Sedimentary Geology 335 (2016) 103–119

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Frost weathering versus glacial grinding in the micromorphology of quartz sand grains: Processes and geological implications

Barbara Woronko *

Faculty of Geology, University of Warsaw, ul. Żwirki i Wigury 93, 02-089 Warsaw, Poland

ARTICLE INFO

Article history:
Received 11 November 2015
Received in revised form 24 January 2016
Accepted 25 January 2016

Editor: Dr. J. Knight

Key words:
Quartz grains
Micromorphology
SEM
Periglacial
Frost weathering
Glacial grinding

ABSTRACT

Micromorphology of quartz sand grains is used to reconstruct processes occurring in the glacial environment and to distinguish the latter from other environments. Two processes dominate in the glacial environment, i.e., crushing and abrasion, or a combination thereof. Their effect is a wide range of microstructures on the surface of quartz grains, e.g., chattermarks, conchoidal fractures and multiple grooves.
However, the periglacial environment also effectively modifies the surface of quartz grains. The active layer of permafrost is considered to have a significantly higher contribution to the formation of crushed grains and the number of microstructures resulting from mechanical destruction (e.g., breakage blocks or conchoidal fractures), as compared to deposits which are not affected by freeze–thaw cycles. However, only a few microstructures are found in both environments. At the same time, there are several processes in subglacial environments related to freeze–thaw cycles, e.g., regelation, congelation, basal adfreezing, and glaciohydraulic supercooling. Most likely, therefore, the role of the glacial environment in the destruction of quartz grains has been misinterpreted, and consequently the conclusions regarding environmental processes drawn on the basis of the number of crushed grains and edge-to-edge contacts are erroneous.

1. Introduction

As revealed by the scanning electron microscope (SEM), a range of surface textures and features of quartz grains can be used to identify and understand the erosional, transportation and depositional processes operating in glacial environments (e.g., Krinsley and Doornkamp, 1973; Whalley and Krinsley, 1974; Mycielska-Dowgiałło, 1978; Sharp and Gomez, 1986; Mahaney, 1990, 1995, 2002; Mahaney and Kalm, 1995; Hiemstra and van der Meer, 1997; Evans and Benn, 2004; Strand and Immonen, 2010; Traczyk and Woronko, 2010; Immonen, 2013; Immonen et al., 2014; Molén, 2014; John et al., 2015). The presence of crushed sand grains or edge-to-edge grain crushing are important parameters used to interpret the conditions prevailing in the subglacial environment (e.g., Hiemstra and van der Meer, 1997; Mahaney, 1995, 2002; Tulaczyk et al., 1998; van der Meer et al., 2003; Rose and Hart, 2008; Immonen, 2013; Immonen et al., 2014). However, despite the fact that evidence of sand grain crushing, fracturing and attrition are commonly registered in subglacial environments, the direct observation of these processes is restricted only to microscopic analysis (Evans et al., 2006).

At the same time, grains with similar features can also occur in non-glacial environments, because the same mechanisms responsible for their formation act in different environments (e.g., Margolis and Krinsley, 1974; Sharp and Gomez, 1986; Mahaney, 2002; Molén, 2014; Vos et al., 2014). An example of these can be conchoidal fractures, which are formed as a result of a powerful impact or pressure on the grain surface (e.g., Mahaney, 2002; Immonen, 2013; Immonen et al., 2014; Vos et al., 2014) and are registered on grains from different environments, including aeolian and littoral (Margolis and Krinsley, 1974; Mahaney, 1995, 2002), as well as glacial and periglacial. Besides, most quartz grains of the sand fraction found in glacial deposits have a polygenetic history, and could have taken part in many sedimentary cycles or be shaped in several different environmental settings.

