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Fine-grained quartz from cryoconite holes of the Russell Glacier, southwest Greenland – a scanning electron microscopy study

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Abstract The western ablation zone of the Greenland ice sheet is darker than the surrounding ice, because a higher amount of fine-grained particles, known as a cryoconite, occur. To date, biotic cryoconite components have gained a lot of attention, in contrast with mineral components, which have been studied to a limited extent. In this study, fine-grained quartz grains from the cryoconite holes of the Russell Glacier, southwest Greenland are, therefore, examined. Authors use scanning electron microscope to elucidate shape, surface character and origin of these mineral quartz particles. Triangular-faceted, sharp-edged grains dominate in most of the investigated samples, and originate from local sources, where grain-to-grain contact in the ice prevail. Grains with smooth corners and edges result from chemical weathering in meltwater of alkaline pH, in which quartz solubility significantly increases. However, part of these rounded grains is due to mechanical abrasion by wind action. Postsedimentary frost action is visible through grains entirely or partially covered by scaly-grained encrustation. Local processes and sources are largely responsible for aforementioned grain outlines. However, few grains with bulbous silica precipitation argue for a dry and warm climate, and distant, out-of-Greenland origin.

Keywords • *glacial* • *periglacial* • *weathered* • *aeolian* • *quartz grain* • *SEM*

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INTRODUCTION

Cryoconite holes occur upon glacier surfaces worldwide and result from melting of biota and organic-mineral aggregates (Wharton *et al.* 1985) to a depth of thermal equilibrium (McIntyre 1984). These near-spherical forms contain dark coloured material called cryoconite (Takeuchi *et al.* 2000), which was first described by Nordenskiöld (1872). This material consist of (1) variable microbial community being a valuable biomarkers (Hodson *et al.* 2010), (2) black carbon being a product of incomplete combustion of fossils and biofuels (Cook *et al.* 2015), and (3) fine-grained mineral material having a source either in wind action or ice melting (Wientjes *et al.* 2011). Whereas biotic cryoconite components have been studied in detail (Cook *et al.* 2015; Hodson *et al.* 2010; Kaczmarek *et al.,* 2016; Uetake e*t al.* 2010), studies about abiotic components are rather limited and focus on, for instance, their physical and mineralogical properties (Nagatsuka *et al.* 2014; Tedesco *et al.* 2013). In this study, we analyse the shape and character of surface of the fine-grained mineral particles, which gained, so far, a limited attention (*see* Wientjes *et al.* 2011).

The fine-grained mineral component can be simply determined as a broken sand (Wright 2007), and may be produced under numerous conditions as both tropical (Pye 1983) and arid climate weathering (Smith *et al.* 1987), aeolian abrasion (Bullard *et al.* 2004; Whalley *et al.* 1987) or fluvial processes (Wright, Smith 1993). Traditionally, glacial grinding combined with wind action produce a large silt volume, and, therefore, these processes are favoured as an explanation for, for example, loess formation (Smalley 1995, 1990). However, glacial abrasion itself is also often responsible for a final production of silt-sized sediments (Langroudi *et al*. 2014). In the cold and arid areas, particularly important are glacial outwash floodplains that provide a silt-dominated deposit and dust source (Bullard, Austin 2011; Sugden *et al.* 2009). For example, up to 0.7 m thick silt wind-blown deposits occur at higher altitudes of the broad valley floodplains in Greenland (Dijkmans, Törnqvist 1991; Willemse *et al.* 2003). Because wind is important agent in sediment transport within extramarginal zones to glaciers (Hobbs 1942), fine-grained sediment may appear on the glacier surface (Marra *et al*. 2017), subsequently absorbing sunlight, melting in the ice, and finally producing a hole.

Natural silt is nearly always composed of quartz (Kumar *et al.* 2006), except of volcanic areas, where quartz is in a deficient (Noda 2005). In this study, quartz is abundant (Hodson *et al.* 2010), and thus we have a closer look at properties of fine-grained quartz material that originates from the cryoconite holes of the Russell Glacier, south west Greenland (Figs. 1, 2). This western ablation zone of the Greenland ice sheet is darker than the surrounding ice (Fig. 2A-B), likely due to a higher amount of fine-grained particles (Bøggild *et al.* 2010). Especially during the last years, increased snow impurity accelerates Greenland surface melt (Dumont *et al.* 2014). Compared to other localities of west Greenland, the darker surface of Russell Glacier contains a higher both biovolume and inor-

