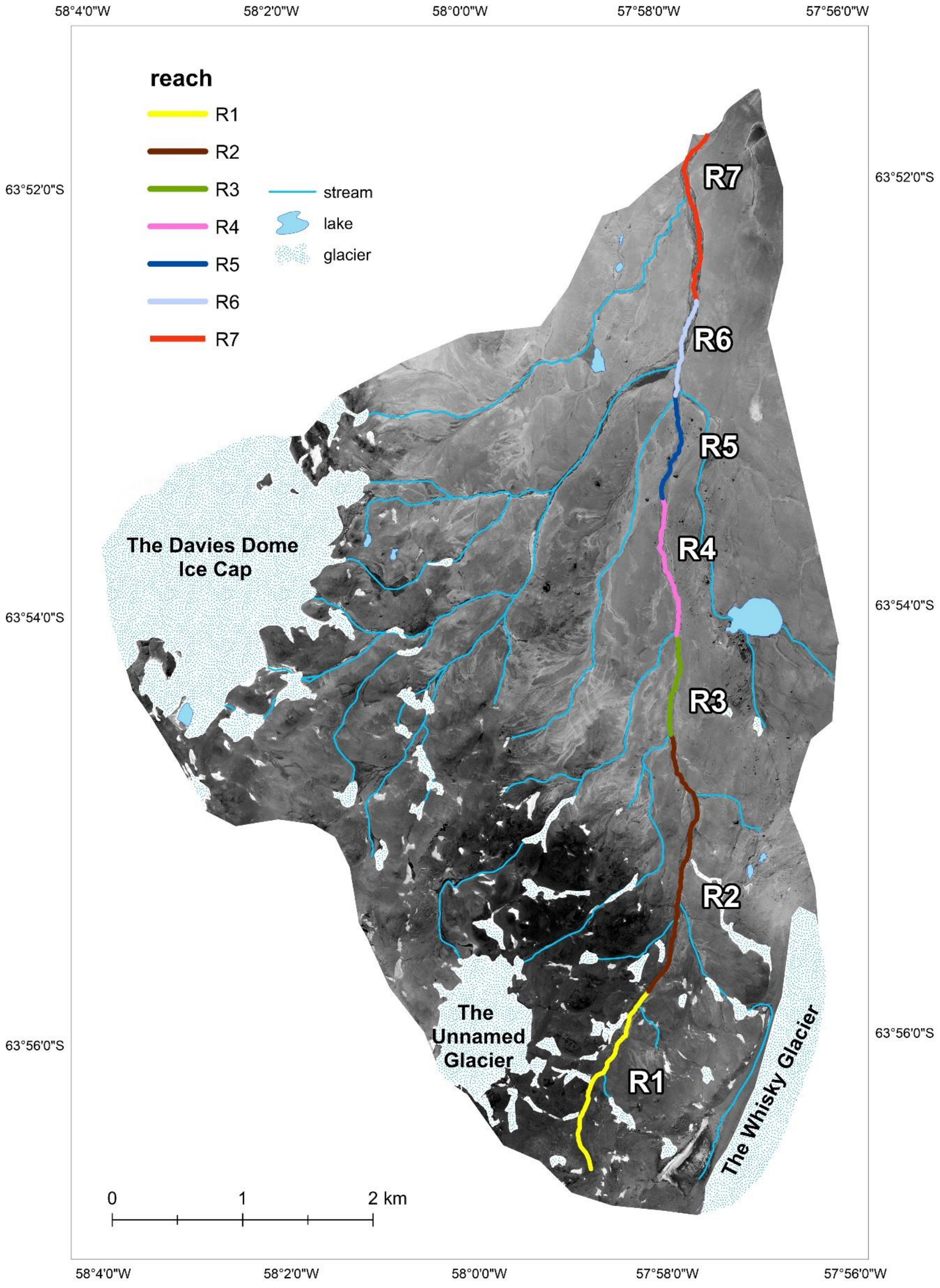
