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# Micromorphological changes as an indicator of the transition from glacial to glaciofluvial quartz grains: Evidence from Svalbard

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ABSTRACT

The micromorphology of quartz grains in a sedimentary environment is determined by the transport mechanism and the nature of weathering. Both these aspects change during the transport history of grains. Thus important questions include how are quartz grains affected by possible changes in the transport medium, and how quickly do the different micromorphological features develop or disappear. The main goal of this study was to characterize the changes in the micromorphological features of quartz grains during the transition from a glacial to a glaciofluvial environment, and to identify a set of diagnostic microtextures that can be used to distinguish between glacial and glaciofluvial quartz grains. The samples came from the moraines of the Bertilbreen and Hørbyebreen glaciers (Svalbard) and from the sediments of glacier-fed rivers in the forelands of these glaciers. A total of 30 different micromorphological features was observed on 800 different quartz grains from 13 samples of glaciofluvial sediment and 3 samples of glacial sediment. It was found that the frequency of rounded grains, V-shaped pits, meandering ridges and cemented microblocks on glaciofluvial grains increased significantly with increasing length of fluvial transport, whereas the frequency of angular grains, straight steps, straight and curved grooves, adhering particles, pitting and oriented etch pits decreased significantly. Different types of micromorphological features of quartz grains change with fluvial transport at different rates. Adhering particles (after the first kilometer of fluvial transport), straight steps and meandering ridges (after the second kilometer of fluvial transport), and V-shape pits, angular shape and straight grooves (after the third kilometer of fluvial transport) are reliable mechanical micromorphological features for distinguishing between glacial and glaciofluvial quartz grains.



## 1. Introduction

Glaciofluvial sediments are deposited by glacier-fed rivers in either ice-contact or proglacial settings (Benn and Evans, 1998). Glaciofluvial sediments initially develop as glacial sediments and are then subsequently transported by streams. Quartz grains in glacial sediments are characterized by the greatest range of microtexture types (Mahaney, 2002). Typical mechanical microtextures include parallel striations, curved grooves, straight grooves, conchoidal fractures, crescent-shaped features, straight and arcuate steps and adhering particles (e.g., Krinsley and Doornkamp, 1973; Cremer and Legigan, 1989; Helland et al., 1997; Mahaney et al., 2001; Mahaney, 2002; Strand et al., 2003; Alekseeva, 2005; Křížová et al., 2011; Immonen et al., 2014; St John et al., 2015; Woronko, 2016). The shape of glacial grains is often angular, with edge abrasion and a high relief (Mahaney, 2002), but not all broken grains in tills result from crushing in glacial environments (Woronko, 2016). Silica pellicles and silica precipitation, formed during diagenesis, may occur on some glacial grains (Mahaney et al., 2001). The frequency of the constituent micromorphological features developed on quartz grains in fluvial environments depends primarily on transport length, stream energy and sediment concentration (Mahaney, 2002). If the transport length is short or the stream energy is low, quartz grains are not influenced by the fluvial environment and pass through it almost intact (Mahaney and Kalm, 2000). Quartz grains transported by running water often have a rounded shape with V-shaped pits, straight and curved grooves and other impact features (Krinsley and Donahue, 1968; Kleesment, 2009; Longhinos, 2009; Madhavaraju et al., 2009). Various chemical microtextures, such as silica precipitation, and various forms of etching and quartz crystal overgrowths, have also been observed on fluvial quartz grains (Manker and Ponder, 1978; Manickam and Barbaroux, 1987; Cremer and Legigan, 1989). However, Manker and Ponder (1978) noted that these microtextures occur in other environments and that investigators should be wary of using these features alone as environmental indicators.

Glacier-fed rivers have considerable energy and transport large quantities of sediment eroded by glaciers (Bogen and Bønsnes, 2003;

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Zajączkowski and Włodarska-Kowalczuk, 2007). On the other hand, glacier-fed rivers are characterized by seasonal and diurnal changes in flow regime leading to formation of braided and anastomosing networks (Goudie, 2004). Thus, glaciofluvial sediments can be alternately exposed to subaquatic and also subaerial environments. In the literature, the micromorphological features of glaciofluvial quartz grains have merely been listed and not related to the length of fluvial transport. Mahaney and Kalm (2000) reported that the quartz grains of glaciofluvial sediments are rounded and exhibit edge abrasion and that the surface of the quartz grains is largely covered with percussion cracks and microtextures, bearing evidence of glacial transport. According to Bull and Morgan (2006), subangular to subrounded grains, with traces of mechanical abrasion in the form of V-shaped pits and precipitation and dissolution features are typical of glaciofluvial grains.

From these observations, it is clear that micromorphological features typical of both glacial and fluvial transport should be present on glaciofluvial quartz grains. The frequency of fluvial micromorphological features should grow with increasing length of fluvial transport; conversely, glacial micromorphological features should gradually disappear. This allows us, on the one hand, to study the rate of formation of some types of micromorphological features and, on the other hand, the resistance of other micromorphological features at interfaces between glacial and glaciofluvial environments. In terms of the micromorphological analysis of quartz grains and its interpretation, it is essential to ask questions regarding the rates of formation of different micromorphological features and how resistant these features are. However, few authors have pursued this topic (e.g., Mahaney, 2002; Górska-Zabielska, 2015; Woronko and Pisarska-Jamroży, 2015). The main goal of this work is to characterize the frequency change of micromorphological features of quartz grains as they move from a glacial to a glaciofluvial environment over the first 4 kilometers of fluvial transport (i.e., to express how quickly micromorphological features respond to changes in the transport medium), and to identify a suitable set of micromorphological features for distinguishing between glacial and glaciofluvial quartz grains.

## 2. Study area

The samples come from moraines situated near the terminus of Bertilbreen and Hørbyebreen and from recent fluvial sediments of their glacier-fed rivers from the northern Billefjorden area, central Svalbard (Fig. 1).

Bertilbreen and Hørbyebreen are polythermal valley glaciers (Evans et al., 2012). In 2002, the total area of Bertilbreen (ca 640–240 m a.s.l.) was 3.91 km$^2$, and its total length was 4.69 km (Rachlewicz et al., 2007). Its width in 2013 was approximately 100 m (Hanáček et al., 2013), and its thickness in the 1980s reached 73 m (Zhuravlev, 1981). In 2002, the total length of Hørbyebreen (ca 450–75 m a.s.l.) was 6.75 km (Rachlewicz, 2003), and its total area was 13.9 km$^2$ (Rachlewicz et al., 2007), with a maximum width of 1 km (Hanáček et al., 2013). Since the Little Ice Age, both glaciers have retreated (Rachlewicz et al., 2007).

