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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

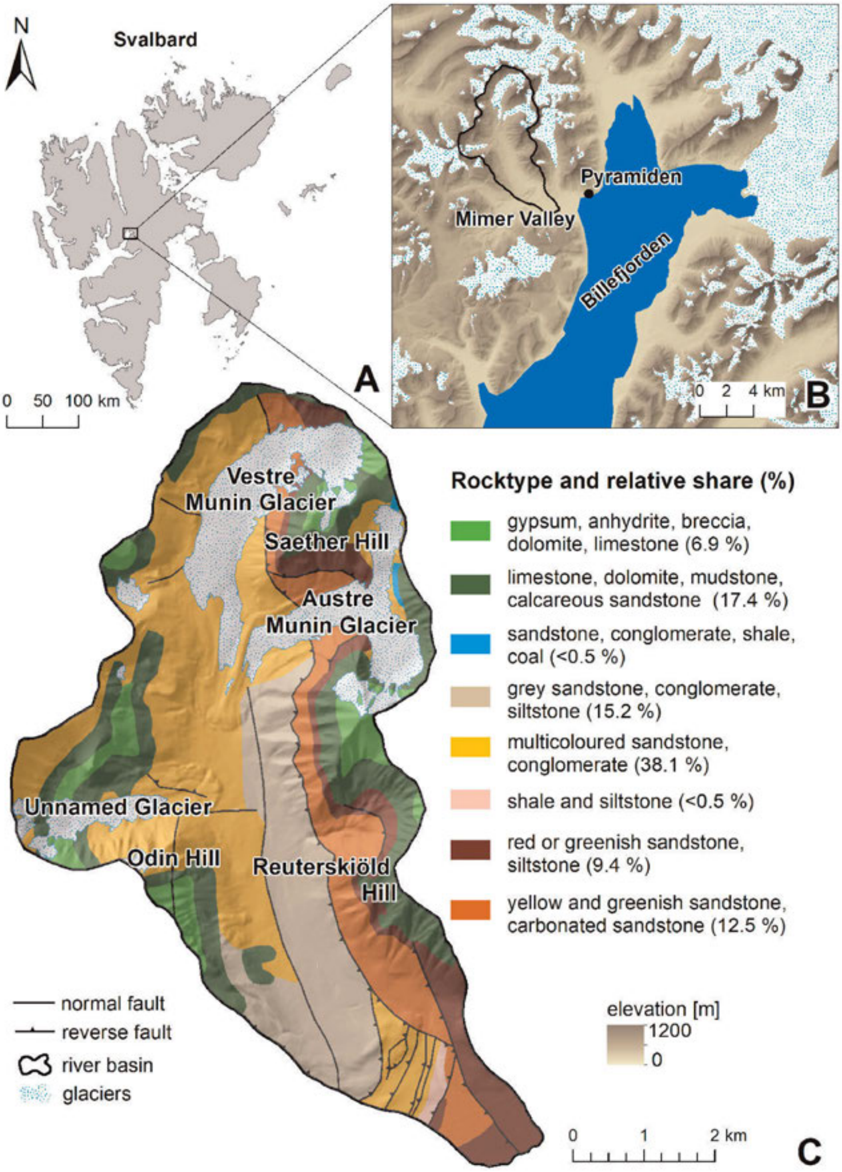

Fig. 1. Location of the study area: **A** - the archipelago of Svalbard with the largest island of Spitsbergen, **B** - the area of Billefjorden, **C** - geological map of the Munin Valley, based on geological map of Billefjorden by Dallmann *et al.* (2004).

(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).