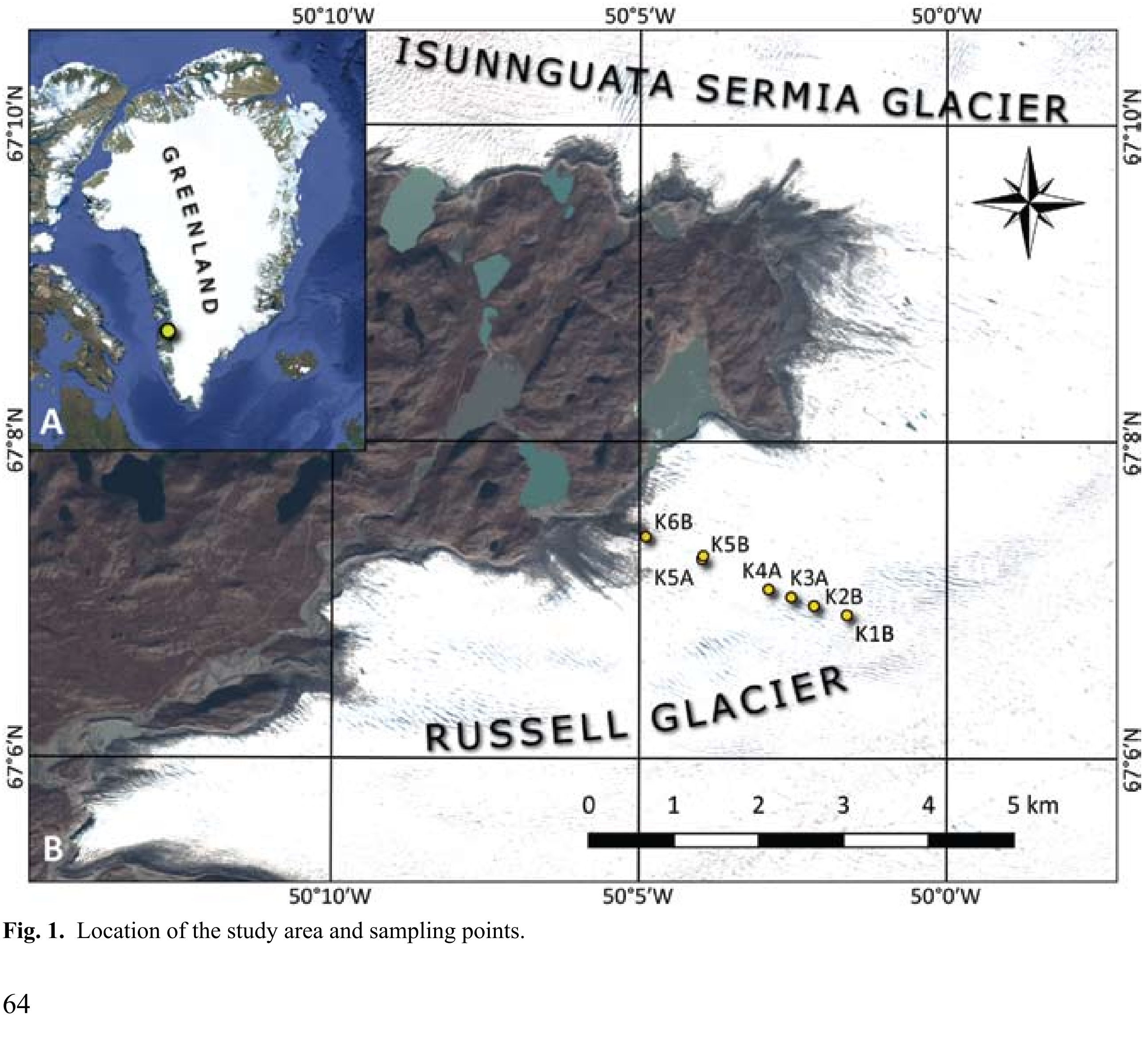

Fig. 1. Location of the study area and sampling points.