Unconsolidated sediments forming the moraines (Fig. 2) of both glaciers are rich in quartz grains because the underlying rocks are mainly composed of sandstone and orthogneiss, with subordinate amphibolite, conglomerates, siltstones and claystones (Fig. 3), in which there are rare layers of coal (Dallmann et al., 2004). Svalbard features an arctic climate, with an average annual temperature of −6.5 °C for the period 1961–1990 (Rachlewicz, 2003). The warmest months are July and August, with an average annual temperature of 5–6 °C for the period 1961–1990 (Rachlewicz, 2003). The coldest months are January, February and March (Gibas et al., 2005). The average annual

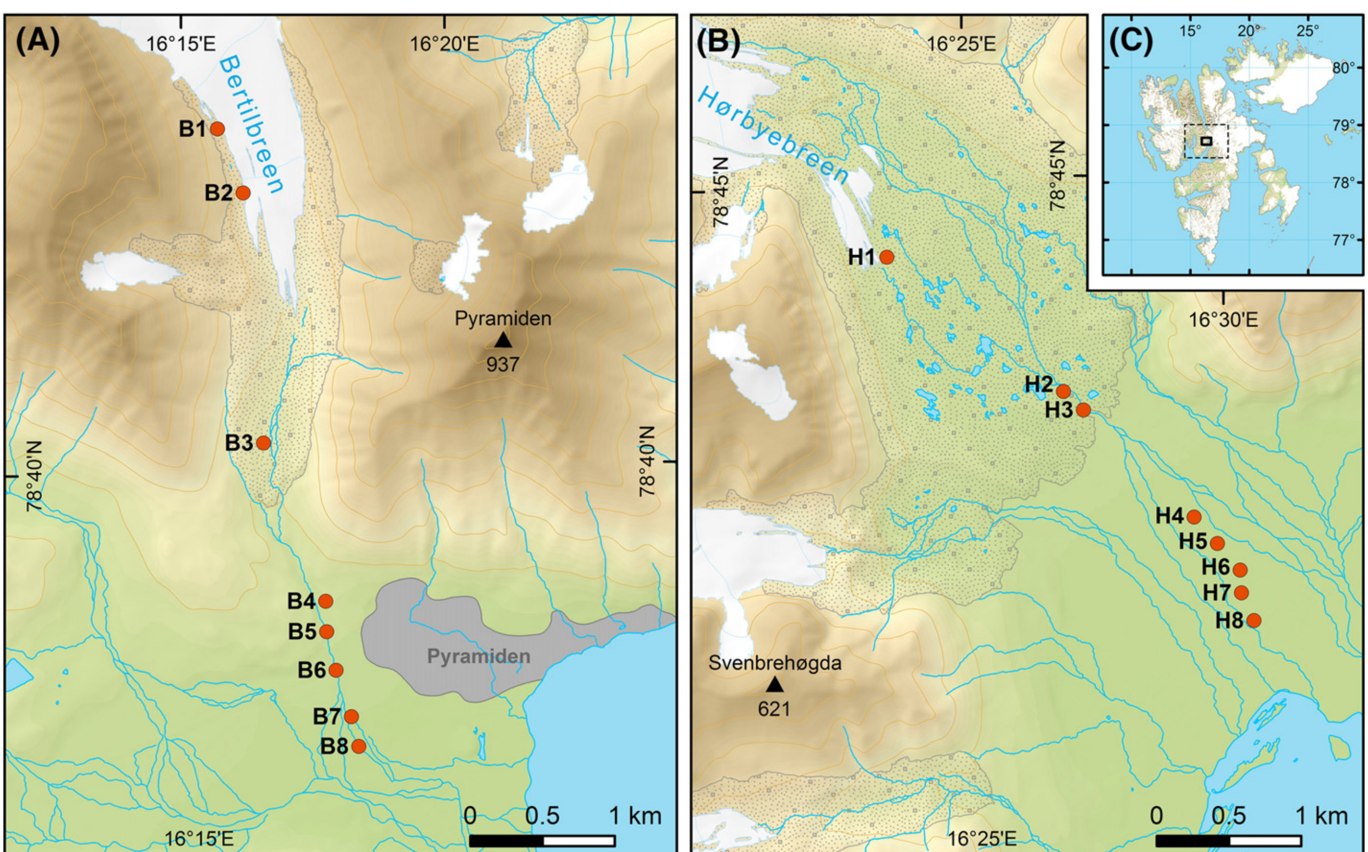


**Fig. 1.** Study area: (A) the Bertilbreen area with location of glacial (B1, B2) and glaciofluvial (B3–B8) sample sites; (B) the Hørbyebreen area with location of glacial (H1) and glaciofluvial (H2–H8) sample sites; (C) Svalbard archipelago. Contour interval is 100 m. Topography basemap: TopoSvalbard by Norwegian Polar Institute, 2017.