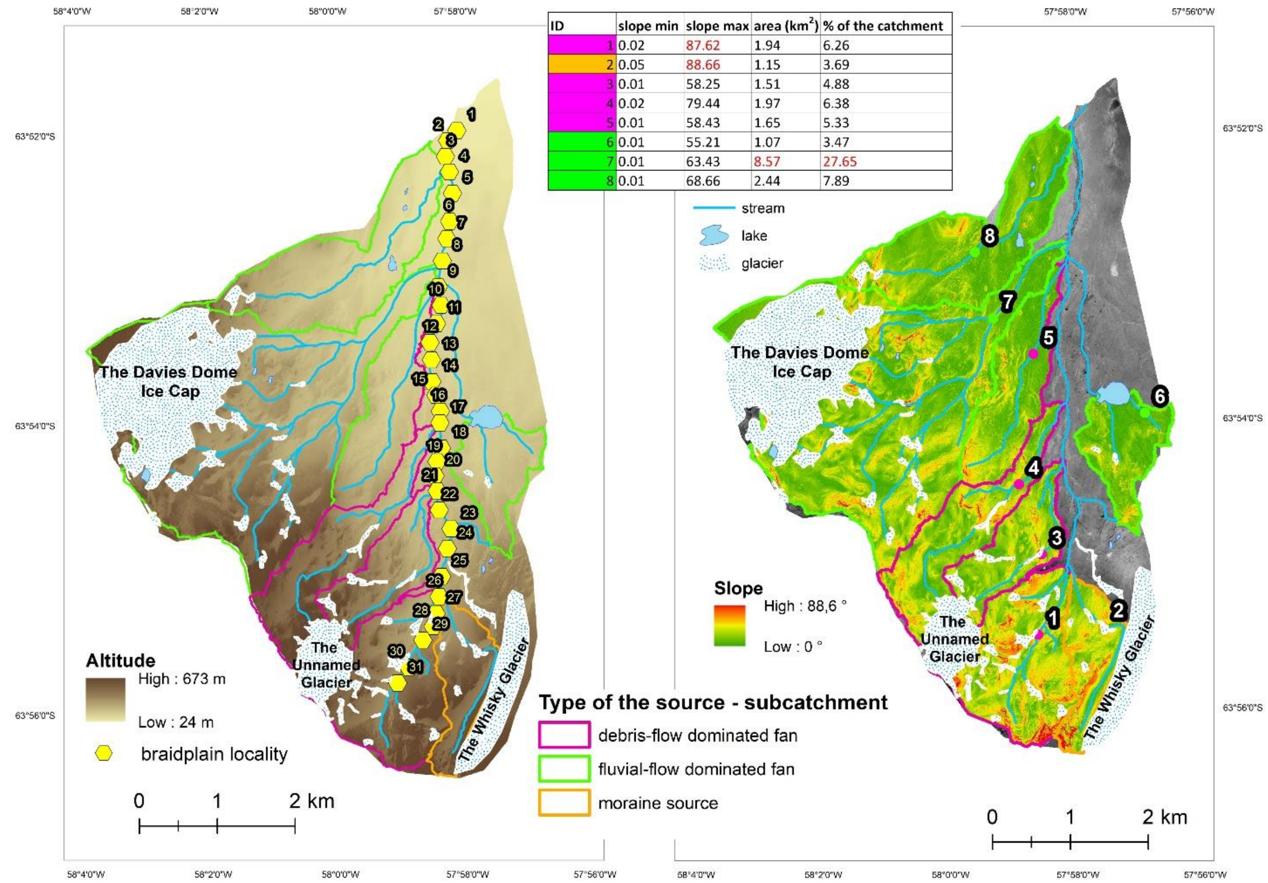


