Sand in Early Holocene lake sediments – a microscopic study from Lake Jaczno, northeastern Poland

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Abstract. Deep moraine lakes prevail in northeastern Poland and their sediments serve as a powerful information about past environment. Apart from conventional organic horizons, the sediments may contain clastic and chemically-induced components such as sand, fines or sulphates, thus providing additional insight into the lake history.

Sand consists primarily of quartz grains and their study is a well-established method to infer palaeoenvironmental conditions. Quartz grains from lacustrine sediments, however, are still poorly studied. We examined for the first time quartz grains found among organic sediment of Lake Jaczno, northeastern Poland, which deposited before ca 10 700 cal yr BP. By applying the light microscope and scanning electron microscope techniques, we debate about the quartz grain source and discuss possible palaeoenvironmental scenarios. Grains with fresh and sharp edges and diagnostic glacial microtextures coexist with rounded grains with matt surface. Loads of glacial grains originate from the surrounding glaciogenic sediments, which were transported from adjacent steep slopes and further deposited in the lake. Grain rounding and matting, combined with oriented etch pits, result from intense weathering processes associated with a high carbonate content. Part of the microtextures of chemical origin may be due to inflow/outflow activity in the lake. Gypsum crystals occur in the uppermost part of the investigated sediment and likely reflect drier climate conditions at the beginning of the Holocene, which has also been documented in numerous sites in northeastern Poland.

Key words: sand, gypsum, scanning electron microscopy, microtextures, glacial grains, chemically-induced grains, weathering.

INTRODUCTION

Lake sediment data serve as a proxy that provides information about past environment (Last & Smol 2001). These are widely used to determine for example water properties, palaeoclimatic events, the history of vegetation and human impact (Battarbee 2000; de Jong et al. 2006). Conventionally, organic sediment horizons including sapropel (Niessen et al. 1992), gyttja (Hoek et al. 1999), dy, peat or freshwater tufa (Pedley 1990) are present in a lake, as a result of the mixing of water plants, plankton and benthic organisms (Vincevica-Gaile & Stankevica 2017). Inorganic components may occur along with the organic accumulation. The most important substances with respect to the biomineralization process are calcium carbonate and its modifications such as calcite, aragonite and vaterite (Qiao et al. 2008), combined with an amorphous phase and several hydrated forms (Fernández-Díaz et al. 2010). Further, chemically-induced processes like the evaporation of pore water may lead to sulphate crystallization (Rydelek 2013). Finally, clastic components such as sand or fines are likely wind-transported. In coastal lakes they may record extreme weather conditions, for example, storm (Szkornik et al. 2008) or tsunami events (Kempf et al. 2017). Inland, sand and dust signals in lake sediments may be interpreted to be sourced from adjacent dunes (Baca et al. 2014) and loess plateau (An et al. 2012) or record colder climate phases and human activity, for example deforestation (Majewski 2014; Margielewski et al. 2015). Additionally, the runoff, soil erosion and allogenic input into the lake basin have been detected during colder periods, and pedogenesis – under the humid, interstadial conditions (Hošek et al. 2017).

Sand sediments consist primarily of quartz (Götze 2009, 2012), which is a durable mineral representing almost all common parent rocks (Basu 1985). Importantly, quartz grain morphology and microtextures on the surface allow the interpretation of sedimentary environments and potential transport mechanisms, since the sedimentary histories are recorded on grains (Krinsley & Doornkamp 1973; Vos et al. 2014). For example, different types of surface microtextures can be used to differentiate between aeolian, marine and glacial depositional environments along with pre- (inherited) and post-depositional processes (Tsakalos 2016). Visualization of single quartz grains is, therefore, an established method to infer palaeoenvironmental processes and conditions that have affected grain history (Nieuwendam et al. 2016). Still, quartz grains found in lake sediments are as yet poorly studied.

Our study focuses on Lake Jaczno in northeastern Poland, where the Late Holocene sediments have recently gained some attention (Tylmann et al. 2013; Weisbrodt et al. 2016; Butz et al. 2017; Poraj-Górska et al. 2017). We explore the sand component found among the organogenic sediments of this lake. The characteristics of quartz grains, as mentioned above, allow us to entirely focus on their shape, surface character and specific microtextures. By using light microscope (= LM) and scanning electron microscope (= SEM) techniques, we decipher sand record in lacustrine deposition and try to answer the research questions about (1) where these grains originate from and (2) what kind of signal these grains exhibit.