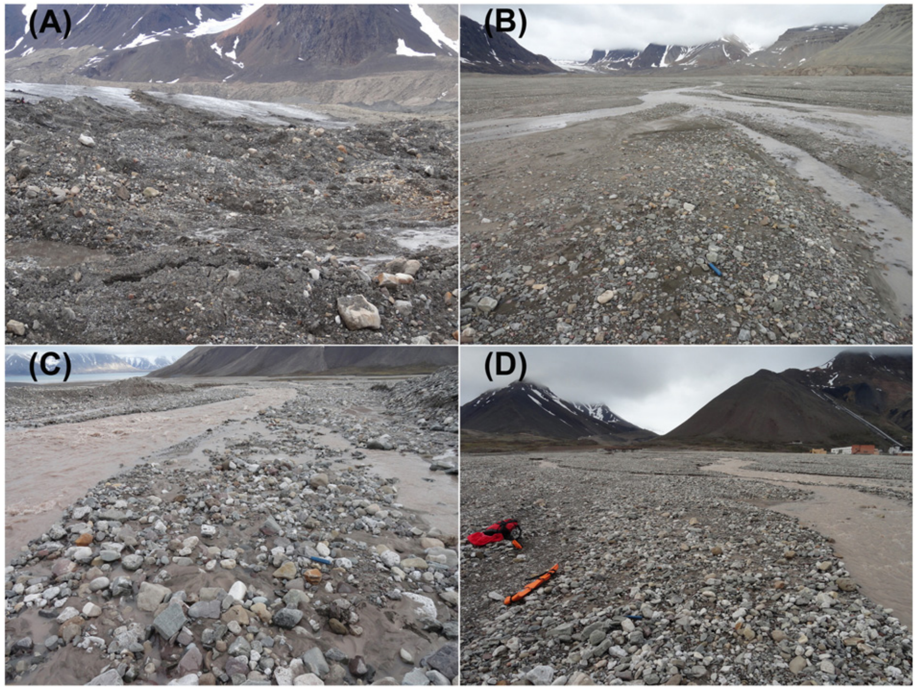


**Fig. 2.** Examples of sample sites: (A) the H1 sample site on the frontal moraine of Hørbyebreen; (B) the H7 sample site on one of the islands of the braided channel of the anastomosing glacier-fed river flowing from Hørbyebreen; (C) the B6 sample site on island of braided channel of glacier-fed river flowing from Bertilbreen; (D) the B7 sample site on one of the islands of the anastomosing part of glacier-fed river flowing from Bertilbreen.

precipitation amounted to 190 mm/year for the period 1961–1990 (Førland and Hanssen-Bauer, 2003).

The glacier-fed river flowing from Bertilbreen at 200 m a.s.l. is approximately 5 km long and creates braided channels and anastomosing network (Fig. 2) in the lower part of an outwash fan. The braided glacier-fed river (Fig. 2) flowing from Hørbyebreen (Fig. 1) at 165 m a.s.l. is 5.5 km long and creates an anastomosing channel network. A few meters wide channels of this river cut the frontal moraine and create an outwash plain in its foreland. Both glacier-fed rivers are characterized by a glacial regime with runoff from June to September (Kane and Yang, 2004), as evidenced by the results of surface runoff measurements of the river fed by Bertilbreen in 2012, when maximum discharge (1.6 $m^3/s$) was in July (Kavan, unpublished data). In winter, these rivers have very low or no discharge. Fluctuating discharge has an important effect on yearly, seasonal and diurnal variability of transport capacity of these glacier-fed rivers, changes of sediment transport processes (i.e., saltation, suspension), and sedimentation processes. Furthermore, these rivers change continually their braided pattern and channel location. High percentage of fine particles suspended in the running water can be documented with glacier milk (glacial flour), i.e., light brown, grey or milky white coloured meltwater (Fig. 2B–D).

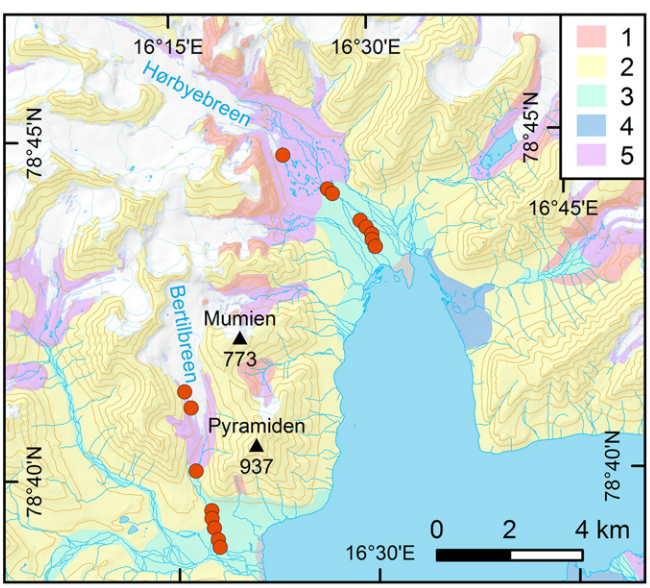


**Fig. 3.** Simplified geological map of the study area (created based on geological GIS map database 1:250,000 by Norwegian Polar Institute, 2015): 1 - gneiss, with subordinate amphibolite, mica schist, migmatite and quartzite; 2 - sandstone, with subordinate conglomerate, shale, siltstone, claystone, limestone, coal; 3 - glaciofluvial sediment; 4 - marine sediment; 5 - glacial sediment.

## 3. Methods

A total of 3 glacial and 13 glaciofluvial samples, with 50 grains per sample, was analyzed (Fig. 1). The glacial grains were sampled from inner sides of recent moraines in contact with the glaciers to avoid contamination by material of non-glacial origin. Because Bertilbreen (B) did not have a developed frontal moraine, samples were collected from a lateral moraine near the current glacier terminus. The maximum potential length of glacial transport of samples B1 and B2 could be 2.5 km, which is the distance of the samples from the source area of the glacier. Sample H1 of glacial sediment from Hørbyebreen (H) comes from a frontal moraine, and the maximum potential length of glacial transport could be 7.4 km. Glaciofluvial sediments were collected from channel bars and channel banks of glacier-fed rivers (melt streams). The distance of sample sites from fronts of Bertilbreen and Hørbyebreen (and hence the probable lengths of fluvial transport) was 1.51 km (B3), 2.63 km (B4), 2.89 km (B5), 3.17 km (B6), 3.51 km (B7) and 3.73 km (B8) for Bertilbreen, and 1.46 km (H2), 1.66 km (H3), 2.84 km (H4), 3.08 km (H5), 3.34 km (H6), 3.50 km (H7) and 3.72 km (H8) for Hørbyebreen (Fig. 1).

Samples for micromorphological analysis of quartz grains were prepared following a standard procedure (sensu Krinsley and Doornkamp, 1973). Grains were wet sieved to obtain a fraction of 250–500 μm and dried at 45 °C. These grains were cleaned in boiling concentrated HCl to remove carbonates. 50 quartz grains with a diameter of 250–500 μm were randomly selected from each sample. A Quantax 70 energy-dispersive X-ray spectrometer was used to confirm that the selected grains were composed of silica. Subsequently, the grains were fixed to carbon tape, gilded and analyzed using scanning electron microscopes (JEOL 6380 LV and Hitachi TM3030). A total of 800 quartz grains was used for micromorphological analysis. 7 shape characteristics of grains, 22 microtextures as defined by Krinsley and Doornkamp (1973), Higgs (1979), Cremer and Legigan (1989), Mahaney (2002) and Vos et al. (2014), and cemented microblocks were observed (Fig. 4). We define cemented microblocks as blocky features indurated and cemented together, as reported by Mahaney (2002) and Rattas et al. (2014). Frequencies of these 30 different micromorphological features (Fig. 5) were calculated as percentages for each sample.