In periglacial environments, the modification of quartz grain microfeatures can also take place, but it is largely ignored in the discussion on the process of quartz grains destruction (e.g., Mahaney, 2002; Vos et al., 2014). Quartz is a mineral of lower resistance to frost weathering compared to, e.g., unweathered feldspar, garnet and muscovite (Konishchev, 1982; Konishchev and Rogov, 1993; French and Guglielmin, 2000; Wright, 2007), and thus can produce large amounts of cracked grains and conchoidal fractures (Woronko, 2012). However, there are many processes based on freeze–thaw events and identified by glaciologists in the subglacial environment, including regelation, congelation, basal adfreezing and glaciohydraulic supercooling. These processes are responsible for basal ice formation (e.g., Weertman, 1957; Lawson et al., 1998; Knight, 1997; Rempel, 2008; Waller et al., 2009; Cook et al., 2011; Creyts et al., 2013) and the increasing consolidation of till (Christoffersen and Tulaczyk, 2003a, 2003b).

---

* Tel.: +48 22 55 40 423; fax: +48 22 55 40 001.
E-mail address: bworonko@uw.edu.pl.

http://dx.doi.org/10.1016/j.sedgeo.2016.01.021

The question of this paper is: are these processes responsible for *in situ* frost weathering of quartz grains in the subglacial environment? Accordingly, a number of issues can be brought up, likely to be of crucial importance in the interpretation of microstructures of quartz grains, originating in both glacial and periglacial environments: (1) to what extent are fractured grains diagnostic of subglacial crushing or can they be inherited from periglacial weathering processes?, (2) do subglacial conditions support frost weathering of quartz grains? and (3) is the role of the glacial environment overemphasized in discussions on the destruction of quartz grains? These issues are also important for the identification of microstructures derived from glacial and periglacial environments. The present study is aimed at providing answers to the above-mentioned questions.

2. Mechanisms of grain fractures and micromorphology of quartz sand grains

2.1. Glacial environment

Subglacial environments are dominated by two comminution processes affecting the micromorphology and surface texture of quartz sand grains, namely abrasion (grinding or attrition) and crushing (fracturing) (e.g., Halderson, 1981; Sharp and Gomez, 1986; Iverson, 1990; Iverson et al., 1996; Mahaney, 1995, 2002; Hart, 2006; Rose and Hart, 2008; Benn and Evans, 2010; Cowan et al., 2014; Immonen et al., 2014).

Efficiency of comminution processes depends on the packing arrangement, size of particles, grain micromorphology and texture (Wright, 1995; Iverson et al., 1996; Hiemstra and van der Meer, 1997), as well as fluctuating pore water pressure in till, which creates changing till rheology ranging from ductile to brittle shear stress (Mahaney, 1995). Fractures and abrasion of quartz grains may predominate in till with low pore water content (Mahaney, 1995), when increasing inter-granular contacts occur within the till, reflected in a fall in porosity and increase in density (Evans et al., 2006).

In experimental studies of lithified materials with a porosity of ca. 21–29%, fracturing of quartz grains was observed at effective pressures of 300–380 MPa (Zhang et al., 1990). In unlithified materials, grain fracturing in granular sediments (more typical of glacial environments) was initiated at noticeably lower effective pressures of 15–75 MPa (Hiemstra and van der Meer, 1997). Moreover, the effective pressure is reduced by zones of weakness such as bubble trails, gas–liquid inclusions, or dislocation patterns along sub-grain boundaries (Whalley and Krinsley, 1974; Mahaney et al., 1988; Hiemstra and van der Meer, 1997; Schwamborn et al., 2012).

Distinguishing between the effects of abrasion and crushing in quartz grains is a difficult task, although Rose and Hart (2008) have shown that crushed grains reveal a 'hand axe' form (Fig. 1A) and are represented by large conchoidal fractures, whereas grains subject to grinding or attrition have a smoothed and rounded form as small 'flakes' (small conchoidal fractures) removed from larger grains (Fig. 1B).