STUDY AREA

Formed entirely within the Last Glacial Maximum (Rinterknecht et al. 2005; Marks et al. 2006;), Lake Jaczno belongs to the Suwalskie Lakeland of north-eastern Poland (Fig. 1). Glacial and glaciotectonic processes during the Pomeranian Phase of the last glaciation, dated back to 15.0 ka based on ^{10}Be exposure ages in northeastern Poland (Rinterknecht et al. 2005, 2006) and to ca 17.2 ^{10}Be ka based on the recent recalculation (Hardt & Böse 2016), seriously contributed to a general sediment and landform outline (Ber 2006). Therefore, vivid moraine hills, sandurs, kame terraces, eskers, deep depressions and peatlands occur in the lake catchment (Ber 1965) where Quaternary deposits are up to 281.5 m thick (Ber 1968). Lake Jaczno is an example of a deep moraine lake, which was formed due to the melting of a dead ice block, similar to the majority of lakes in northern Poland (e.g. Gałka & Sznel 2013; Słowiński et al. 2015; Mendyk et al. 2016). The total area of the lake is 40.64 ha with a maximum water depth of 25.7 m (Borowiak et al. 2016). Three permanent inflows and one outflow, combined with several groundwater springs, feed and drain Lake Jaczno. The present trophic status of the lake is stated as mesotrophic

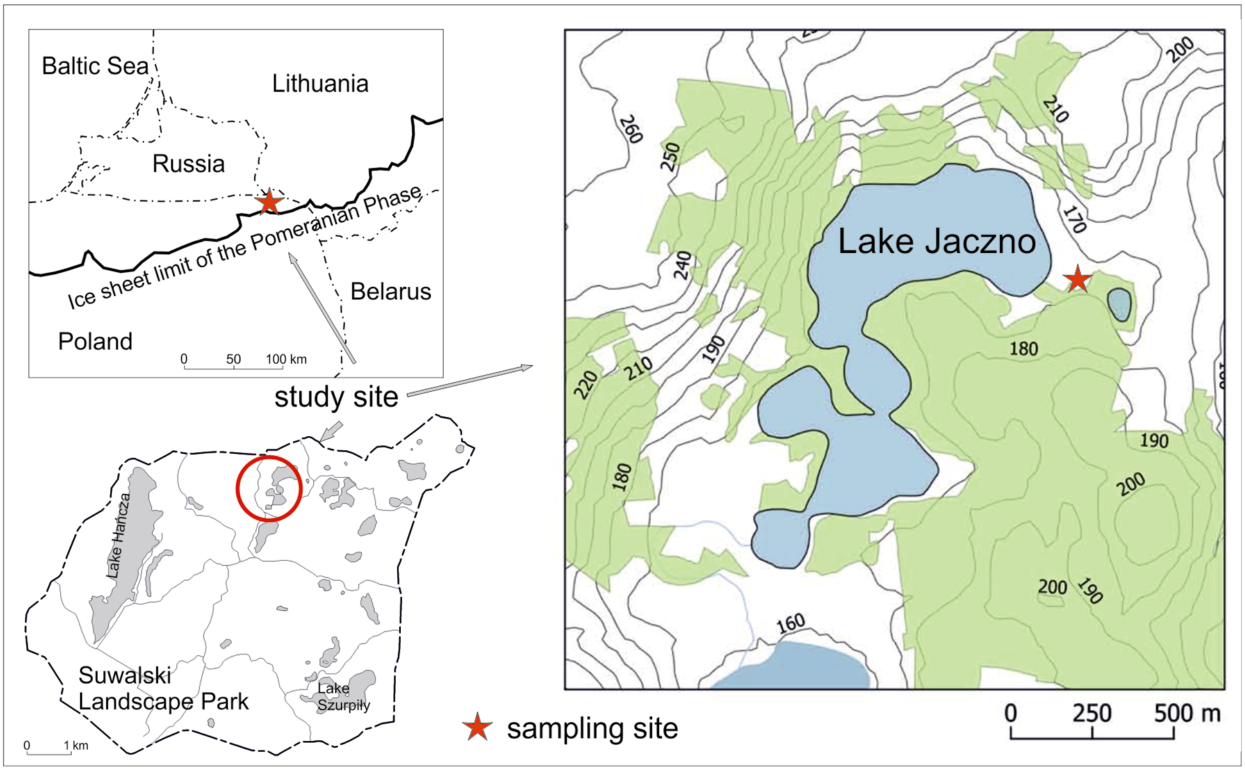

Fig. 1. Location of the study area.

Table 1. Sediment lithology of the lowermost core section from Lake Jaczno

Depth (cm)	Sediment description
315–322	Calcareous gyttja with plant macrofossils and mollusc shells
322–339.5	Detritus-calcareous gyttja with plant macrofossils and mollusc shells
339.5–346	Coarse detritus gyttja and sand grains
346–365	Sand

with low fertility (Górniak et al. 2016). Sediments of the lake are largely laminated and composed of the alternation of diatom, calcite, amorphous organic matter and detrital matter (Tylmann et al. 2013). In this study, geological drilling was performed in the peatland between Lake Jaczno and a small unnamed lake (Fig. 1), which previously constituted a bigger lake. The sediment sequence contains gyttja with a variable mineral matter content. Sand occurs in the bottommost part of the profile (for details see Table 1).

MATERIAL AND METHODS

The geological drilling and sampling of the cores for laboratory analyses were performed in 2008 with a Russian peat corer, 5 cm in diameter and 50 cm in length. The lowermost sections of the sediments were sampled and placed in PVC tubes. In the laboratory, the sediment was unpacked, cleaned and cut into 1 cm slices for detailed palaeoecological analyses, which will be presented in a separate paper.