FIG. 3 The Keller River segmentation and identification of the seven reaches



ID	slope min	slope max	area (km^2)	% of the catchment
1	0.02	87.62	1.94	6.26
2	0.05	88.66	1.15	3.69
3	0.01	58.25	1.51	4.88
4	0.02	79.44	1.97	6.38
5	0.01	58.43	1.65	5.33
6	0.01	55.21	1.07	3.47
7	0.01	63.43	8.57	27.65
8	0.01	68.66	2.44	7.89

FIG. 4 Map of the sediment sampling localities within the braidplain of the Keller River (on the left side); the sediment sources within the Keller Catchment with the slope characteristics (on the right side)

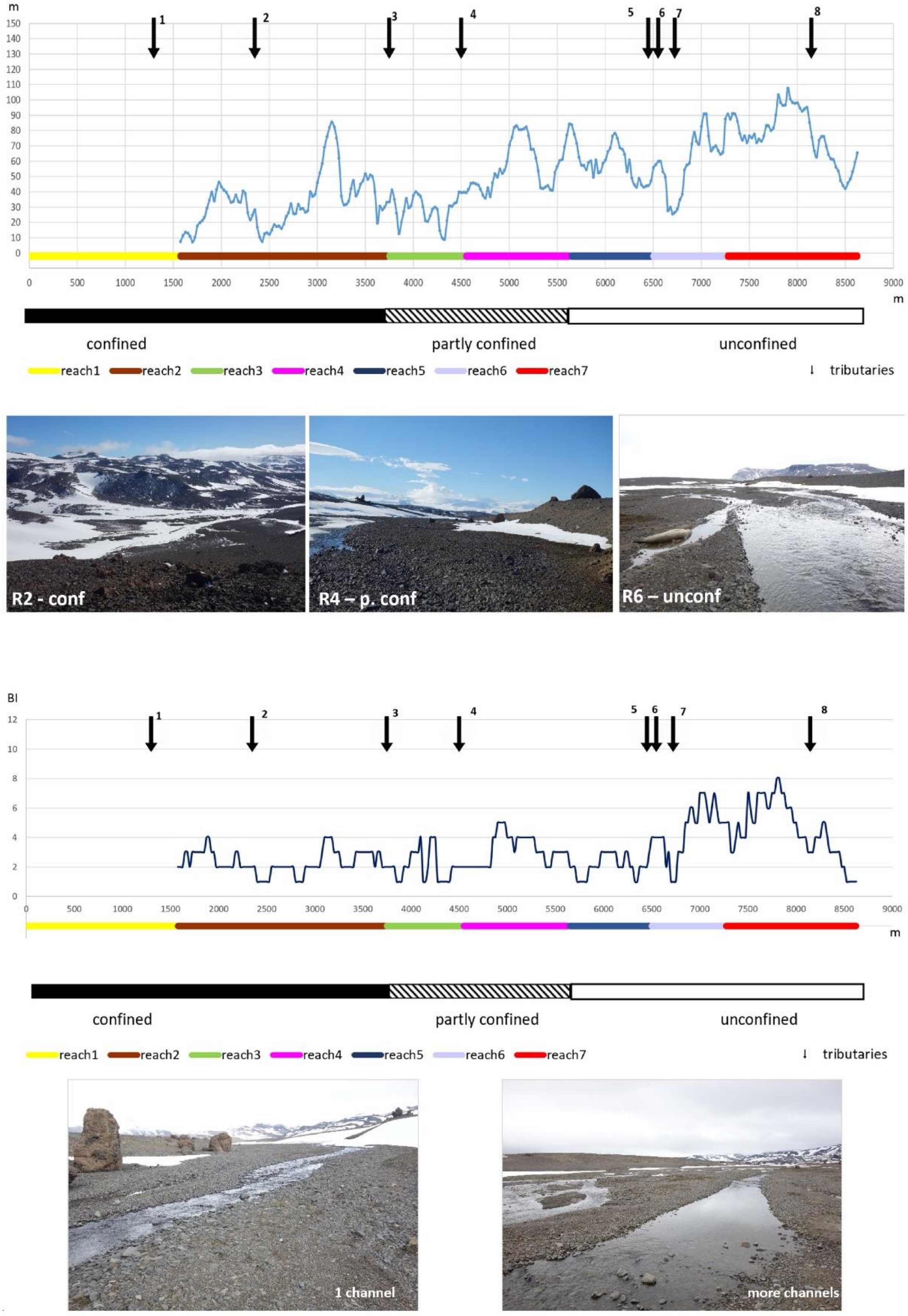


FIG. 5 Downstream change of channel width (a - above) and braiding index (b - below) in the Keller River