Quartz grains representing the glacial environment display a broad spectrum of microstructures, including (1) directional curved troughs or grooves, (2) crescentic gouges, (3) subparallel linear fractures, (4) arc-shaped steps, (5) chattermarks and (6) different sizes of conchoidal fractures (Fig. 2A-D; Table 1A) and a range of dissolution microfeatures resulting from weathering that occurred prior to glacial entrainment, e.g., in the preceding interglacial. Some of them, e.g., conchoidal fractures or crescentic gouges may develop under high cryostatic pressure during grain-to-grain, grain-to-clast and grain-to-bed interactions in the subglacial environment (Mahaney, 1995, 2002). Others, e.g., directional curved troughs or grooves may arise as a result of vibrational energy released during stick–slip processes and basal sliding and abrasion (Echelmeyer and Wang, 1987; Atkins et al., 2002; Mahaney, 1995, 2002; Van Hoesen and Orndorff, 2004). Stick–slip processes produce high basal shear stress and high strain rate (Barcilon and MacAyeal, 1993). According to Hooke and Iverson (1995), crushing of quartz grains can result from sand 'grain bridges', which are formed when the shear stress exceeds the grain resistance (Iverson et al., 1996). On the other hand, van der Meer et al. (2003, pp. 1673) argue that these types of microstructures "...*have never been observed in any of our thin sections*", adding that skeleton grains (>20 μm in size) in tills are not in contact with each other but are separated by a fine-grained matrix. At the same time, edge-to-edge contact observed in thin section does not always lead to the cracking of quartz grains. Furthermore, these microstructures have been detected in many other sediments and environments (e.g., periglacial) (van der Meer, 1993, 1996; Menzies et al., 2006).

Debris in supraglacial and englacial environments is only slightly modified in the glacial environment. Quartz sand grains from supraglacial and englacial environments are characterized by surface textures such as angular forms or irregular breakage patterns (which are typical textures of quartz sand grains also for subglacial conditions) are "inherited" from the source material as a result of mechanical weathering of the bedrock (Sharp and Gomez, 1986). In turn, in the subglacial environment monomineral quartz sand particles are mostly produced by the crushing of larger particles. Abrasion in the basal part of glaciers does not significantly affect quartz grains because of their relatively large hardness (Mohs hardness of 7, equivalent to an indentation hardness of 671 kg mm^{-2}) (Halderson, 1981). Quartz particles most commonly act as tools, which produce comminution of softer minerals (Sharp and Gomez, 1986); as a result, they may be abraded only by minerals with a hardness exceeding 778 mm^{-2} (Mohs hardness of 7.3, i.e., garnet or zircon) (Halderson, 1981).

From the analysis of quartz sand grains originating from the Saalian and late Vistulian glacial tills of central Poland, Goździk and

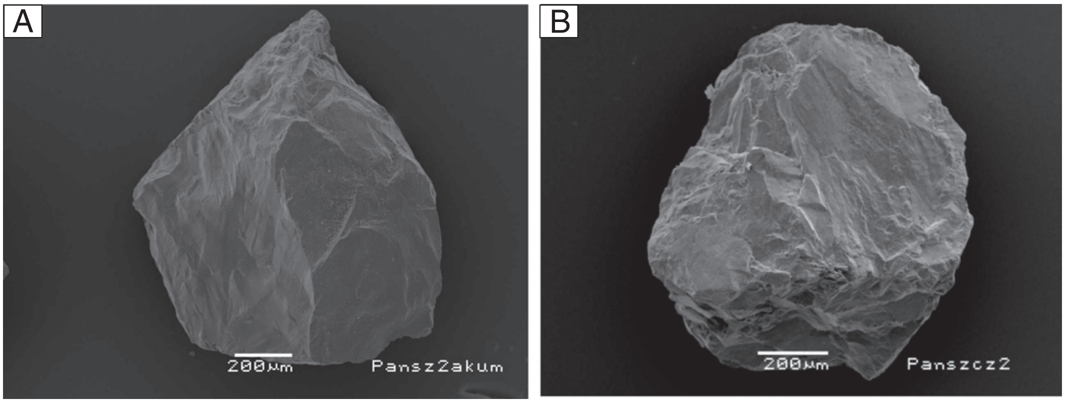

Fig. 1. SEM micrographs of a sand-sized quartz grain surface. (A.) The 'hand axe' form of quartz sand grain. (B.) Isometric form of quartz sand grain as the effect of grinding or attrition.