One Accelerator Mass Spectrometry (AMS) radiocarbon date (JJacz I 339-340) was measured on hand-picked plant macrofossils (needles of *Pinus sylvestris*, fruits and fruit scales of *Betula* sect. Alba) of the 339–340 cm sample (Fig. 2). Radiocarbon dating was undertaken at the Poznań Radiocarbon Laboratory (Poz-86188). The calibration of the radiocarbon date was performed with OxCal 4.1 software (Bronk Ramsey 2009).

Samples of mineral material were collected from five depths of the investigated profile: 341–342, 342–343, 344–345, 345–346 and 348–349 cm after preparing them for plant macrofossil analysis. The samples were sieved under warm running water on sieves with 0.20 mm mesh size. The material was dried at room temperature prior to analysis. Mineral grains were randomly picked up under the LM with a 40–50-time magnification. A total of 101 to 115 mineral grains per sample were analysed.

Quartz grains were classified into one of the following groups according to the recommendations of Mycielska-Dowgiałło & Woronko (1998), in which both grain roundness and surface are considered. Seven groups of grains were distinguished: (1) well-rounded and matt across the whole surface, (2) partially rounded and matt only in the most convex part of the grain, (3) well-rounded and shiny grains, (4) partially rounded and shiny grains, (5) grains with a fresh surface and sharp edges and corners, (6) broken grains with at least 30%

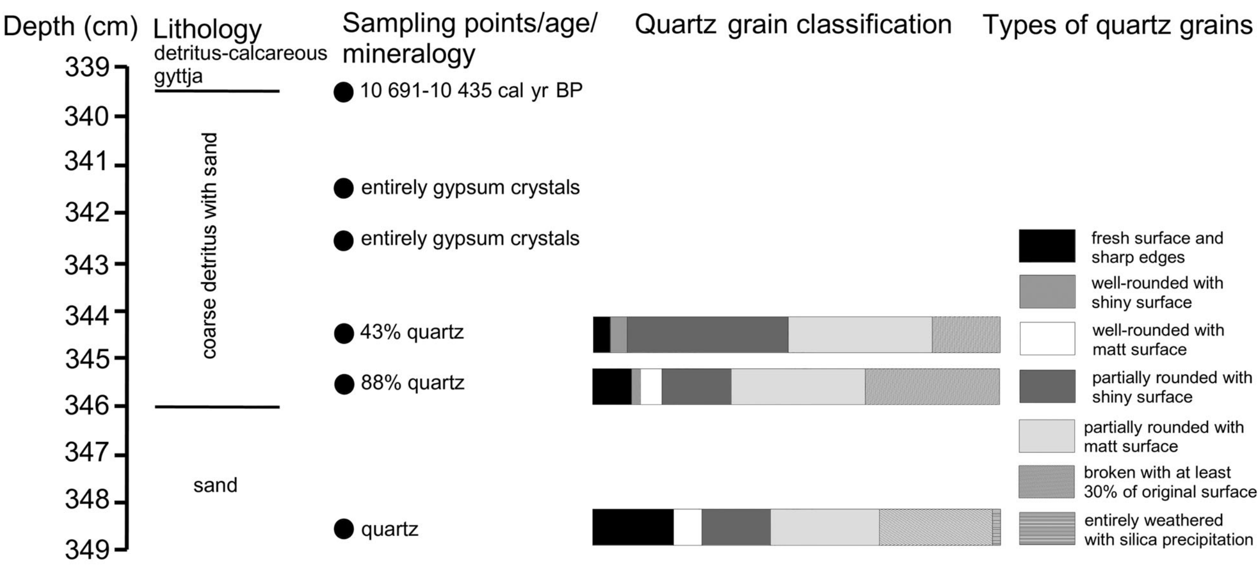

Fig. 2. Lithology, sampling point and quartz grain classification of the investigated samples (according to Mycielska-Dowgiałło & Woronko 1998 analysis) observed with the light microscope.

of the original grain surface affected and (7) entirely weathered by silica precipitation.

Energy dispersive spectrometer (EDS) analysis was used to determine the elemental concentration for an individual pixel and to distinguish gypsum minerals. The SEM analyses of 100 quartz grains and gypsum crystals (20 grains/sample) were performed using the Zeiss EVO MA 15 SEM at the Department of Geology, University of Tartu. Grains were randomly selected and positioned onto a double-sided carbon tape on top of a specimen holder. The general grain outline and surface microtextures were determined by using ×300–400 and ×800–1200 magnification, respectively. Quartz microtextures were classified following the methodology of Mahaney (2002) and further semi-quantified based upon their occurrence as abundant (>75%), common (50–74%), medium (26–49%), sparse (6–25%), rare (<5%) and not observed, partially following the recommendation of Vos et al. (2014). Microtextures of mechanical origin were further grouped as resulting from high-stress, percussion and polygenetic origin according to recommendation of Sweet & Soreghan (2010), and the ratio of fluvially to glacially induced microtextures (F/G) was calculated (for details see Sweet & Brannan 2016).

RESULTS

The radiocarbon date shows that sediment with the studied sand grains was accumulated before ca 10 700 cal yr BP (Fig. 2), assuming that no interruptions or sediment mixing took place (see the 'Discussion' section).