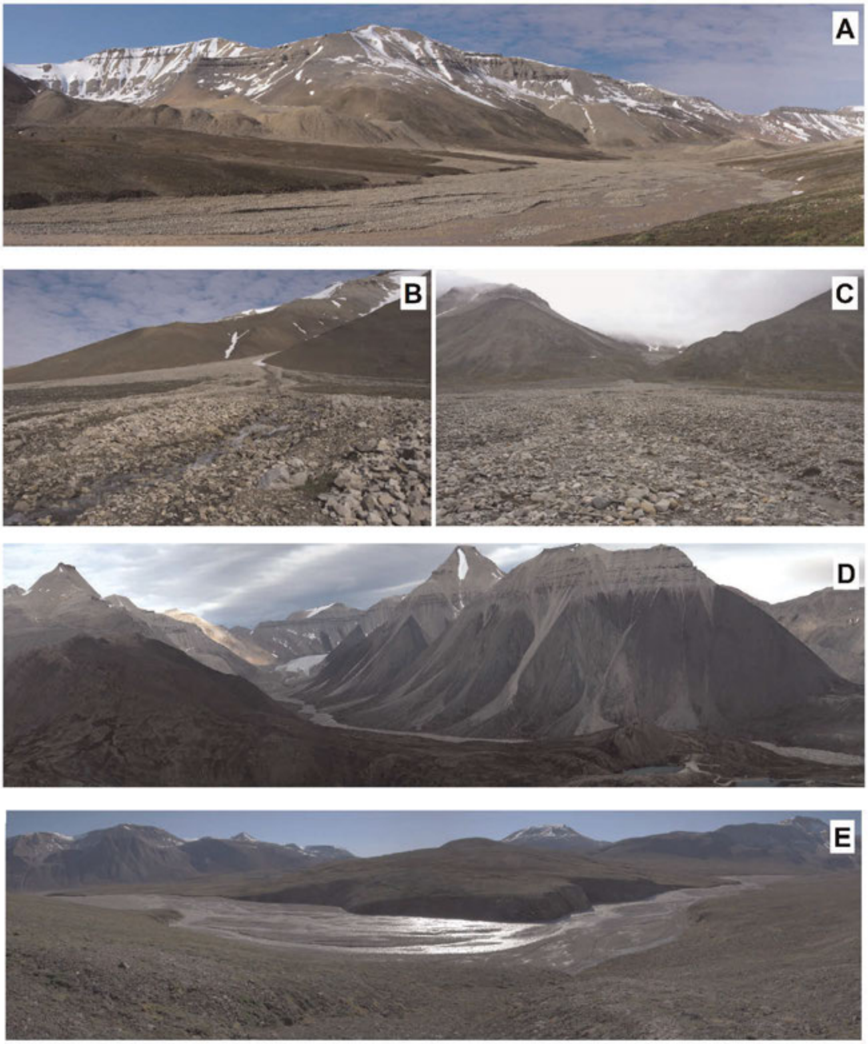

Fig. 2. Examples of the material sources in the Munin Valley: **A** - Morainic sources, **B** and **C** - Fluvial-flow dominated sources, **D** - Debris-flow dominated sources, **E** - Gorge at the lower part of the Munin River.