The relationships between the occurrence of microtextures and the length of fluvial transport (from 0 km to 3.73 km) were detected using Pearson's correlation coefficient, and their significance was tested using a $t$-test at the significance level of $p = 0.05$. To examine whether micromorphological features differ significantly between glacial and glaciofluvial environments, three intervals (1–2 km, 2–3 km, more than 3 km) of fluvial sediment transport length were considered to determine how quickly certain micromorphological features respond to changes in the transport medium. Significant differences in the occurrence of all evaluated microtextures and micromorphological features between the glaciofluvial and the glacial samples were analyzed by one-way analysis of variance (ANOVA) and tested using an F-test at the significance level of $p = 0.05$. All statistical analyses were performed using STATISTICA 9.0 (StatSoft, Inc., 2009).

## 4. Results

The quartz grains of samples B1, B2 and H1 showed typical glacial micromorphological features (sensu Ying and Deonarine, 1985; Immonen et al., 2014). They are angular to subangular, and rounded grains occurred only sporadically (Fig. 5). The most frequent relief was medium (sensu Mahaney, 2002) and adhering particles often covered the surface of the glacial quartz grains. Pitting and silica precipitation were present on 72% and 67% of glacial grains, respectively (Fig. 5).

Glaciofluvial quartz grains (samples B3–B8 and H2–H8) mostly had medium relief, and the most frequent microtextures (Fig. 5) were edge abrasion, meandering ridges, adhering particles, pitting, silica precipitation, and quartz crystal overgrowths (Fig. 4). Adhering particles were almost absent on rounded grains. Compared with glacial quartz grains, glaciofluvial grains had a lower frequency (Fig. 5) of angular grains with high relief, conchoidal fractures, straight and arcuate steps, fracture faces, parallel striations, edge abrasion, straight and curved grooves, crescent-shaped features, grinding features, parallel ridges, adhering particles, pitting, and oriented etch pits (Fig. 4). In addition, there was an increased abundance (Fig. 5) of subangular, subrounded and rounded grains with low and medium relief, V-shaped pits, dish-shaped breakage concavities, meandering ridges, irregular hollows, cleavage plates, silica precipitation, silica pellicles, quartz crystal overgrowths and cemented microblocks (Fig. 4).

The frequency of occurrence of nineteen (subangular shape, subrounded shape, low relief, medium relief, high relief, conchoidal fracture, arcuate steps, fracture faces, parallel striations, edge abrasion, dish-shaped breakage concavities, crescent-shaped features, irregular hollows, grinding features, parallel ridges, cleavage plates, silica precipitation, silica pellicle, quartz crystal overgrowths) of the thirty