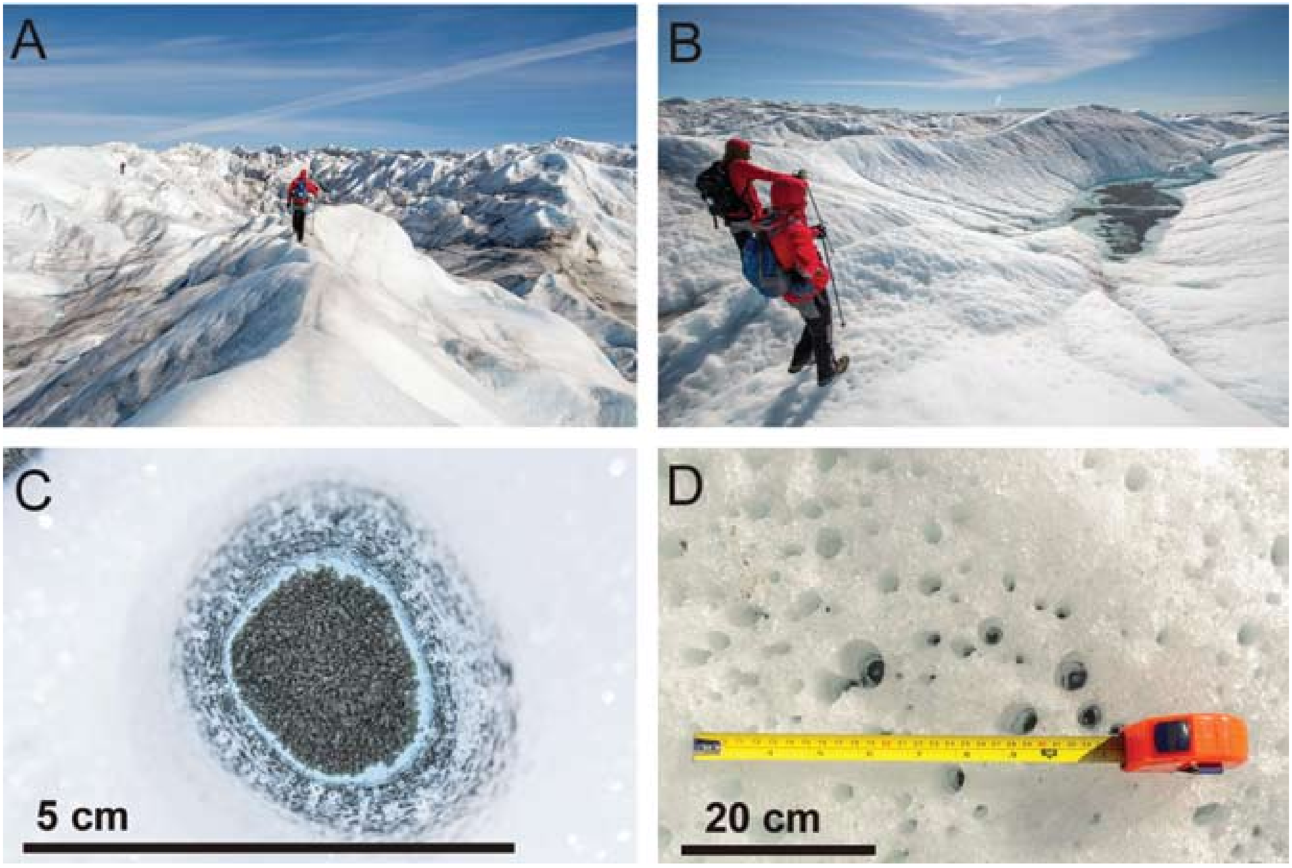

Fig. 2. A – a general view of study area with visible cryoconite on ice (darker zones), B – area with a lot of cryoconite holes in foreground and concentrated cryoconite sediments in supraglacial lake. C – close-up view of cryoconite hole with cryoconite granules at the bottom, D – group of cryoconite holes.

ganic quartz matter (Uetake *et al.* 2010). Quartz, in turn, is an excellent tool, which records transportation and post-depositional processes in its shape and on its surface (Vos *et al.* 2014). Combined all these features, the aim of this study is to elucidate the origin and characteristics of quartz particles from the cryoconite holes. We analyse the shapes, character of surfaces and microtextures of mineral quartz particles in scanning electron microscope (SEM).

STUDY AREA

Our study area is located in southwest Greenland, where the Greenland ice sheet is drained by the Russell and the Isunnguata Sermia outlet glaciers (Fig. 1). The melting of the Russell glacier is a source for proglacial streams flowing into the 1–2 km wide Sandflugtdalen valley-sandur. The Sandflugtdalen is a major source area for wind-transported dust, which forms small-scale aeolian features along the valley and distal part of sandur plain (Engels, Helmens 2010), and occurs atop the ice margin as well. The deposition of silt and sand sediments along sandur is facilitated by periodical Jökulhlaups (Česnulevičius, Šeirienė 2009; Russell 2007, 1989), with the latest ones occurred in 2007 and 2008 (Russell *et al.* 2011).