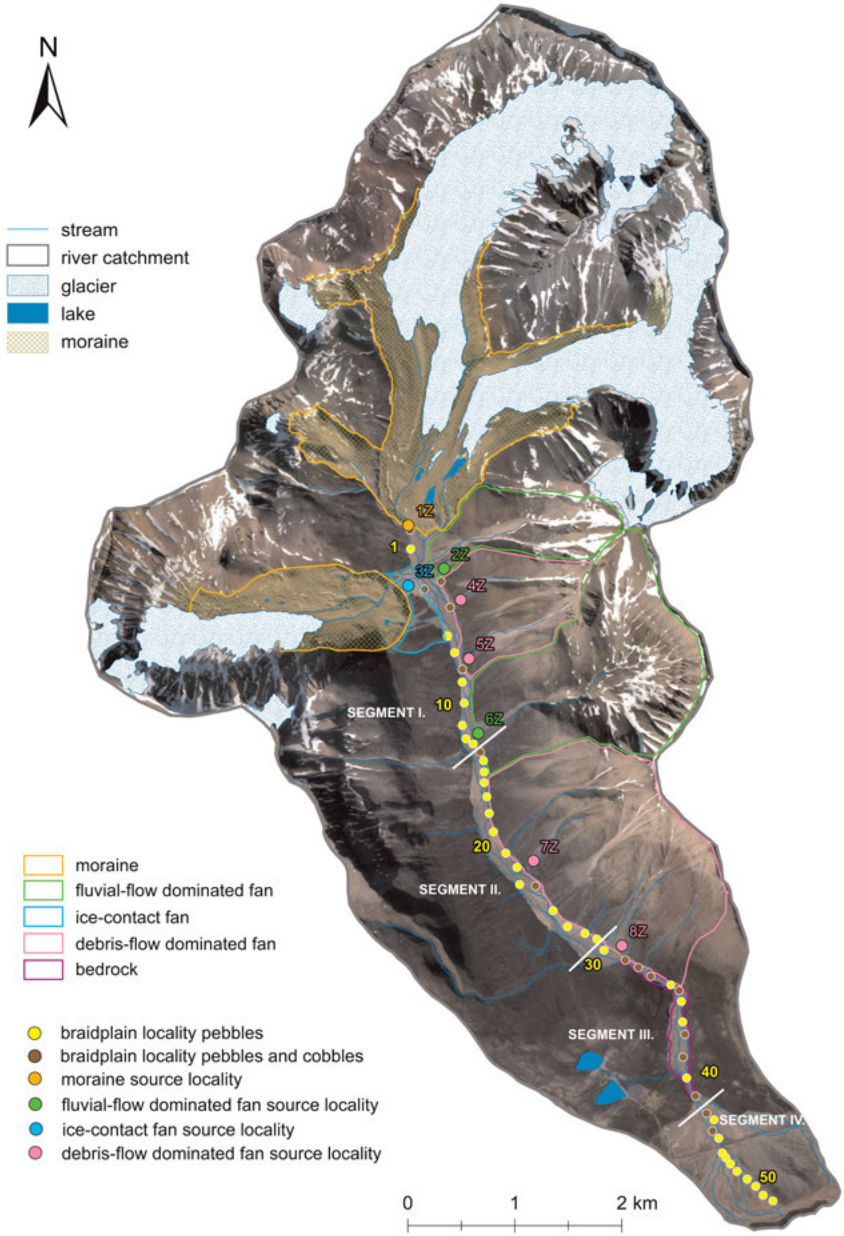

Fig. 3. Topographic map of the Munin Valley with location of the material sources and the sediment sampling localities.

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).