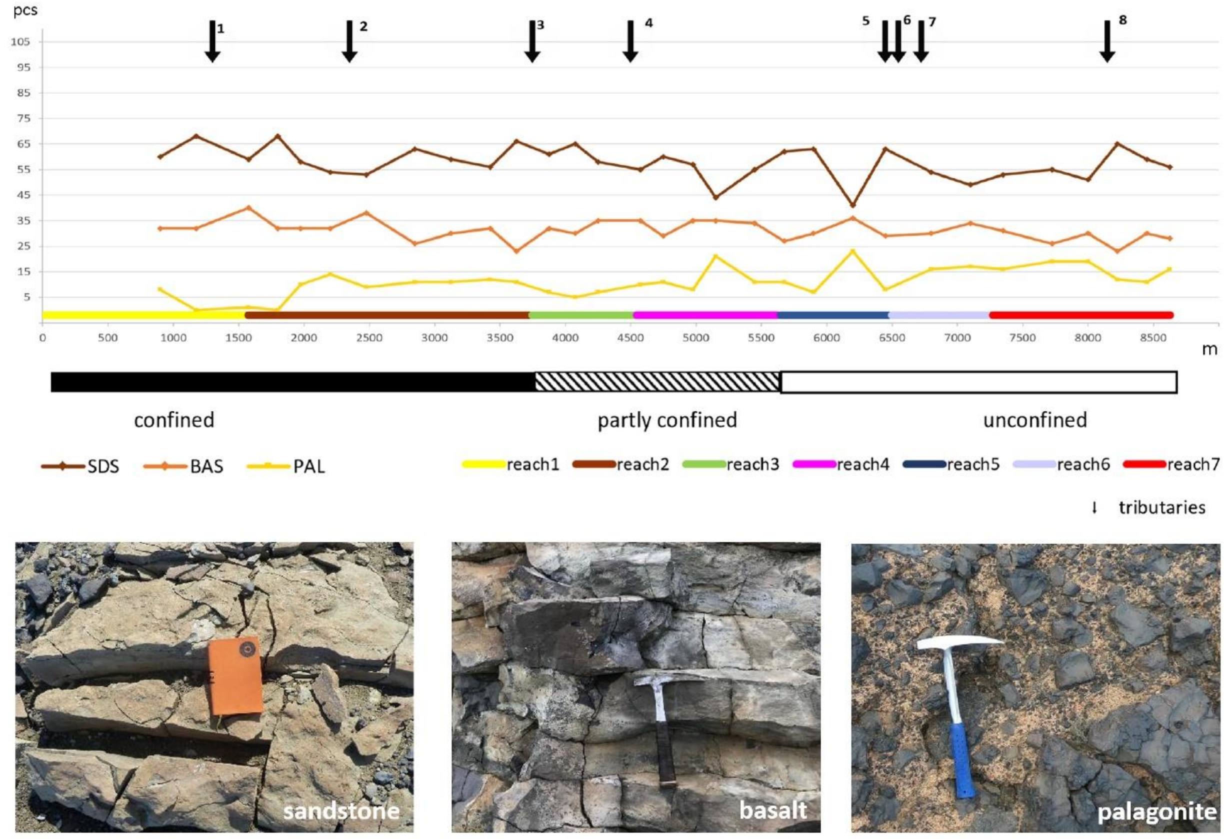


FIG. 6 Downstream change of the main petrological types of sediments in the Keller River braidplain