Marginal moraines are also the sources for aeolian silt, which even has deposited nearby in the small depressions and terrace-like forms of the moraine ridges themselves. As the airborne silt can remain in aerial suspension for a long time and can be transported over considerable distances (Clarhäll 2011), it is likely that some fine-grained particles could have been blown from distant localities in Northern Hemisphere. For example, black carbon particles originating from the forest fires in North America were found in the Arctic (Stohl *et al.* 2006).

The main bedrock constituent of the area near the Russell glacier is the Archaean ortho-gneisses, which construct the southern part of the Nagsugtoqidian Orogen (Van Gool *et al.* 2002). Gneisses are reworked in the Palaeoproterozoic era before 1.9-1.8 Ma (Van Gool *et al.* 2002) and later affected by glacial erosion, postglacial faulting and deposition of glacial and, in places, aeolian sediments. Thin cover of silty aeolian deposits is common in the uphill areas, and as suggested by Willemse *et al.* (2003), favourable conditions for continuous aeolian deposition have been prevailed at least since ca. 4,750 years BP with influx rates between 0.075 and 0.60 kg/m^2/year.

In the investigated area, dry sub-arctic climate prevails with mean annual temperature of -5.1ºC and mean annual precipitation of 173 mm (Cappelen 2012). The predominant wind direction is from east and southeast (Van den Broeke, Gallée 1996) with a mean speed at 2 m above ground level of 3.6 m/s (years 1985–99; Cappelen *et al.* 2001) with the highest values > 10m/s in December and January (Bullard, Austin 2011). However, Dijkmans and Törnqvist (1991) reported that 25% of winds with this speed occur in May and June.

MATERIAL AND METHODS

Seven samples (K1B, K2B, K3A, K4A, K5A, K5B and K6B) of cryoconite material from six sampling sites were collected from the surface of Russell Glacier during field expedition in July, 29, 2016 (Figs. 1, 2). First sampling site (K1B) was set 3 km from glacier margin at 552 m a.s.l. and each successive sampling site was set 30 m lower (see Table 1 for details). Because we have not found any cryoconite holes close to glacier margin, the last sampling site was set approximately 500 m from the glacier margin.

The altitude and coordinates of each sampling point were determined by using a GPS Magellan Promark 3. All measurements were performed in UTM coordinate system, zone 22N, whereas the elevations were calculated using the EGM 2008 geoid model. The K5A and K5B sampling sites were located at the same elevation, but 10 metres apart to test whether grain type distribution is similar or different.

At each sampling point pH (+/- 0.01) for each hole were measured by using Multiparameter meter WTW 2FD460. Before the beginning of measurements, the device was calibrated using calibration solutions with pH values of 7 and 4.01.

In laboratory, samples were dried at room-temperature, and further, sediment particles were randomly placed onto a carbon double-sided sticky tape on top of SEM holder. Because sediment itself was silty, and quantity was small, no extra separation (i.e. by sieving) was performed prior analyses with SEM. Altogether 736 quartz grains (between 100 and 115 grains per sample) were examined by the Hitachi FE-SEM S-4800 at the Institute of Chemical Physics, University of Latvia. Grains were classified into one of the five groups following a recommendation of Woronko (2007). These are: (1) A type = fresh grains, with all sharp edges and corners; (2) B type = grains entirely covered and transformed by chemical weathering; (3) C type = grain with scaly-grained cover; (4) D type = grains with bulbous cover, and (5) E type = cracked grains with at least 30% of the original grain affected. Information about grain type was, additionally, supplemented by a closer look at the grain surface and edges to find out the possible microtextures (Mahaney 2002; Vos *et al.* 2014).

RESULTS

Two groups of quartz grains significantly contribute in all studied cryoconite holes. In the first group, fresh (A-type) grains occur at between 14% and 43% (Fig. 3; Table 1). Fresh, different size of conchoidal features associated with (sub-)parallel and curved steps and graded marks occur on grains surface (Fig. 4A-E). In the second group, weathered (B-type) grains vary between 28% and 50% (Fig. 3). Their corners and edges are rounded by smooth etch surfaces (Fig. 4F-G) and caverns and holes are present on their surface (Fig. 4H). However, in part of the grains, edges are bulbous with no traces of chemically-induced features (Fig. 4I-J). This is especially relevant to the K6B sample, in which most grains carry bulbous edges.