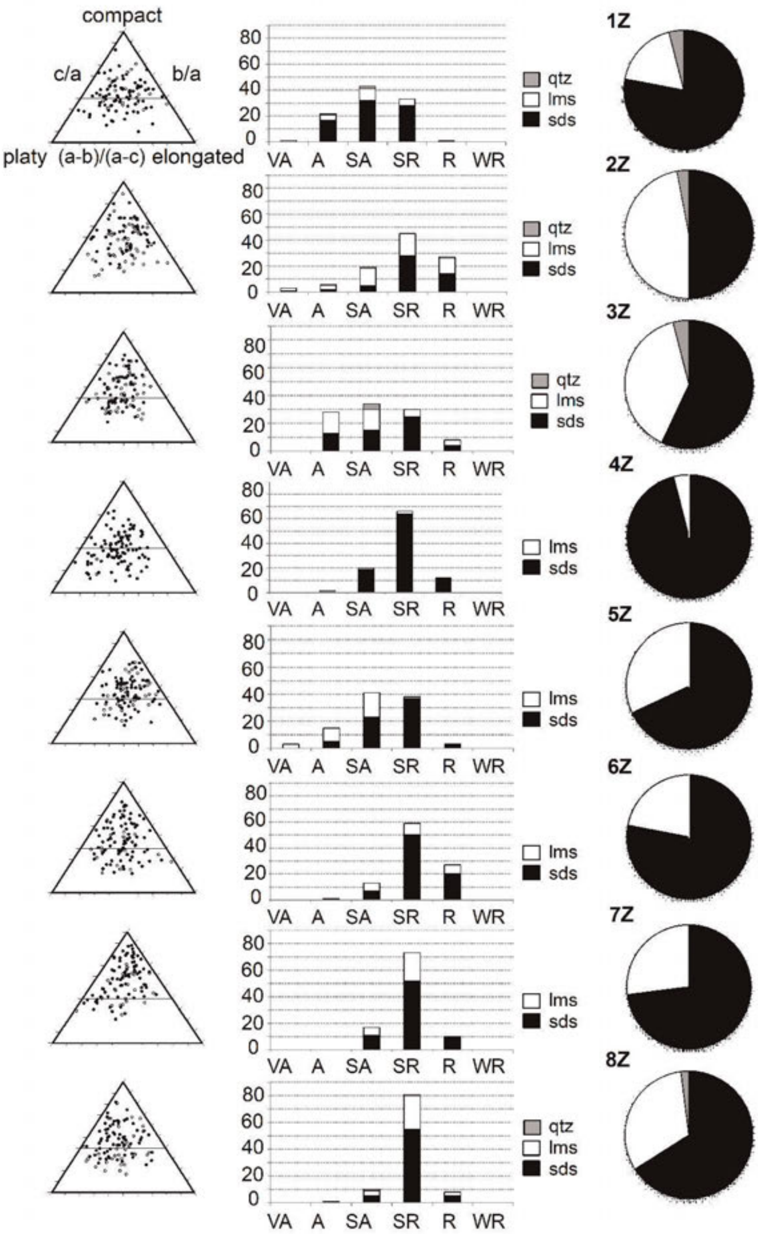

Fig. 4. Triplot graphs from sediment sampling localities at material sources for the pebble fraction 8–16 mm along the b-axis. Abbreviations: VA - very angular, A - angular, SA - subangular, SR - subrounded, R - rounded, WR - well-rounded; qtz - quartzite, lms - limestone, sds - sandstone.