In the two uppermost samples, only crystals of authigenic gypsum are entirely observed (Fig. 3A–C, F), occasionally with silica precipitation (Fig. 3D) and deep crevasses (Fig. 3E) on their surfaces. Lower in the profile (in samples 344–345 cm and 345–346 cm), both gypsum (57% and 12%, respectively) and quartz (43% and 88%, respectively) occur (Figs 2, 4A). In the bottommost sample (348–349 cm), no gypsum was found and mostly quartz grains are present (Figs 2, 4B).

As observed under the LM, broken and fresh grains (28% and 20%, respectively), combined with partially rounded matt (27%) and shiny (17%) grains, dominate among the investigated quartz grains. In contrast, partially rounded matt grains and broken grains are the most important elements in the 345–346 cm sample, both constituting up to 29% (Fig. 2).

The SEM observations favour the occurrence of sub-rounded quartz grains (medium and common occurrence: 40–55%; Figs 4C, D, 5), followed by rounded (medium occurrence: 35–40%; Figs 4E–G, 5) and angular grains (rare to sparse: 5–20%; Figs 4H, I, 5). Rounded quartz grain surfaces display common and abundant micro-textures resulting from mechanical abrasion (bulbous edges; 65–90%; Figs 5, 6A) and chemical processes (solution pits; 70–100%; Figs 5, 6B) which are present in most of the investigated quartz grains. Also adhering particles (Fig. 6C) and precipitation (Fig. 6D) are found on most of the grain surfaces (Fig. 5). The SEM analysis revealed a number of dulled surfaces (from medium to

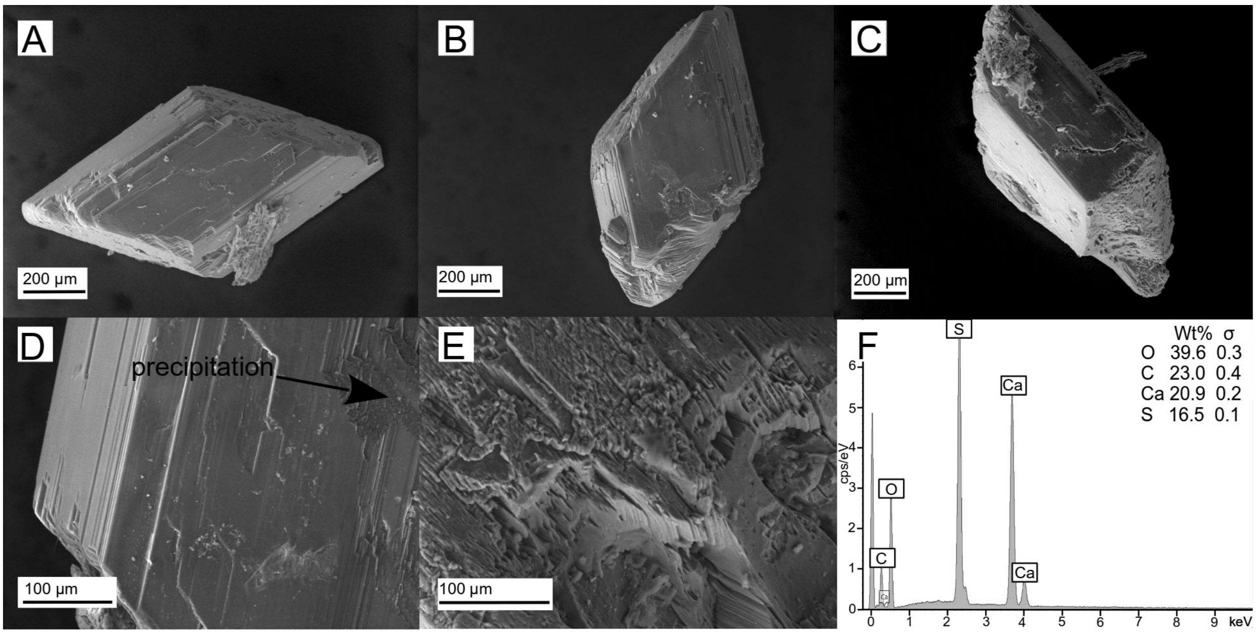

Fig. 3. SEM micrographs of gypsum crystals. **A–C**, general gypsum outline; **D**, details of gypsum surface with precipitation; **E**, deep pits and crevasses on gypsum surface; **F**, EDS spectrum for gypsum.