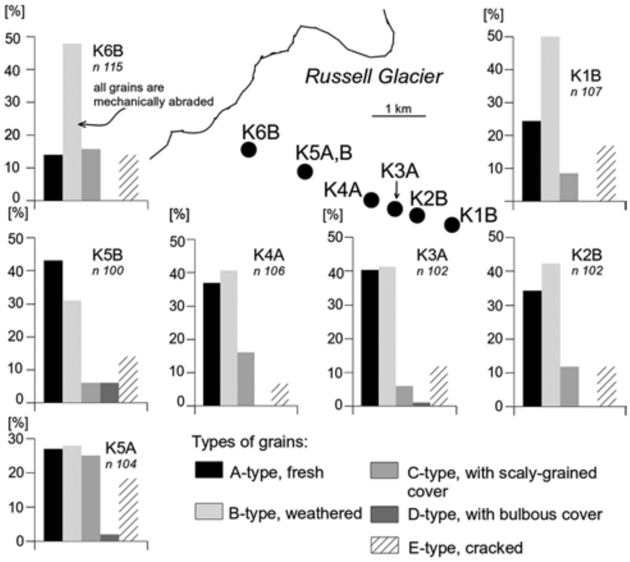

Fig. 3. Spatial distribution of fine quartz grain types from cryoconites of the Russell Glacier, southwest Greenland.

Table 1. Types of quartz grains of silty fraction in the material of the cryoconite holes of the Russell Glacier along with a sample altitude and pH value for each hole.

Sample	Altitude (m a.s.l.)	pH	Types of quartz grains [%]				
			A	B	C	D	E
K1B	552	9.27	24	50	8	0	17
K2B	522	9.17	34	42	12	0	12
K3A	494	9.49	40	41	6	1	12
K4A	465	9.13	37	41	16	0	7
K5A	433	8.10	27	28	25	2	17
K5B	433	8.00	43	31	6	6	14
K6B	423	7.20	14	48	16	0	14

Contribution of grains with scaly-grained encrustation (C-type) varies between 6–25% (Fig. 3). Either surface of these grains is intensively weathered and entirely encrusted, or weathering occurs only in depressions and at the bottom of the negative microforms (Fig. 4K). Cracked (E-type) grains contribute