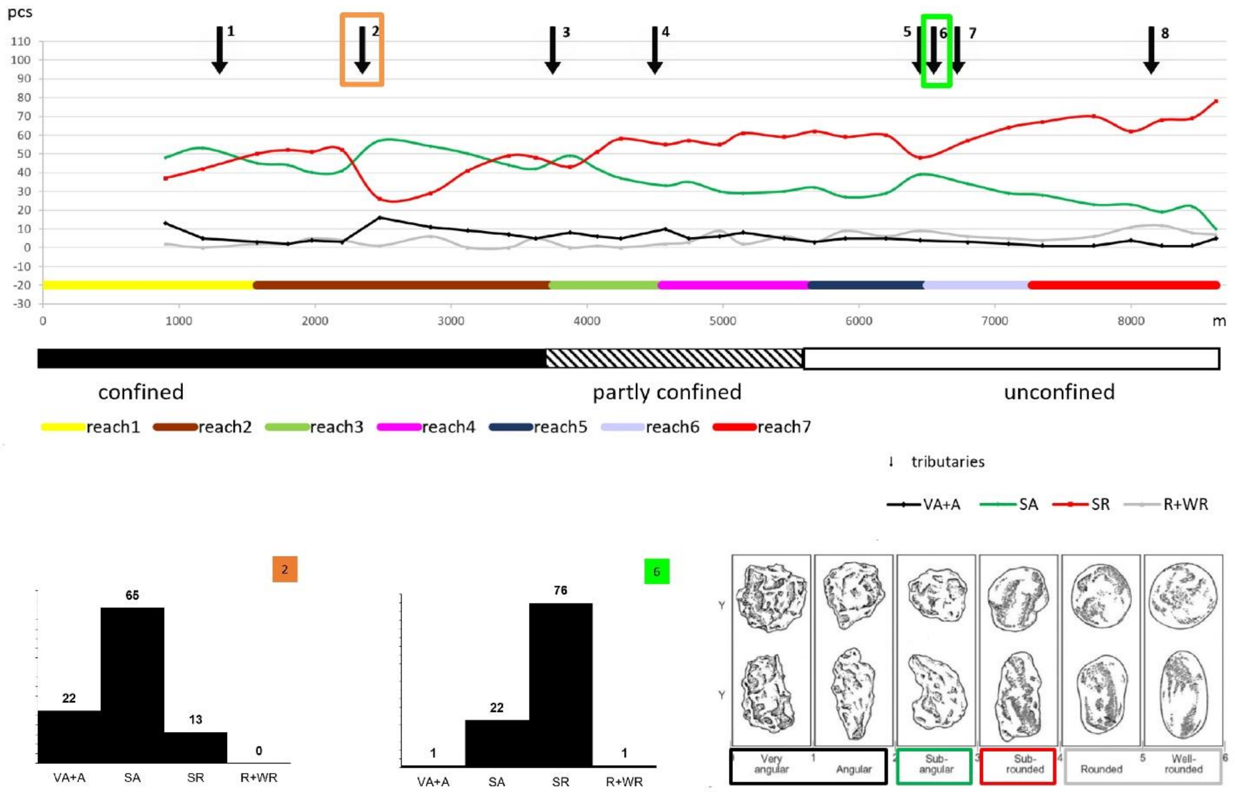


FIG. 7 Downstream change of sediment roundness in the Keller River braidplain

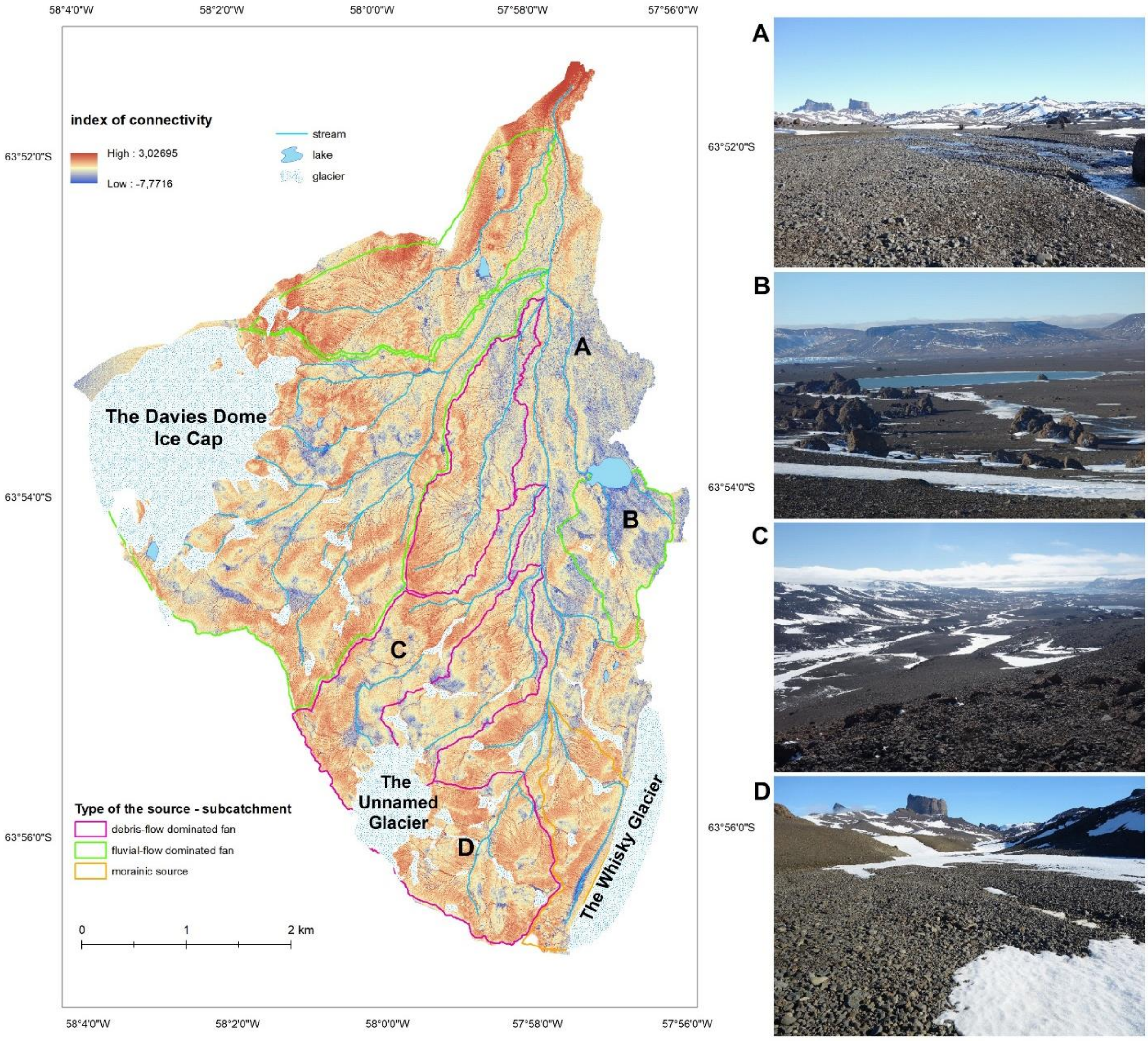


FIG. 8 The sediment connectivity map; the photographs (A to D) show areas with different degree of connectivity.

Paper 3

Ondráčková, L., (2020). Longitudinal development of clast shape characteristics from different material sources in Hørbye River, Central Svalbard. Czech Polar Reports, 10(2), 189–202.

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

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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

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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).