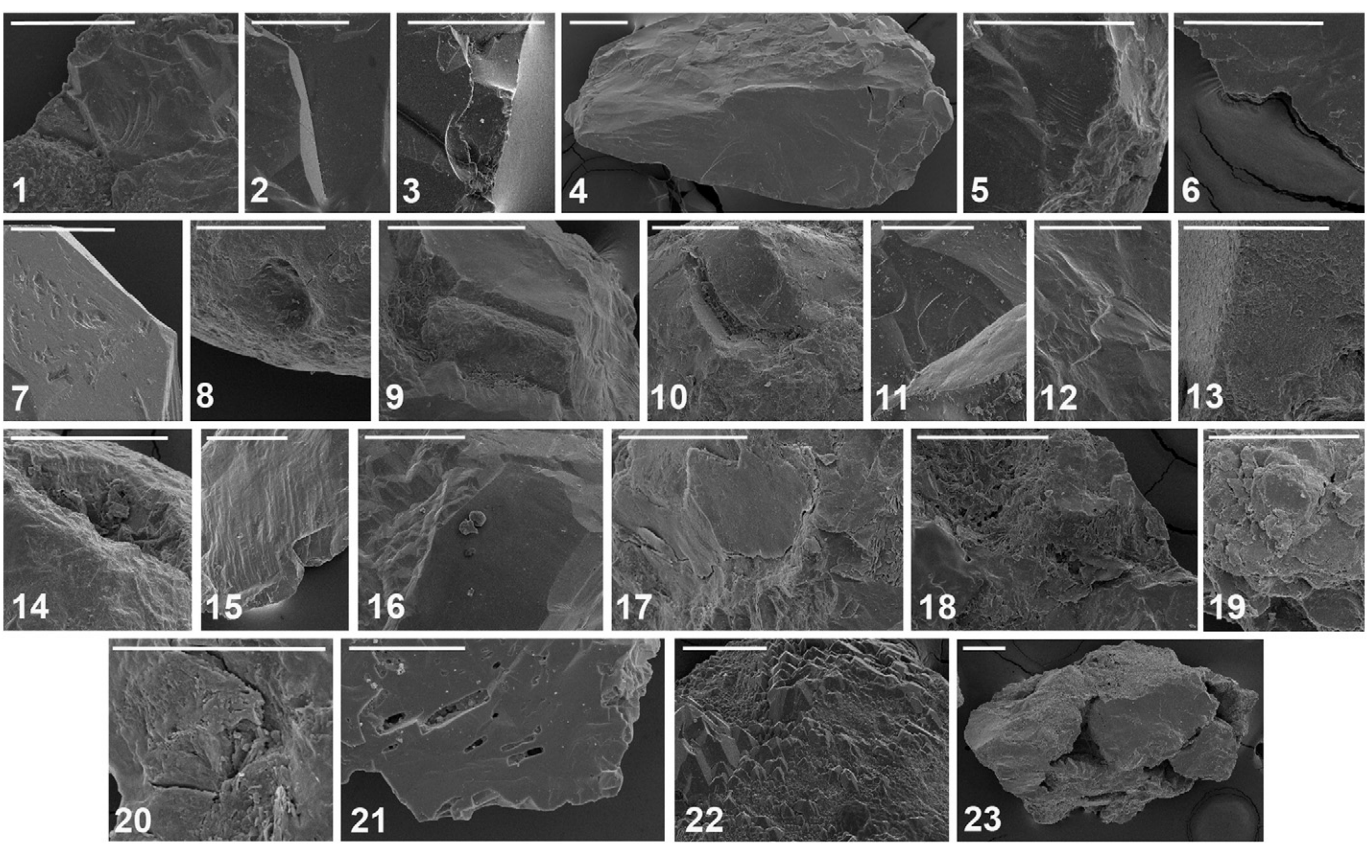


**Fig. 4.** Studied microtextures: 1 - conchoidal fracture, 2 - straight steps, 3 - arcuate steps, 4 - fracture faces, 5 - parallel striations, 6 - edge abrasions, 7 - V-shaped pits, 8 - dish-shaped breakage concavities, 9 - straight grooves, 10 - curved grooves, 11 - crescent-shaped features, 12 - meandering ridges, 13 - irregular hollows, 14 - grinding features, 15 - parallel ridges, 16 - adhering particles, 17 - cleavage plates, 18 - pitting, 19 - silica precipitation, 20 - silica pellicle, 21 - oriented etch pits, 22 - quartz crystal overgrowths, 23 - cemented microblocks. Note: white bar on each image corresponds to 100 μm.

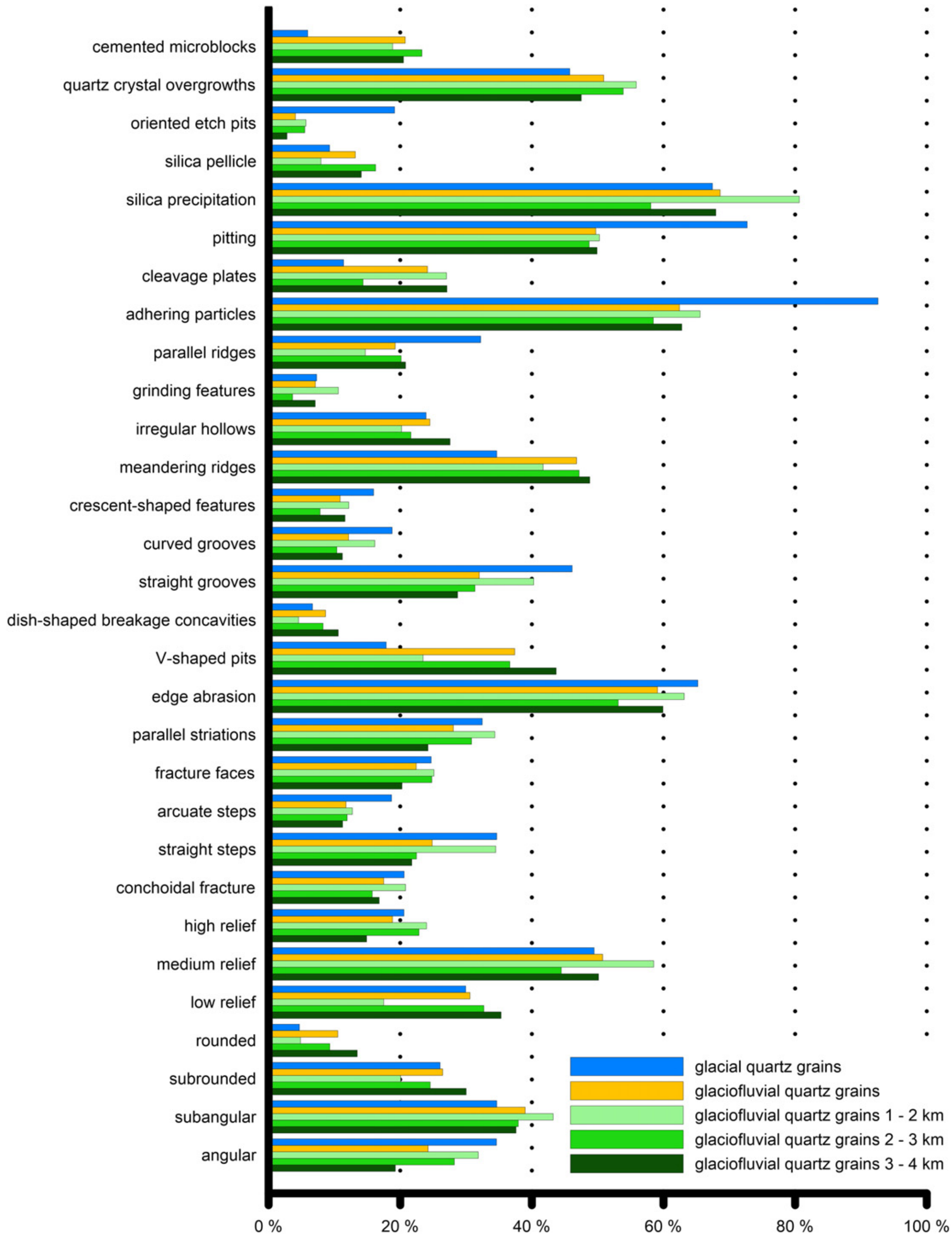


**Fig. 5.** Mean frequencies of micromorphological features on glacial and glaciofluvial quartz grains.

micromorphological features studied here did not respond to increasing fluvial transport length to any significant degree (Fig. 6, Table 1). On the other hand, the frequency of rounded grains, V-shaped pits, meandering ridges and cemented microblocks (Fig. 6, Table 1) significantly increased with increasing length of fluvial transport. In contrast, the frequencies of angular grains, straight steps, straight grooves, curved grooves, adhering particles, pitting, and oriented etch pits significantly decreased with increasing length of fluvial transport (Fig. 6, Table 1).

With increasing length of fluvial transport, the number of micromorphological features that differ significantly between glacial and glaciofluvial sediments increases from 3 to 5 to 10, respectively, for each distance interval (Table 2). Between the first and second kilometer of fluvial transport, glacial and glaciofluvial samples differed significantly in the abundance of adhering particles (which were more abundant in glacial samples), cleavage plates and cemented microblocks (which were more commonly observed in glaciofluvial samples). Between the second and third kilometer of fluvial transport, glacial and glaciofluvial samples differed significantly in abundance of straight steps, crescent-shaped features, meandering ridges, and both adhering particles and cemented microblocks again (Table 2). After the third kilometer of fluvial transport, glacial and glaciofluvial samples differed significantly in abundance of angular shape, arcuate steps, V-shaped pits, straight grooves, pitting, and again straights steps, meandering ridges, adhering particles, cleavage plates and cemented microblocks (Table 2).