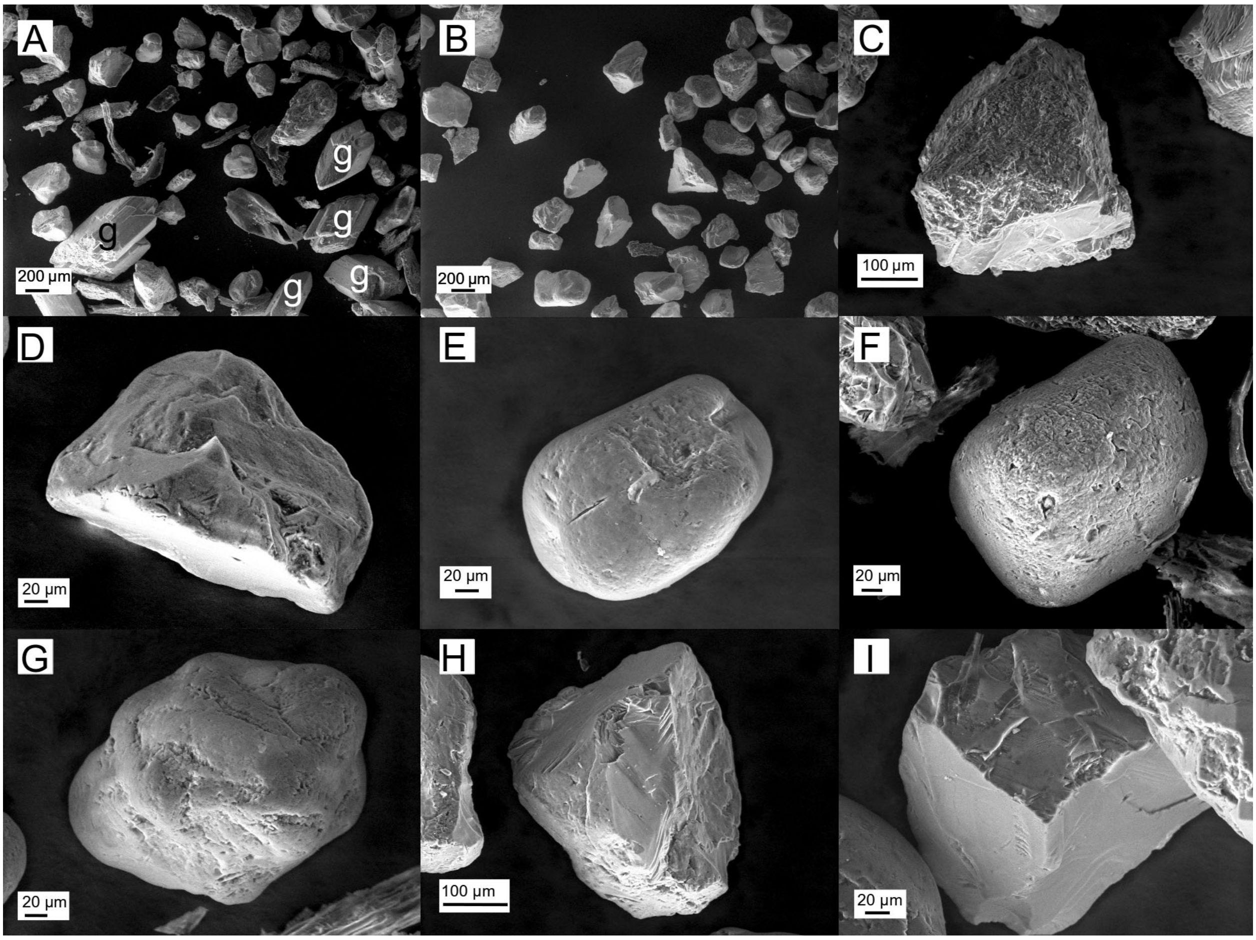

Fig. 4. Explanatory images of gypsum and quartz-sand grain types observed under SEM. **A**, gypsum (g) and quartz from the 345–346 cm sample; **B**, quartz from the 348–349 cm sample; **C**, **D**, subrounded quartz grains; **E**–**G**, rounded quartz grains; **H**, **I**, angular quartz grains.

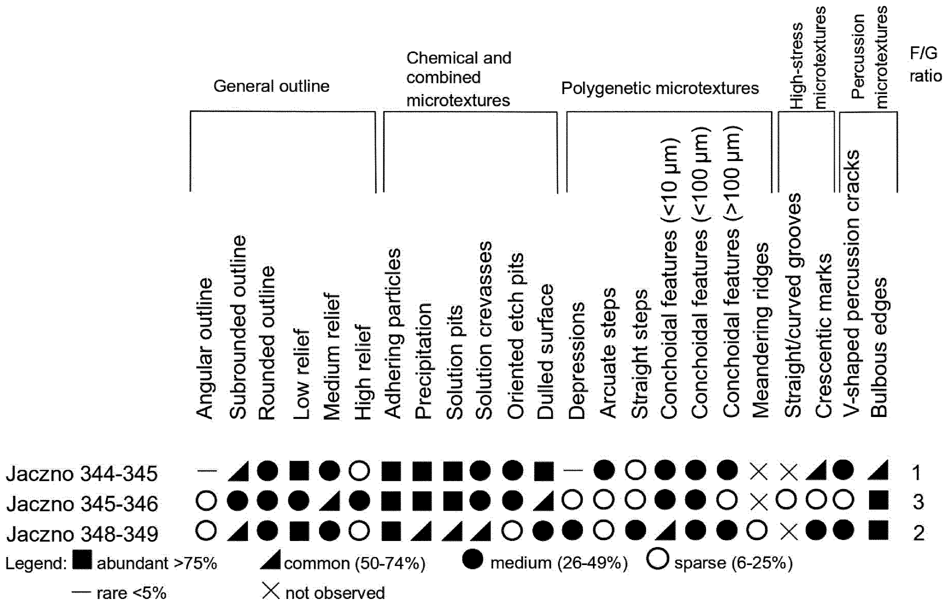

Fig. 5. Frequency of microtextures observed on quartz surface.