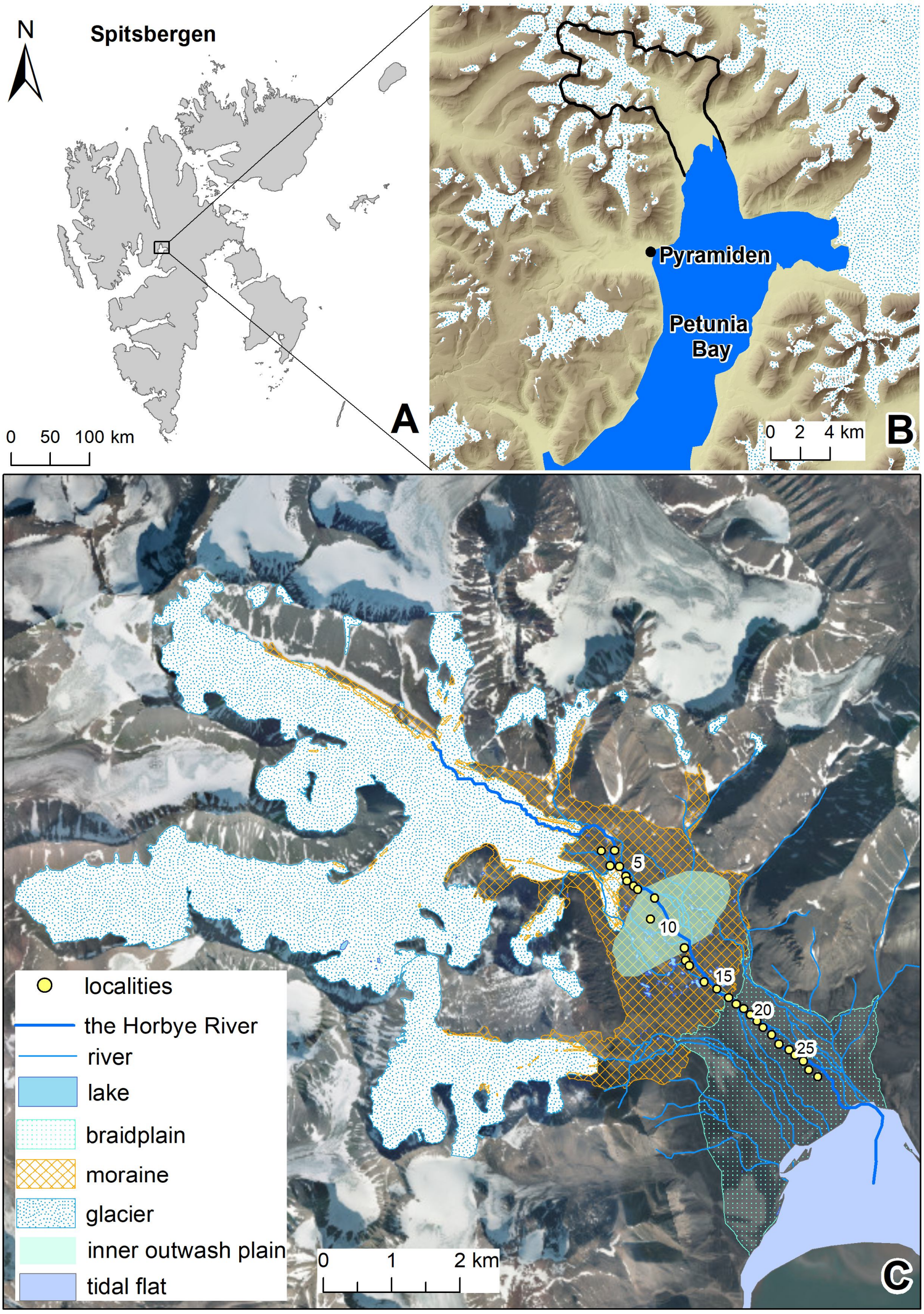

Fig. 1. Location of the study area: A – Spitsbergen, B – Billefjorden, C – The Hørbye River catchment.

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).

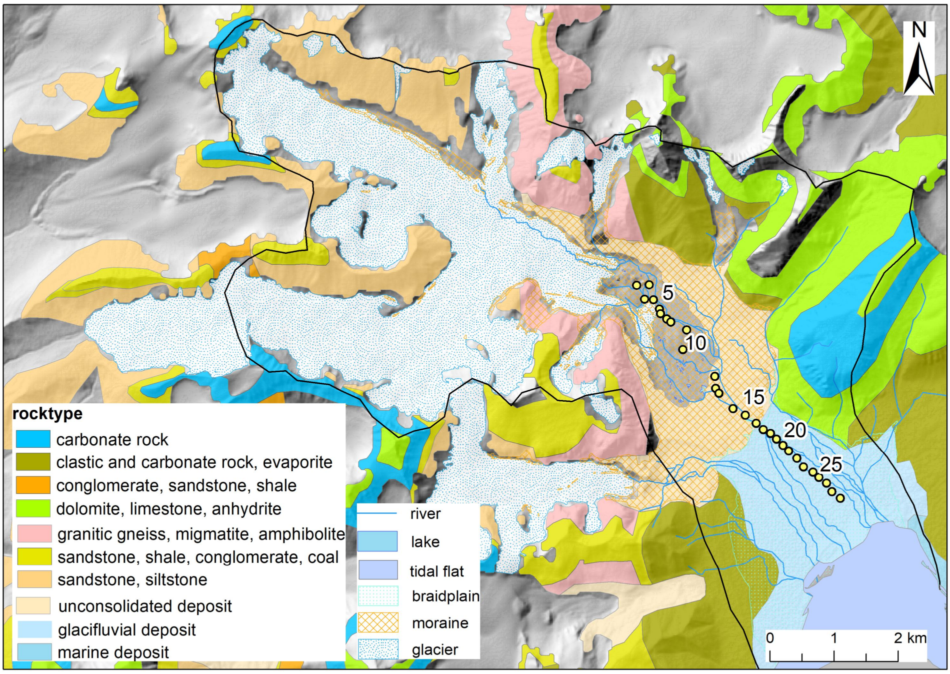

Fig. 2. Geological map of the Hørbye River catchment (based on geological map of Billefjorden by Dallmann et al. (2004)).

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.