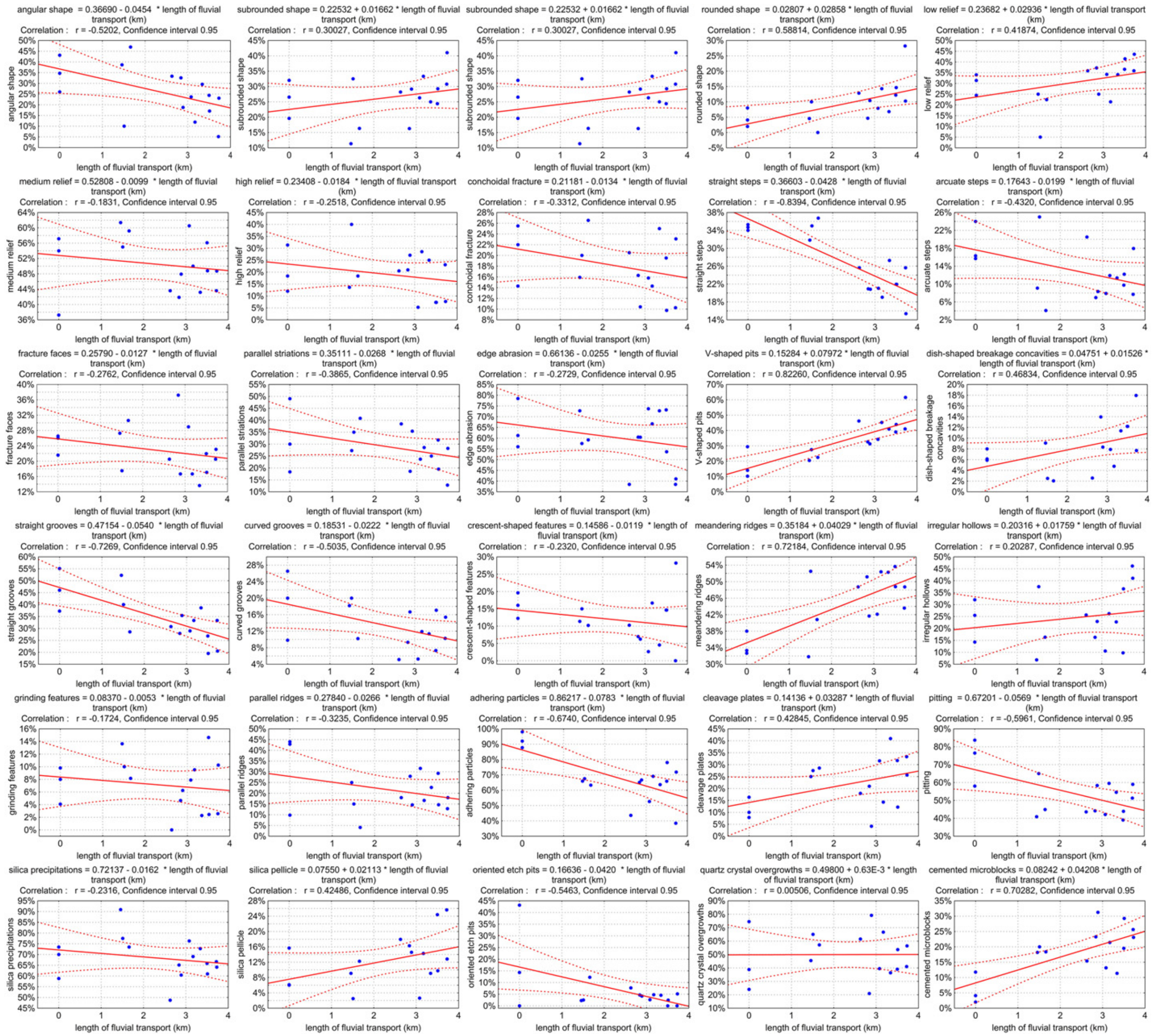


**Fig. 6.** Frequency of micromorphological features depending on the length of fluvial transport. Note: each dot represents the average value of frequency of micromorphology feature for a given sample site.

## 5. Discussion

### *5.1. Micromorphological features of glacial and glaciofluvial quartz grains and their relation to fluvial transport*

A relatively high number of quartz grains with straight steps, parallel striations and edge abrasion, which are characteristic of glacial environments (Krinsley and Donahue, 1968; Vočadlová et al., 2015; Woronko, 2016), were observed (Fig. 5). Adhering particles often covered the surface of the glacial quartz grains, which may be evidence of glacial grinding (Smalley, 1966). High number of glacial grains with pitting and silica precipitation probably proves that the quartz grains were exposed to chemical weathering.

A decrease in angularity accompanied by an increase in roundness of the quartz grains is typical for an increasing length of fluvial transport (Madhavaraju et al., 2009). Górska-Zabielska (2015), who observed roundness and abrasion on glacial and glaciofluvial quartz grains, showed a close similarity in roundness between glacial and glaciofluvial quartz grains. Mahaney and Kalm (2000) noticed that glacial grains showed various degrees of glacial crushing and rounding by abrasion in meltwater.

The increase in frequency of meandering ridges and V-shaped pits, both of which are microtextures of mechanical origin, constitutes evidence of frequent grain-to-grain collisions in a fluvial environment (Bull, 1986; Madhavaraju et al., 2009). Nevertheless, meandering ridges are also associated with the aeolian (Krinsley and Donahue, 1968; Margolis and Krinsley, 1974) and glacial (Mellor, 1986) environment. The increasing abundance of cemented microblocks (Fig. 4) with increasing length of fluvial transport corresponds with the combined process of dissolution and precipitation of silica (sensu Margolis and Krinsley, 1971; Manickam and Barbaroux, 1987) during subaerial stages of glacier-fed river transport (Kane and Yang, 2004), because the pH of the both watercourses in the study area varies between 8.2 and 8.6 (Kavan, oral communication).