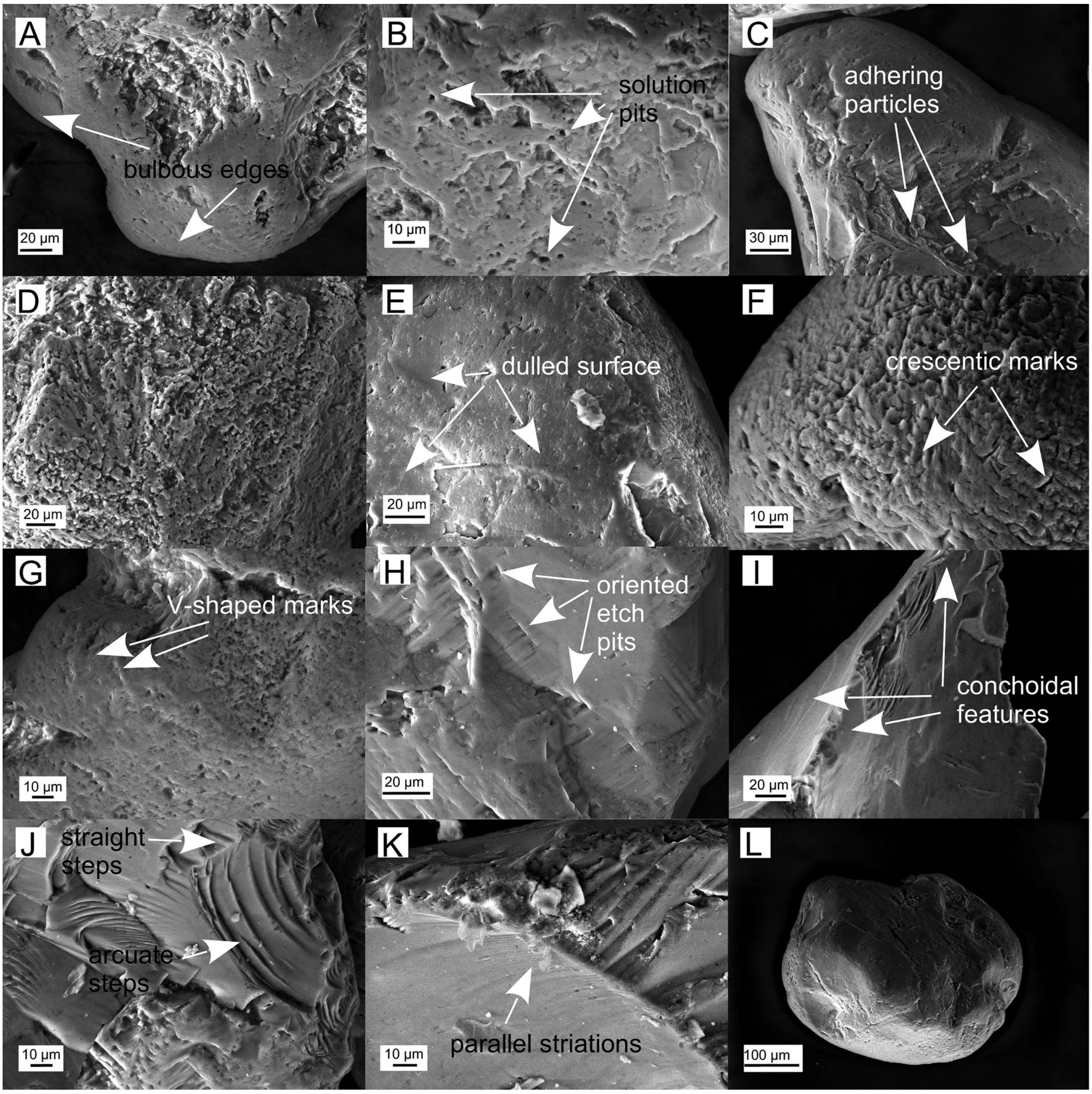

Fig. 6. Explanatory images of quartz surface microtextures observed under SEM. **A**, bulbous edges; **B**, solution pits; **C**, adhering particles; **D**, intense precipitation; **E**, dulled surface; **F**, crescentic marks; **G**, V-shaped percussion marks; **H**, oriented etch pits; **I**, conchoidal features; **J**, straight and arcuate steps; **K**, parallel striations; **L**, low grain relief.

abundant: 40–90%; Figs 5, 6E), sometimes accompanied by crescentic marks (sparse to common: 25–65%; Figs 5, 6F), V-shaped percussion marks (sparse and medium: 20–30%; Figs 5, 6G) and oriented etch pits (sparse and medium: 10–30%; Figs 5, 6H). Conchoidal features of various sizes (Figs 5, 6I), along with straight and arcuate steps (Figs 5, 6J) and parallel striations (Figs 5, 6K), occur on angular and sometimes on subangular grains. The investigated grains carry all types of relief, however, low relief prevails (medium and abundant: 35–55%; Figs 5, 6L). The group of mechanical microtextures of polygenetic origin dominates in all investigated samples, varying between 47% and 53%, followed by the group of percussion (28–39%) and high-stress textures (14–19%). The F/G ratio varies between 1 and 3 (Fig. 5).