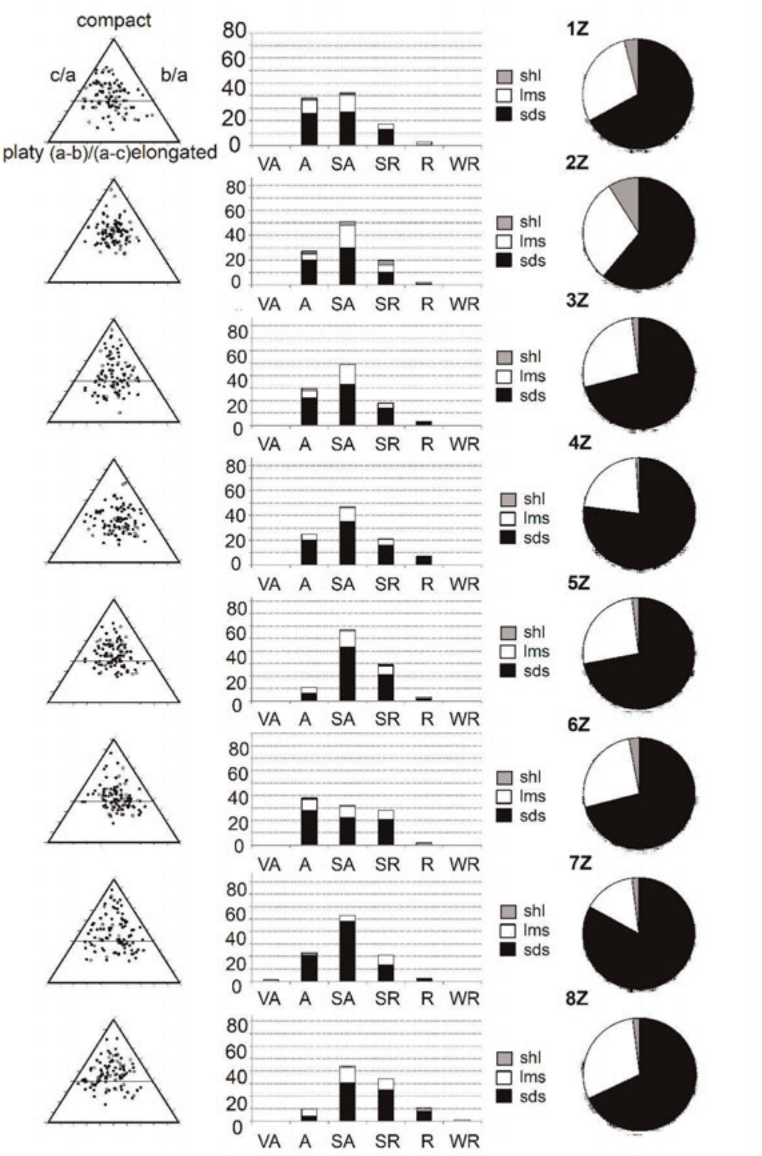

Fig. 5. Triplot graphs from sediment sampling localities at material sources for the cobble fraction 64–256 mm along the b-axis. Abbreviations: VA - very angular, A - angular, SA - subangular, SR - subrounded, R - rounded, WR - well-rounded; shl - shale, lms - limestone, sds - sandstone.