The decreased frequency of straight steps, which were considered a typically glacial microtexture (Krinsley and Donahue, 1968; Mahaney

**Table 1**
Relationship between frequencies of micromorphological features and increasing length of fluvial transport. Significant (significance level $p = 0.05$) correlation coefficients are indicated in bold.

| Micromorphological feature | Correlation coefficient | Micromorphological feature | Correlation coefficient |
|---|---|---|---|
| Angular shape | **−0.52** | Straight grooves | **−0.73** |
| Subangular shape | 0.03 | Curved grooves | **−0.50** |
| Subrounded shape | 0.30 | Crescent-shaped features | −0.23 |
| Rounded shape | **0.59** | Meandering ridges | **0.72** |
| Low relief | 0.42 | Irregular hollows | 0.20 |
| Medium relief | −0.18 | Grinding features | −0.17 |
| High relief | −0.25 | Parallel ridges | −0.32 |
| Conchoidal fracture | −0.33 | Adhering particles | **−0.67** |
| Straight steps | **−0.84** | Cleavage plates | 0.43 |
| Arcuate steps | −0.43 | Pitting | **−0.60** |
| Fracture faces | −0.28 | Silica precipitation | −0.23 |
| Parallel striations | −0.39 | Silica pellicle | 0.42 |
| Edge abrasion | −0.27 | Oriented etch pits | **−0.55** |
| V-shaped pits | **0.82** | Quartz crystal overgrowths | 0.01 |
| Dish-shaped breakage concavities | 0.47 | Cemented microblocks | **0.70** |

and Kalm, 2000; Woronko, 2016), was probably connected with the rounding of grains in the fluvial environments (Mahaney, 2002). Although Kleesment (2009) and Krinsley and Donahue (1968) classified grooves as abrasion microtextures typical of fluvial transport, Mahaney and Kalm (2000) stated that grooves were not especially common on glaciofluvial grains. The opinion of Mahaney and Kalm (2000) is supported by our findings showing that the frequency of straight and curved grooves decreased with increasing length of fluvial transport (Table 1), which shows that these microtextures tend to reflect glacial transport as a result grain-to-grain contact (Krinsley and Doornkamp, 1973). During fluvial transport, in contrast, these microtextures are gradually polished out, while new ones are not created, because the energy of the running water was probably not sufficiently high for grooves to be carved by contact between grains (Krinsley and Donahue, 1968). Adhering particles occurred on the surface of quartz grains from the glacial sediments, where they were formed as a result of glacial grinding (Smalley, 1966; Warnke, 1971), but their frequency dropped abruptly as the length of fluvial transport increased because running water removes these particles (Pandey et al., 2002). Based on the inverse relationship with distance of the frequency of pitting, oriented etch pits and cemented microblocks (Table 1), all of which are chemical microtextures, one can assume that the disintegration of quartz grains surfaces into cemented microblocks, caused by cementation mainly with $SiO_2$, also smoothed out pitting and oriented etch pits (Table 1). The decreasing frequency of both pitting and oriented etch pits with increasing length of fluvial transport suggests that these microtextures are characteristic more of glacial than of glaciofluvial environments. Fitzpatrick and Summerson (1971) confirm that pitting is probably the result of weathering in glacial environments. The variability in the abundance of oriented etch pits and pitting present on grains, especially at the beginning of fluvial transport, was apparently caused by diurnal and annual fluctuations in discharge from proglacial streams and by more frequent channel changes in the braided glacier-fed rivers in the area (Kane and Yang, 2004), due to which the sediments were exposed to a non-aquatic environment, where slow etching by alkaline solutions was possible (Krinsley and Doornkamp, 1971).

**Table 2**
Differences in micromorphological features between glacial and glaciofluvial quartz grains in three sections of fluvial transport. Significant differences are expressed by *p*-values ($p = 0.05$) of one-way ANOVA (bold).

| Micromorphological feature | *p*-Value for the first section (1–2 km) | *p*-Value for the second section (2–3 km) | *p*-Value for the third section (3–4 km) |
|---|---|---|---|
| Angular shape | 0.8330 | 0.4032 | **0.0301** |
| Subangular shape | 0.0614 | 0.6313 | 0.4045 |
| Subrounded shape | 0.4596 | 0.7984 | 0.3603 |
| Rounded shape | 0.9629 | 0.1989 | 0.0808 |
| Low relief | 0.1448 | 0.5974 | 0.2745 |
| Medium relief | 0.2332 | 0.4794 | 0.9032 |
| High relief | 0.7475 | 0.7289 | 0.4365 |
| Conchoidal fracture | 0.9634 | 0.3335 | 0.3811 |
| Straight steps | 0.9270 | **0.0017** | **0.0006** |
| Arcuate steps | 0.4342 | 0.2547 | **0.0220** |
| Fracture faces | 0.9243 | 0.9889 | 0.1987 |
| Parallel striations | 0.8550 | 0.8876 | 0.2440 |
| Edge abrasion | 0.8147 | 0.2919 | 0.6129 |
| V-shaped pits | 0.4203 | 0.0680 | **0.0033** |
| Dish-shaped breakage concavities | 0.4214 | 0.6554 | 0.1687 |
| Straight grooves | 0.5330 | 0.0578 | **0.0103** |
| Curved grooves | 0.6674 | 0.2285 | 0.0837 |
| Crescent-shaped features | 0.2171 | **0.0298** | 0.4930 |
| Meandering ridges | 0.3203 | **0.0193** | **0.0011** |
| Irregular hollows | 0.7402 | 0.7138 | 0.7006 |
| Grinding features | 0.2294 | 0.2204 | 0.9463 |
| Parallel ridges | 0.2408 | 0.3679 | 0.1911 |
| Adhering particles | **0.0011** | **0.0131** | **0.0064** |
| Cleavage plates | **0.0048** | 0.6344 | **0.0408** |
| Pitting | 0.1034 | 0.0566 | **0.0096** |
| Silica precipitation | 0.1275 | 0.2285 | 0.9010 |
| Silica pellicle | 0.7737 | 0.1050 | 0.3927 |
| Oriented etch pits | 0.3622 | 0.3445 | 0.0662 |
| Quartz crystal overgrowths | 0.5628 | 0.7404 | 0.8801 |
| Cemented microblocks | **0.0130** | **0.0336** | **0.0090** |