DISCUSSION

Our microscopic study revealed two primary signals on the sand grains in the organogenic sediments of Lake Jaczno, which are strongly related both to the processes in the lake and its catchment likely before ca 10 700 cal yr BP. We know that (1) grains with fresh and sharp edges and corners and (2) somewhat rounded grains with matt surfaces coexist, and these are likely associated with glacial processes and chemical solution, respectively. We discuss possible scenarios in the following sections.

Gypsum crystals are, in contrast, often associated with arid conditions in saline lakes (Grimm et al. 2011), when precipitating directly from the water column (González-Sampériz et al. 2008) or attributed to the gypsum occurrence in the watershed (Apolinarska et al. 2012). Nevertheless, gypsum signal may also be common in, for example, peat bog sediments (Kalaitzidis & Christanis 2003; Skreczko et al. 2015) likely due to pH changes (Rydelek 2013) or lower water table episodes (Śmieja-Król & Fiałkiewicz-Kozieł 2014). Gypsum origin is unknown at Lake Jaczno, thus two scenarios are proposed. In the first scenario, gypsum may have formed as a secondary mineral in postsedimentary recrystallization, because an abundance of calcite matter has been observed in lake sediments of the region (Tylmann et al. 2013). The second scenario favours gypsum precipitation as an indicator of a low water table episode, which has been recorded in numerous lakes of northeastern Poland in the Early Holocene (Gałka et al. 2015). If this is the case, gypsum from Lake Jaczno seems to be another evidence for a dry and warm climate at the beginning of the Holocene related to the influence of continental air masses (Lauterbach et al. 2011). No dating has been performed for the bottommost sand horizon, meaning that this horizon may have been accumulated, for example, during the cold Younger Dryas. Following this assumption, the Younger Dryas–Holocene boundary should have been recorded in the investigated profile, likely with a hiatus, whose occurrence is supported by an increase in gypsum crystals in coarse detritus gyttja (Fig. 2).

Glacial grains

Our results, as obtained from the LM, stay in agreement with a general statement that sharp, angular-shaped grains without overgrowths are produced by glacial grinding, crushing and attrition (Krinsley & Doornkamp 1973; Mahaney 2002; Vos et al. 2014), and these grains may dominate in sediments of the recently glaciated areas (Hart 2017; Mazumder et al. 2017). Along with the angular grain outline, grain-to-grain contact in ice results in the occurrence of straight and curved grooves, deep troughs, crescentic marks on the grain surface and a general high grain relief (Mahaney 2002; Chakroun et al. 2009; Sweet & Brannan 2016). Our SEM study shows that some of these diagnostic glacial microtextures occur on grain surfaces, as seen from a limited occurrence of grooves, relatively large number of crescentic marks, high grain relief and a certain proportion of high-stress microtextures (see the 'Results' section). Since a nearly 7.5 ka time span occurs between the latest glacial event in the investigated area and sediment deposition in the lake, a load of glacial grains must originate from the surrounding glaciogenic sediments, which became a solid source of glacial quartz grains. Unconsolidated mineral material must have been transported from adjacent steep slopes and further deposited in the lake. Similar material runoff from the slopes due to rapid changes in temperature and vegetation cover has been noted in lake sediments in Poland during the Late Glacial (Karasiewicz et al. 2014; Marks et al. 2016) and in Holocene spring-fed fen deposits accumulated on the hill slope in northeastern Poland due to shifts in climate humidity (Apolinarska & Gałka 2017). In Lake Jaczno, similar clastic material occurred later, during the Late Holocene, and its major source may have resulted either from the catchment topography as episodic streams or surface inflow as observed by Tylmann et al. (2013). Considering the general geological situation of the investigated site, where both glacial and glaciofluvial deposits are found, we assume that quartz grains should additionally carry a fluvial imprint. This might be somehow visible through the occurrence of the V-shaped percussion marks, which are generally accepted fluvial grain-to-grain collision micromorphological features (Krinsley & Donahue 1968; Vos et al. 2014; Křížek et al. 2017). Yet, the F/G ratio reveals that the number of microtextures induced by fluvial impact is either as high as of these induced by glacial environment or 2–3 times higher. These values are similar to those of some recent glaciated areas, where glacial and fluvial processes coincide (Sweet & Brannan 2016). The number of glacially-induced grains drastically decreases towards the top of the investigated profile, meaning that slopewash processes stopped and the glacial source was surely hampered, most probably due to a denser vegetation cover in the lake catchment during the Early Holocene (Lauterbach et al. 2011; Gałka et al. 2014).