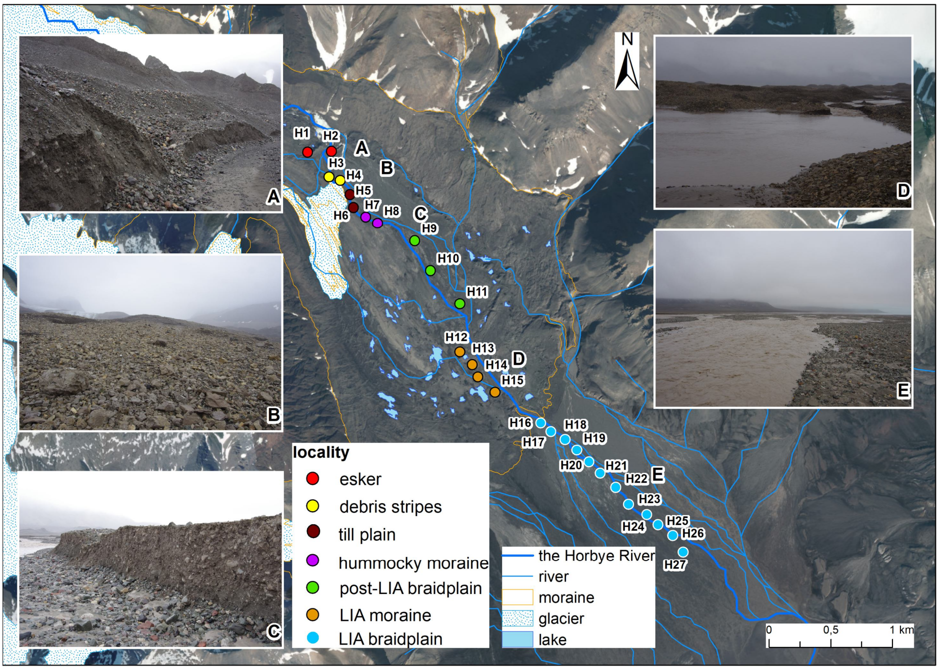

Fig. 3. Topographic map of the Hørbye River braidplain with location of the material sources and the sediment sampling localities.

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%).

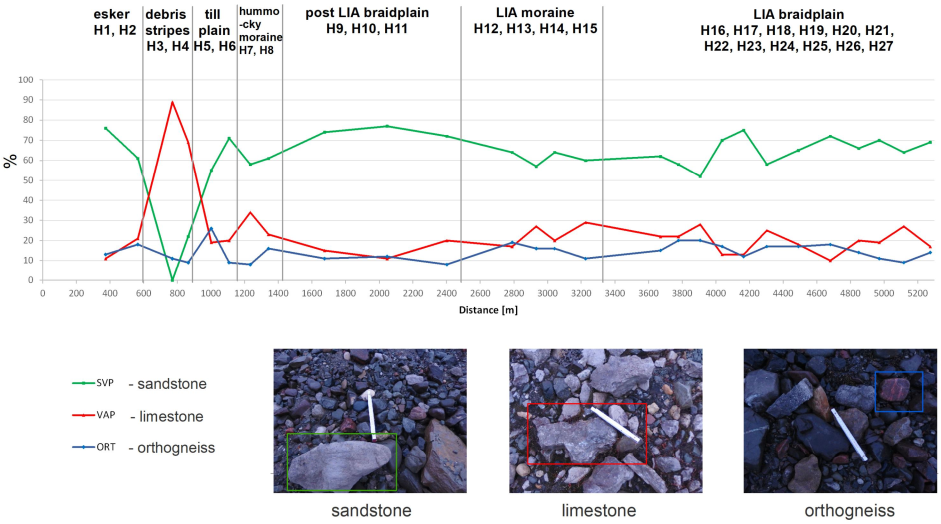

Fig. 4. Downstream change of the main petrological types of sediments in the Hørbye River braidplain.

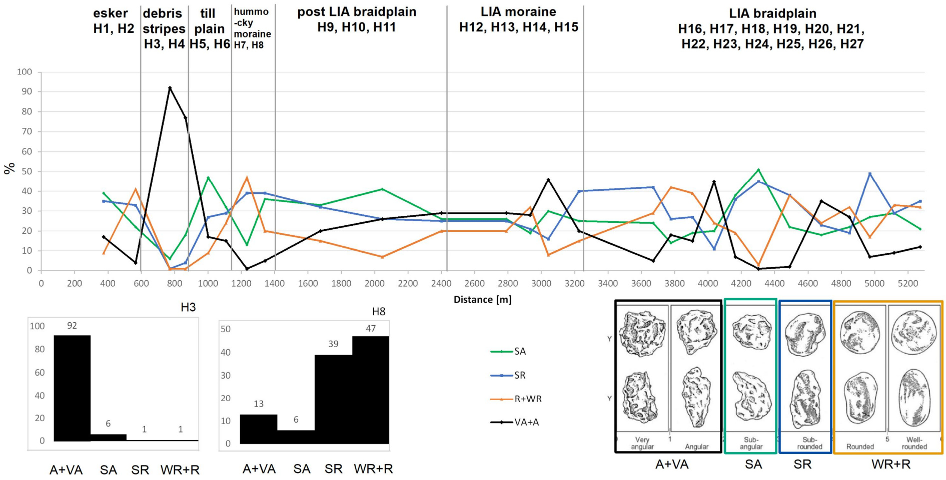

Fig. 5. Downstream change of sediment roundness in the Hørbye River braidplain.

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.

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