### *5.2. Micromorphological features distinguishing glacial and glaciofluvial sediments*

Adhering particles, cleavage plates and cemented microblocks respond faster to changes in the transport medium (between the first and second kilometer of fluvial transport onwards) than other micromorphological features (Table 2). Adhering particles (a typical glacial microtexture (Nieter and Krinsley, 1976; Pandey et al., 2002), originated by glacial grinding (Smalley, 1966)) are more prevalent on abraded grains (Mahaney, 2002). Thus, these microtextures were probably removed from fluvially smoothed grains, whose percentage increased with increasing length of fluvial transport (Fig. 5). The significant difference in the frequency of cemented microblocks between glacial and glaciofluvial quartz grains indicates that processes of silica dissolution and precipitation (during subaerial stages of glacier-fed river transport, when the sediments were exposed to a non-aquatic environment) are very rapid and are able to increase the frequency of this microtexture above the statistical significance limit in the first section of fluvial transport (Table 2). The statistically significantly higher frequency of cleavage plates on glaciofluvial grains and the increasing (albeit non-significant due to the outstanding value of one sample, see Fig. 6) trend in the frequency of this microtexture with increasing length of fluvial transport contradict the claims of Krinsley and Doornkamp (1973) that this microtexture is of glacial origin. On the other hand, the frequency of cleavage plates in our glacial sediment samples corresponds to the value reported by Mahaney (2002) for glacial samples.

Furthermore, other typical glacial microtextures that quickly vanished during fluvial transport include straight steps (between the second and third kilometer of fluvial transport) and arcuate steps (from the third kilometer of fluvial transport onwards) (Table 2). It can therefore be reasonably assumed that the removal of arcuate steps requires longer fluvial transport than the erasure of straight steps. V-shaped pits, as a common indicator of fluvial transport (Krinsley and Donahue, 1968; Kleesment, 2009; Longhinos, 2009; Madhavaraju et al., 2009), were indicated by the gradually decreasing *p*-values with increasing length of fluvial transport (Table 2). This significant difference in the frequency of V-shaped pits was nevertheless manifested only from the third kilometer of fluvial transport onwards. The gradual increase in the number of V-shaped pits apparently reflected an increasing number of grain-to-grain collisions, by which V-shaped pits were created (Mahaney and Kalm, 2000; Vos et al., 2014). Lindé and Mycielska-Dowgiałło (1980) reported that natural V-shaped pits were usually variable in size. Nevertheless, V-shaped pits (observed by us) were rather smaller, than larger.

Considering the limited number of samples examined in the first (i.e., 1–2 km) and second (2–3 km) fluvial transport sections, due to the sampling conditions, the micromorphological features that did not retain a meaningful between-section sequence of significant differences between glacial and glaciofluvial samples (Table 2) are not regarded as diagnostic. These include crescent-shaped features, for which a significant difference was found only in the second section (2–3 km) of fluvial transport, and cleavage plates, for which no significant difference was found between glacial and glaciofluvial grains in the second section, in contrast to the first and third sections (Table 2). The combination of one-way ANOVA (Table 2) and Pearson's correlation (Table 1) results indicates that the length of fluvial transport had a significant effect on the abundance of angularity, straight steps, V-shaped pits, straight grooves, meandering ridges, adhering particles, pitting and cemented microblocks on glacial and glaciofluvial quartz grains. As for the frequencies of rounded shapes, curved grooves and oriented etch pits, the only significant relationship was found with increasing length of fluvial transport (compare Tables 1 and 2) without proof of a significant difference (as revealed by the one-way ANOVA test) in their abundance on glacial and glaciofluvial grains in individual sections of fluvial transport. For these three micromorphological features, it is nevertheless possible to trace a decreasing sequence of $p$-values for all three sections (1–2 km, 2–3 km and 3 km onwards) of fluvial transport (Table 2), and in the third section (i.e., from 3 km onwards), their $p$-values are barely above the threshold of $p = 0.05$. This shows that the effect of fluvial transport on the transformation of these three microtextures was less intensive and that a significant difference would probably be detectable only after longer transport by running water.

It follows from the foregoing comparison between the results of our Pearson's correlation analysis (Table 1) and one-way ANOVA (Table 2) that only those micromorphological features of glacial and glaciofluvial quartz grains for which the results of both analyses were significant and consistent can be considered diagnostic. This is true in the cases of adhering particles and cemented microblocks (which respond after the first kilometer of fluvial transport), followed by straight steps and meandering ridges (which respond after the second kilometer of fluvial transport), and angular shapes, V-shape pits, pitting and straight grooves (which respond after the third kilometer of fluvial transport). In addition, chemical weathering and formation of chemical microtextures can be influenced by the occurrence of non-aquatic stages resulting from the natural behavior of glacier-fed rivers (Goudie, 2004), when alkaline solution can act (Krinsley and Doornkamp, 1971). Therefore, these chemical microtextures do not have to be a direct consequence of the length of fluvial transport and can occur in both glacial and glaciofluvial environment (sensu Manker and Ponder, 1978).

## 6. Conclusions

A) With increasing length of fluvial transport even along a section as short as 4 kilometers, a significantly decreasing frequency of generally accepted (in the literature) glacial micromorphological features (i.e., angular grains, straight steps, straight and curved grooves, adhering particles) and significantly increasing frequency of generally accepted fluvial micromorphological features (i.e., rounded grains, V-shaped pits) were detected.

B) Determining a significant change in frequency of micromorphological features during transition from one type of transport to another one makes it possible to assign these features to a given type of transport. Micromorphological features of quartz grains responded to the transition from a glacial to a glaciofluvial environment at different speeds. Of the microtextures that were regarded as typically glacial, the first ones to respond to fluvial transport were adhering particles and straight steps. Among typically fluvial microtextures, the first to respond to fluvial transport via an increase in frequency was V-shaped pits (after the third kilometer of fluvial transport). Glacial micromorphological features began to disappear before fluvial features emerged. This is potentially useful for paleogeographic and paleoenvironmental reconstructions of landscape development.

C) As non-chemical micromorphological features that can be used to reliably distinguish between studied glacial and glaciofluvial quartz grains, it is reasonable to regard the occurrence of adhering particles (after the first kilometer of fluvial transport), followed by straight steps and meandering ridges (after the second kilometer of fluvial transport), and V-shape pits, angular grain shapes and straight grooves (after the third kilometer of fluvial).

D) The study of differences in micromorphological features between different genetic groups of sediments needs numerous samples containing sufficient numbers of examined grains, and a combination of statistical methods to suppress the influence of variation in the occurrence of micromorphological features.

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