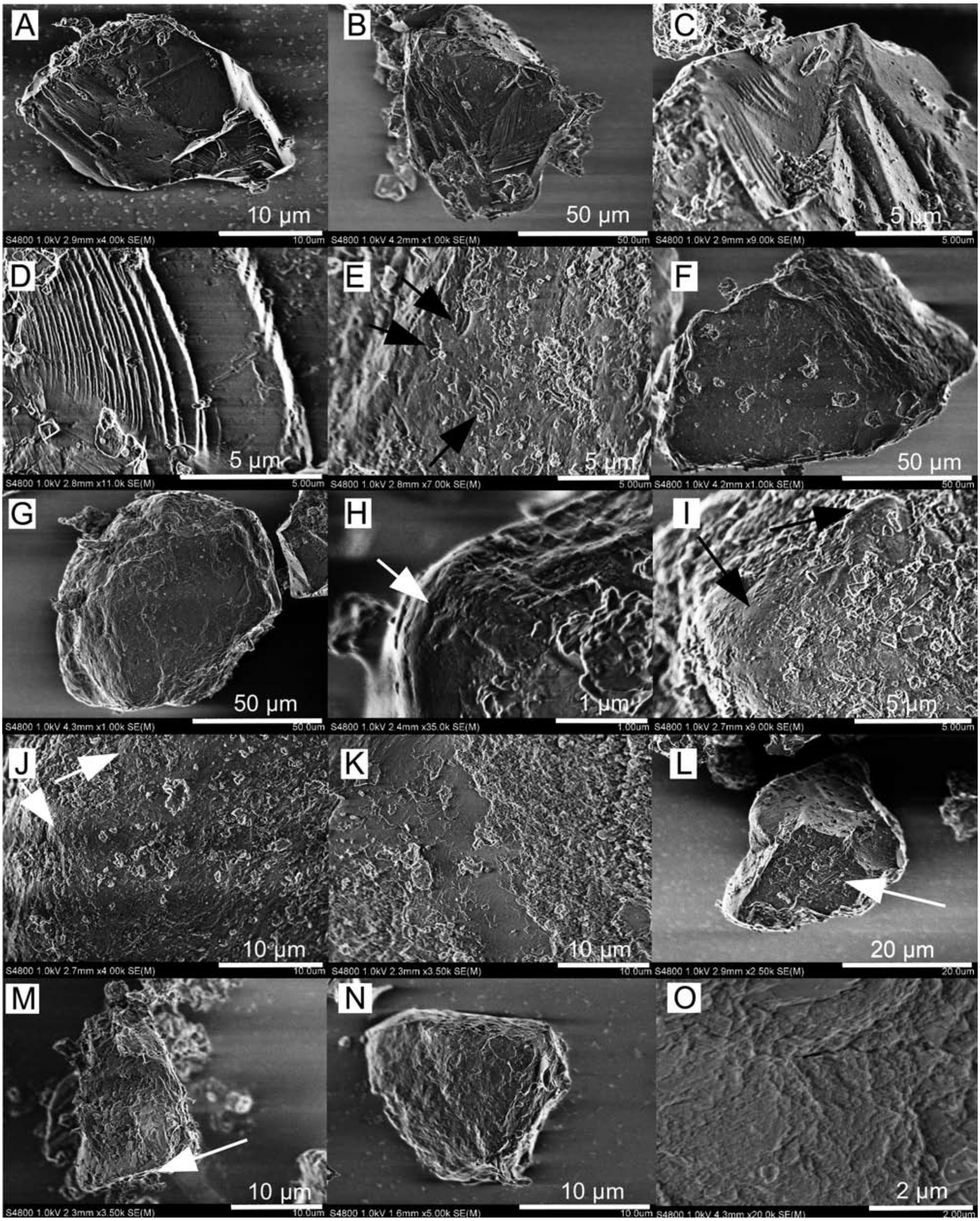

Fig. 4. SEM micrographs of quartz specimens of the investigated cryoconites: (A-B) A-type fresh grains; (C) details of conchoidal feature; (D) subparallel steps; (E) surface with graded arcs (arrows); (F-G) B-type weathered grains; (H) details of grain edge with holes and caverns (arrow); (I-J) mechanically abraded bulbous edges; (K) surface of C-type grain with scaly-grained encrustation; (L-M) E-type cracked grains (arrows show cracked surfaces); (N) D-type grain with bulbous encrustation; (O) details of bulbous encrustation.

between 7–18% (Fig. 3, 4L-M). Grains with bulbous precipitation on their surface (D-type) are either absent or rare (1–2%), except of the K5B, where 6% of D-type grains occur (Fig. 3, 4N-O).

DISCUSSION

In theory, one or a combination of aeolian processes, land-sliding from valley walls and supra-/englacial entrainment may provide sediment onto glacier surface (Lancaster 2002; Macdonell, Fitzsimons 2008; McIntyre 1984). On the ablation zone, as in this study, sediment itself remains a fine powder of dust particles, contrary to the valley glaciers, where the material forming cryoconite holes is often sand or pebbles (Bøggild *et al.* 2010). Previous studies reveal contradictory opinions regarding the origin of fine-grained particles on the Greenland Ice Sheet. Either these particles originate from local wind-transported sources and past-time englacial dust outcropping in the ablation zone (Nagatsuka *et al.* 2016; Wientjes *et al.* 2011) and/or long-travelled dust from distant deserts (Lupker *et al.* 2010; Serno *et al.* 2015; Svensson *et al.* 2000). Others also suggest that only fine-grained minerals originate from long-distanced sources, whereas coarser – from eroded local bedrock (Tepe, Bau 2015). Our study does only partially answer the question whether or not fine-grained particles originate from distant sources. However, we preliminary assume that the investigated quartz particles from the cryoconite holes rather carry a transportation signal originating from numerous but local sources. Additionally, testing material from two cryoconite holes at the same elevation, but located 10 metres apart (K5A and K5B), reveals significant difference in grain type distribution, meaning that holes are independent one another. Through grain observation in SEM, we detect five types of grains that record different environmental signals. We discuss these signals in the following sections.

Glacial grains

Results obtained from an observation of the fine-grained quartz in the SEM, in which fresh (A-type) and cracked (E-type) grains dominate, are consistent with observations of Wientjes et al. (2011), who found that cryoconite quartz in west Greenland reveals triangular-faceted, sharp-edged outline (Fig. 4A-C). Also Yallop *et al.* (2012) reported that angular mineral particles prevail in the cryoconite holes. Our results are also similar to other localities in the world. For example, irregular mineral particles with sharp edges in cryoconites from Svalbard were observed by Edwards et al. (2010) and by Sullivan (1995), and in the Tibetan Plateau by Dong et al. (2016a, 2016b). Likewise, the ash particles taken from Icelandic holes are dominantly characterized by blocky shape with stepped features and clustered clasts (Dragosics *et al.* 2016). Moreover, angular fragments of quartz and other mineral components were detected in the coarser-grained particles (> 62µm) in cryoconite deposits of the Alps (Tomadin *et al.* 1996).