Chemically-induced grains

Matt and rounded grains, as observed through the LM analysis in this study, are normally attributable to intense aeolian abrasion (Krinsley & McCoy 1978; Seppälä 2004) and occur abundantly in sediments of the Late Glacial–Holocene time frame in Poland (Woronko et al. 2015; Kalińska-Nartiša et al. 2016, 2017a). However, not only aeolian abrasion, but also chemical solution may lead to grain rounding and matting (Kuenen & Peredok 1962). Certainly, this is the case in our study, since a closer look at grain surface in the SEM shows that most of the surfaces are intensively silica precipitated with numerous solution pits and crevasses. This proves that the quartz grains were exposed to chemical weathering (Vos et al. 2014; Křížek et al. 2017), which is likely related to the fact that in situ sediments have lain in a depositional basin for a long time (Udayaganesan et al. 2011). Combining these observations with the presence of etching oriented along the crystallographic planes (= oriented etch pits) on some quartz grain, we can state that extreme weathering took place in the lake (Mahaney et al. 2010). Normally, perfectly oriented etch pits are the product of alkaline fluids such as seawater (Bull 1981), which is related, for example, to low-energy marine environments (Margolis & Kennett 1971) and observed in mineral grains of many coastal sediments (Varghese et al. 2016; Achab et al. 2017; Kalińska-Nartiša et al. 2017b). In our study, oriented pits may be associated with high carbonate conditions (Magee et al. 1988; Chakroun et al. 2009). Bearing in mind the 5–15% carbonate content, which has been reported for various Pleistocene tills and glaciofluvial sands in Poland (Bukowska-Jania & Pulina 1999), carbonates likely originate from the lake catchment. However, the study on the adjacent Lake Hańcza has shown that endogenic calcite formed between 11 250 and 9400 cal yr BP (Lauterbach et al. 2011), thus marking high lake productivity in response to increased temperatures (Kelts & Hsü 1978).

Apart from the mentioned weathering processes, various chemical microtextures such as silica precipitation, forms of etching and quartz crystal overgrowths have also been observed on fluvial quartz grains by Cremer & Legigan (1989). Such a scenario may also be valid in this study, considering the presence of inflows and outflows in Lake Jaczno combined with a general dominance of fluvial microtextures atop grain surface (see F/G ratio in Fig. 6). Contrary to glacial grains, the proportion of chemically-induced grains stays approximately at the same level between 344 and 349 cm of the lake profile. This means that intense weathering in the basin was relatively constant over the time and correlated with enhanced carbonate conditions and/or fluvial activity in the Early Holocene.

CONCLUSIONS

The study of the sand component found among the organogenic sediments of Lake Jaczno in northeastern Poland allows of a better understanding of palaeoenvironmental conditions. It helps to find an answer to the research question about sand origin.

Sediment deposition took place in the Early Holocene before ca 10 700 cal yr BP. Two groups of quartz grains dominate in the investigated deposits. Grains with fresh and sharp edges and corners with diagnostic glacial microtextures on the grain surface originate from the surrounding glaciogenic sediments. These must have been transported from adjacent steep slopes and further deposited in the lake. Yet, quartz grains carry a fluvial imprint, since glacial and glaciofluvial deposits co-occur in the investigated area. The slopewash processes surely stopped at some point, since no glacially-induced grains have been observed in the topmost part of the investigated profile. In contrast, the second group consists of matt and rounded grains, with etching oriented along the crystallographic planes on their surfaces resulting from intense weathering likely associated with a high carbonate content. Nevertheless, numerous chemical microtextures may also be related to fluvial activity.

Gypsum crystals, which are abundant in few investigated samples, have either formed as a secondary mineral in postsedimentary recrystallization or mark a low water table, thus drier climate conditions at the beginning of the Holocene.

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Liiv paleokeskkonna indikaatorina Vara-Holotseeni järvesetetes – Jaczno järv Poola kirdeosas

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Kirde-Poolas domineerivad sügavad glatsiaalse tekkega järved, mille setted on väärtuslikuks paleokeskkonna arhiiviks. Lisaks mattunud orgaanikakihtidele esineb neis keemiliselt tekkinud komponente liiva, aleuriiti ja sulfaate, mis lisavad infot järve arengu kohta. Liivas on valdavalt kvartsiterad, mille hästi väljatöötatud uurimismeetodid on paleokeskkonna uuringutes laialt kasutatavad. Samas on kvartsiterade uuringud järvesetetes olnud tagasihoidlikud. Käesolevas artiklis on esmakordselt uuritud liiva fraktsiooni kvartsiteri Jaczno järve orgaanikarikkas setteintervallis, mille vanus on rohkem kui 10,7 cal ka BP. Kasutades valgus- ja elektronmikroskoopi, on arutletud kvartsiterade päritolu ning transpordi ja võimalike paleokeskkonna stsenaariumide üle. Murtud pindade ja teravate servade ning iseloomulike glatsiaalsete mikrostruktuuridega terad eksisteerivad koos hästi ümardunud mati pinnaga kvartsiteradega. Nende lähtematerjaliks on glatsiaalsed setted järve ümbritsevatel suhteliselt suure kaldega nõlvadel. Terade ümardatust, mattide pindade ja orienteeritud söövitusjälgede kujunemist seostatakse suurest karbonaatide sisaldusest tuleneva intensiivse porsumisega. Samas peetakse võimalikuks, et osaliselt pärinevad terade mikrostruktuurid ka setteosakeste transpordist. Suurenenud kipsikristallide sisaldust uuritud setteintervalli ülemises osas seostatakse Holotseeni alguse kuivema kliimaga, mida on järeldatud ka paljudes varasemates uuringutes Poola kirdeosast.