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

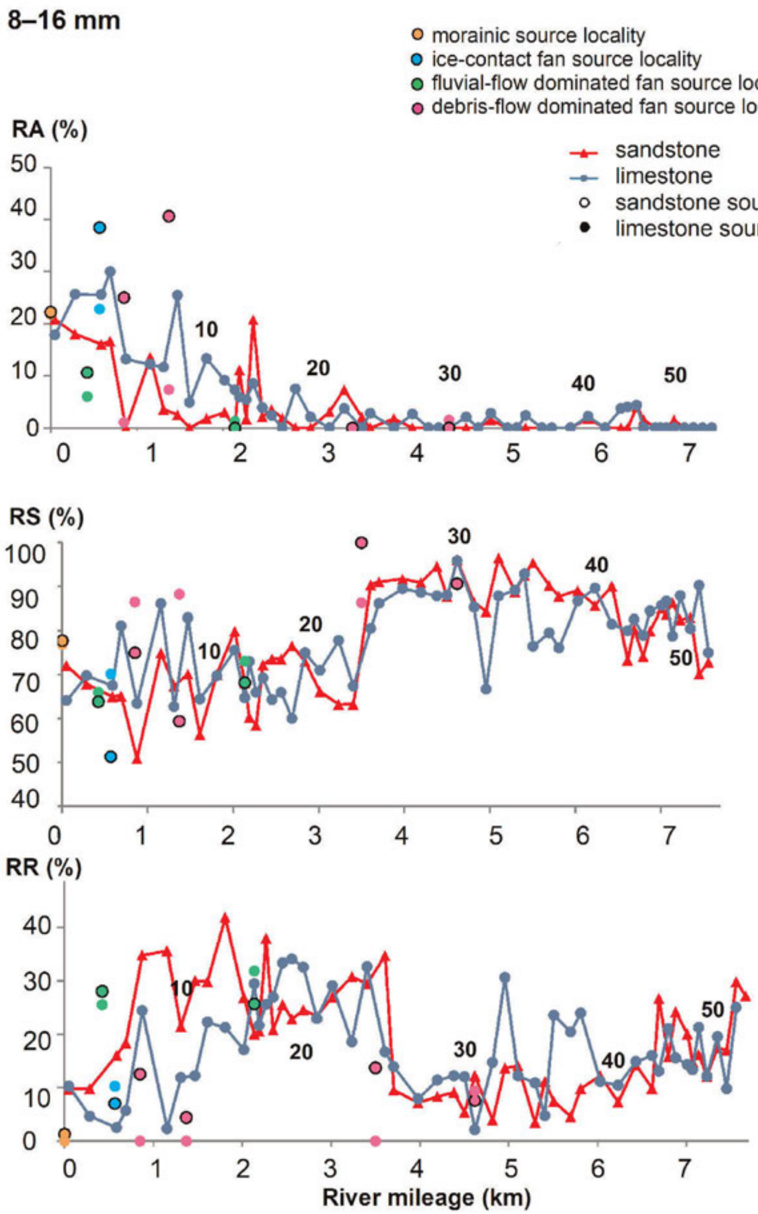

Fig. 6. The covariant plot of the transport distance and degree of roundness (RA, RS and RR shares) comparing sediment sampling localities from material sources and the Munin River channel belt for the fraction 8–16 mm and both petrological types.

(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%,

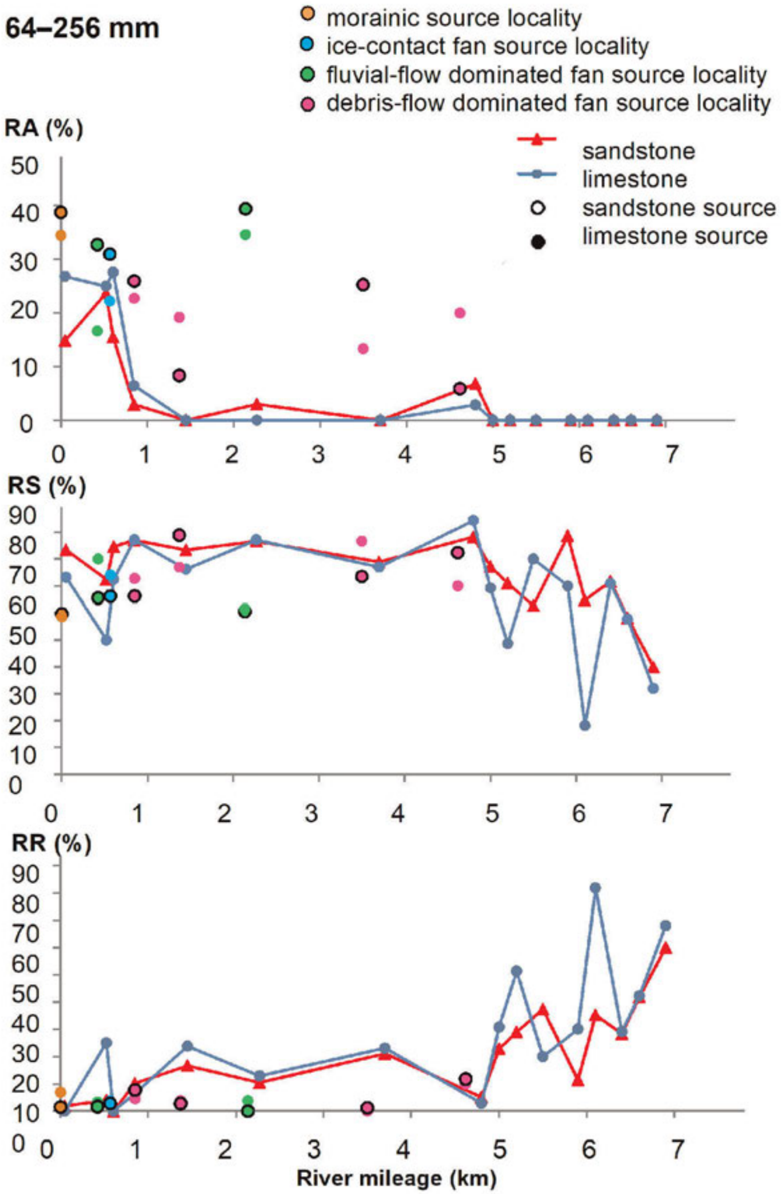

Fig. 7. The covariant plot of the transport distance and degree of roundness (RA, RS and RR shares) comparing sediment sampling localities from material sources and the Munin River channel belt for the fraction 64–256 mm and both petrological types.