In newly produced grains, sharp edges, conchoidal fractures, microsteps and fracture faces prevail (Jonczak *et al.* 2016), which may result from high-pressure fracturing during glacial transport (Immonen *et al.* 2014; Mahaney 2002; Vos *et al.* 2014) and local origin combined with a recent deposition (Edwards *et al.* 2010; Tomadin *et al.* 1996). Fresh-surfaced grains also likely reflect a severe climate conditions (Sokołowski *et al.* 2009), which is visible, for example, through the sample from the lowest altitude (K6B), where the amount of the A-type grains is the lowest, meaning that frost weathering is less intense than in the inner part of the ice sheet. Our investigated grains owe characteristic posed above, and, therefore, greatly originate from local sources, where grain-to-grain contact in the ice prevail as also concluded by Wientjes et al. (2011). This statement may be additionally supported by a number of cracked (E-type) grains, which result from crushing in glacial environment and frost weathering (Matsuoka 2001; Woronko 2016). Other studies, for example of rare earth elements, also show a local bedrock source in cryoconite samples (Tepe, Bau 2015).

Chemical-induced grains

Not only sharp grains were observed in the investigated cryoconite holes. Among some samples, nearly 50% of grains reveal abraded corners and edges and smooth surface (Fig. 3). Shape of a quartz grain is susceptible to change either by chemical and mechanical processes (Mazzullo 1986). During chemical solution quartz crystal structure is easy etched on its corners and edges (*see details in* Gautier *et al.* 2001 and references therein). Fine-grained particles on a melting ice surface are vulnerable to transport by meltwater (Adhikary *et al.* 2000). Since geochemical properties of meltwater are complex, and numerous solutes are found in it (Sanna, Romeo 2016), quartz grains may be affected by this transportation medium. Studies show that quartz solubility significantly increases in alkaline conditions of pH 9.0 or higher (Dove, Rimstidt 1994), and at pH values lower than 3.5 (Brehm *et al.* 2005). In our study, a general pH environment measured in each cryoconite hole varies between 7.20 and 9.49 (Table 1), and is influenced by the mineral contents and active photosynthesis (Tranter *et al.* 2004). Comparing quartz grains in holes with water of pH>9.0 and pH<9.0, our results indicate ca. 20% more B-type (weathered) grains in holes with water of a higher pH value (Fig. 5). This observation agrees with a statement that the dissolution rate of quartz is maximum above pH 9.0 (Brehm *et al.* 2005), but disagrees with our results of the K6B sample. Although the lowest value of pH (7.20) was measured in this sample, almost half of investigated grains seem to reveal rounded edges and corners. Alkaline conditions do, certainly, not trigger grain rounding in this case, and different agent is responsible for this (*see below*).

Mechanical-induced grains

Mechanical processes seem to play a smaller role in fine-grain rounding (Woronko 2007). However a fairly rapid and an efficient rounding of fine-grained particles under suspension conditions is considered by some studies (Foreman *et al.* 2007; Mazzullo *et al.* 1992; Mazzullo 1986; Werner, Merino 1997). Strong winds (*see* Study area) with a potential of mechanical rounding are a common feature in the Kangerlussuaq area, where wind erosion is an important geomorphic agent (Gillies *et al.* 2009) that removes discrete patches of fine-grained soil and further exposing the bedrock (Heindel *et al*. 2017). Along with our previous research, number of aeolian-origin grains of sand fraction occur in the sediments close to the ice margin (Kalińska-Nartiša *et al.* 2017). Certainly, this wind agent should be considered, and possibly part of our investigated grains were also mechanically abraded. For example, grains of the K6B sample are coarser and reveal edge rounding and bulbous edges on the most concave parts of the grains (Fig. 4I, J). These features are principally attributed to aeolian history (Costa *et al.* 2013; Mahaney 2002; Mahaney *et al.* 2014), thus give evidence for wind transportation.