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

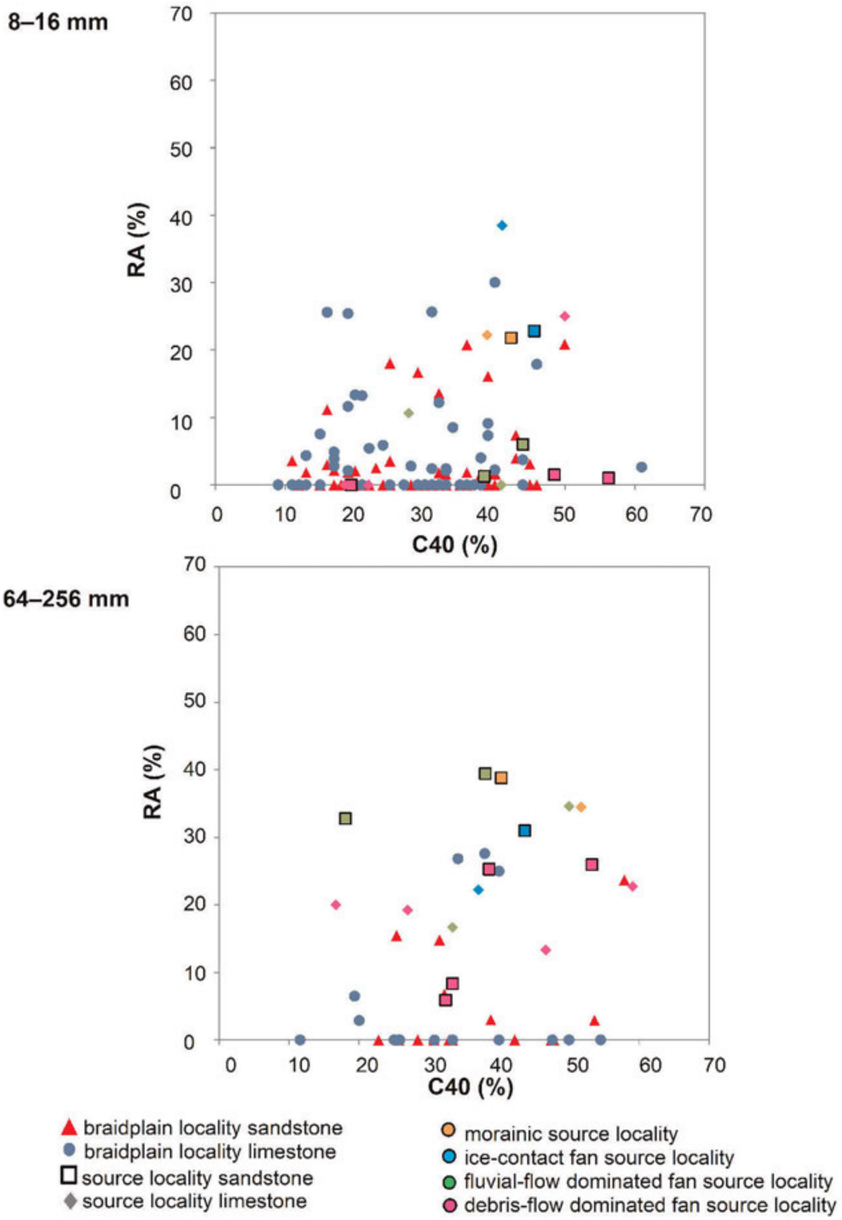

Fig. 8. The covariant plots for C40 ratio and RA share for both studied fractions 8–16 mm and 64–256 mm.

(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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