Periglacial grains

In periglacial environment, quartz grains with scaly-grained cover and very fine mineral particle (C-type according to Woronko (2007) occur, and may be detectable, for example, in glacial streams, which milk colour is due to particles of suspended silica inside (Dietzel 2005). It has been observed that soil solution at specific horizons induces the formation of silicates (Dickinson, Grapes 1997), for example, in young-glacial landscape (Jonczak *et al.* 2016). About 60% of the exposed land surface in the Northern Hemisphere seasonally freezes and thaws (Zhang *et al.* 1999) and polar regions particularly favour repeated freeze-thaw cycles. These cycles further damage of grains (Woronko 2016) thus resulting in deposition of silica is triggered and cause a huge effect on their geochemical and ecological availability (Dietzel 2005).

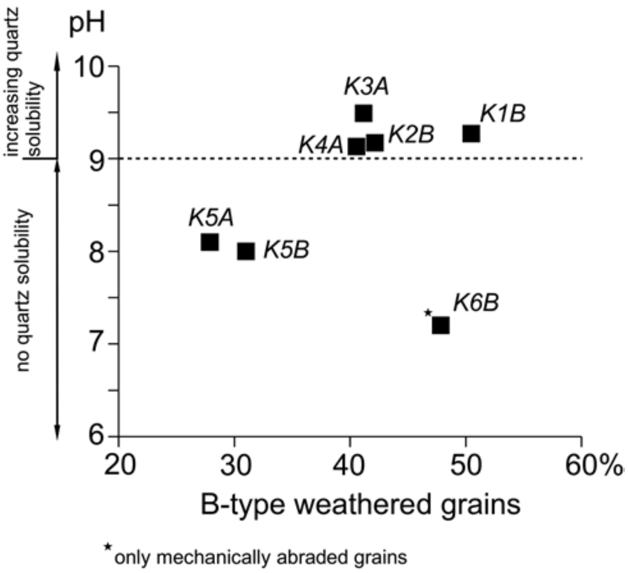

Fig. 5. Biplot of the pH values and percentage occurrence of the B-type weathered quartz grains.

Our study shows a relatively limited number of the C-type grains, however their occurrence is occasionally as high as 25% (Fig. 3). Additionally, encrustation is more or less present at surfaces of practically all investigated grains, for example in tiny microholes and depressions. This clearly argues that a scaly-grained cover results from likely post-sedimentary processes induced by seasonal and daily frost action, since cryoconite holes are frozen during winter and during the night-time. Similar record of freeze-thaw processes can be also found in several palaeoenvironments (Kalińska-Nartiša *et al.* 2015, 2017; Woronko, Pisarska-Jamroży 2016).

Allochthonous (?) grains

Satellite observations (Uno *et al.* 2011) along with isotopic data (Svensson *et al.* 2000) provide strong evidence that fine-grained long-distance particles considerably contribute in mineral deposition in Greenland. The potential source areas are located not only at arid and tropical latitudes (the Sahara and Arabia), but also at higher latitudes, where continental conditions prevail, for example in the Inner Mongolian deserts (Uno *et al.* 2009). In this study, a long-distance signal may be represented by few grains with bulbous incrustation (D-type; Fig. 4O). These rarely observed grains have allochthonous origin, since bulbous silica precipitation is strictly correlated with warm and dry climate conditions, where mineral surface is, at first, etched by highly concentrated, strongly alkaline solutions, followed by silica precipitation in dry periods (Krinsley, McCoy 1978). We can, therefore, assume that these grains originate from distant deserts.

CONCLUSIONS

This study contributes to characterise cryoconite fine-grained quartz from the cryoconite holes of the Russell Glacier, southwest Greenland. By analysing the grain shapes and character of its surface, we decipher sedimentary signals originating from numerous sources.

Irregular, sharp-edged quartz grains prevail in the investigated cryoconites and result from grain-to-grain contact in the ice during glacial transport. Similar sharp grains have been observed in cryoconites elsewhere. Grain rounding is likely due to both chemical and mechanical processes. Under alkaline conditions of pH 9.0 or higher quartz solubility significantly increases, thus rounding grain corners and edges. However, rounded grains are equally present in holes with a lower pH value. These grains reveal abrading by aeolian action, because their edges are bulbous and not affected by etching-induced features. Additionally, part of investigated grains records a postsedimentary frost action, seen as a scaly-grained incrustation occurring on a whole grain surface or at the bottom of negative microforms. Aforementioned grains come from numerous, but local sources. In contrast, few grains with bulbous incrustation are present and they argue for a dry and warm climate origin. These grains may represent long-travelled particles from distant deserts.

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