Geological Quarterly, 2018, **62** (4): 917–924
DOI: http://dx.doi.org/10.7306/gq.1448

Dumpstones as records of overturning ice rafts in a Weichselian proglacial lake (Rügen Island, NE Germany)

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Pisarska-Jamroży, M., Van Loon, A.J., Bronikowska, M., 2018. Dumpstones as records of overturning ice rafts in a Weichselian proglacial lake (Rügen Island, NE Germany). Geological Quarterly, **62** (4): 917–924, doi: 10.7306/gq.1448

Associate editor: Wojciech Granoszewski

Dumpstones and dropstones up to 0.8 m in size occur in a silty/sandy Weichselian glaciolacustrine succession near Dwasieden on Rügen Island in the SW Baltic Sea (NE Germany). The deposits are exceptional because two levels of dumpstones and dropstones are present, suggesting two dumping phases interrupting characteristic fine-grained glaciolacustrine sedimentation. Plastic downwarping of sediments below the dumpstones and dropstones result in soft-sediment deformation structures. The distribution and orientation of the long axes of the clasts are useful tools for the reconstruction of the state of the lake bottom, as well as for the water depth. The horizontal position of the gravels and boulders (parallel to the bedding) suggests deposition in relatively shallow-water. The dumping events are linked to iceberg rafting in a glacial lake during the Weichselian Glaciation (MIS 2).

Key words: dumpstones, dropstones, ice-rafted debris, Weichselian, glaciolacustrine sediments.

INTRODUCTION

Icebergs and ice rafts are free to float in lakes and seas under the influence of the wind and/or currents. Iceberg rafting is a common process in contemporary polar regions (Cowan et al., 1997; Smith and Andrews, 2000; Dowdeswell et al., 2000; Hass, 2002; Menzies, 2002) and was common also during the Pleistocene glaciations (Dowdeswell et al., 2000; Kalm and Kadastik, 2000; Menzies, 2002; Błaszkiewicz and Gruszka, 2005; Williams et al., 2008; Ampaiwan et al., 2009; Yorke et al., 2012; Le Heron, 2015; Livingstone et al., 2015).

Single large icebergs can carry many thousands of particles of all sizes; these are dispersed within the ice and are jointly called “ice-rafted debris” (IRD) (Hoffman and Schrag, 2002). These particles are released when the ice melts. Most IRD released from icebergs is sand-sized, but often there are also larger particles (Hass, 2002).

ICE-RAFTED DEBRIS

Melting of the subaqueous part of a floating ice mass results in the release of sedimentary particles that are embedded in the ice. They sink through the water column and accumulate on the surface of the sea or lake bottom, which most commonly consists of fine-grained sediments. The main process involved in the release of IRD is melting of the ice. Most melting occurs subaqueously, due to thermal subrosion caused by the above-zero temperature of the ambient water. Subaerial melting results in a concentration of IRD on the – commonly irregular – surface of the iceberg.

The grain size distribution of IRD within a sediment depends on the properties of the source material, but the characteristics of deposited IRD also depend on depositional processes such as sorting during settling and winnowing, for instance by wave action and currents, within the water column and at the bottom (e.g., Anderson et al., 1980).

DEPOSITS WITH IRD

IRD can be set free from icebergs or ice rafts in different ways, and there are consequently also different depositional processes involved. The result is that different types of deposits, consisting either exclusively of IRD or of dispersed IRD in autochthonous sediments, can originate.

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Received: May 17, 2018; accepted: September 21, 2018; first published online: December 21, 2018

The released clasts that sink through the water column can, if large enough, easily deform the water-saturated fine-grained sediments that commonly are present at the bottom of an ocean or lake. They can partly or completely penetrate, and occasionally even rupture, the bottom sediments. When a mass of particles is jointly released from an iceberg as a result of overturning or a gravity flow, a chaotic (sometimes large) dump structure is formed (Miller, 1996).

The deposits that consist of – or contain – IRD have been studied by researchers in different disciplines (e.g., Quaternary geologists, marine geologists, climatologists, sedimentologists). The result is that different terms have been used for the various types of such deposits, which has occasionally led to confusion. We therefore indicate in the following two subsections which terms are applied to indicate the dropstone and dumpstone deposits under study here.

DROPSTONES

Dropstones have been described frequently from both glaciolacustrine and marine deposits (e.g., Leckie et al., 1995; Bennett et al., 1996; Smith and Andrews, 2000; Van Loon et al., 2016). They are formed when particles (commonly pebble-sized or larger, as smaller particles cannot always be distinguished from the autochthonous sediments) are released from the subaqueous part of an iceberg by thermal subrosion.

Commonly floating icebergs move so fast, under the influence of currents, that only scattered dropstones occur in the autochthonous sediment. Yet, the total amount of dropstones left by a passing iceberg can be so large that the pathway followed by the iceberg can be traced. This is well-known from, among other features, the Heinrich events that left abundant IRD on the floor of the Atlantic Ocean (Heinrich, 1988; Dowdeswell et al., 1995; Eyles et al., 1997; Hesse and Khodabakhsh, 2016).

Pebble-sized and larger IRD can commonly be recognized as dropstones if they deform underlying laminae. Granules are also called dropstones when their size is larger than the thickness of the strata in which they are embedded (Haarland et al., 1966; Menzies, 2002).

The dropstones found in the glaciolacustrine deposits under study here are described in a following section.

DUMPSTONES

A special situation exists when an iceberg or ice raft becomes unstable because of asymmetrical thermal subrosion of the subaqueous part or – less commonly – by continuous melting of one side of the subaerial part under the influence of solar irradiation. In such a case, the iceberg can suddenly tumble over. The particles set free on the irregular ice surface then are jointly released, which may result in uncommonly high concentrations of IRD – occasionally even in the form of stone heaps – on the lake or sea-floor.

The thus-formed clusters of IRD create lens-shaped beds of coarse deposits and have been called "berg dumps" and "dumpstones" (Thomas and Connell, 1985). They have also been described as "iceberg overturn deposits" (see Gilbert, 1990; Woodworth-Lynas and Dowdeswell, 1994; Cowan et al., 1997; Dowdeswell et al., 2000), "palimpsest lags" (Powell, 1984), "gravel pods" (Yorke et al., 2012), "iceberg dump tills" (if the coarser particles are deposited together with melt-out diamictons), "rain-out diamicts" (Brodzikowski and Van Loon, 1991), "dropstone diamictons" and "dropstone mud" (Benn and Evans, 1998). Dumpstones have only fairly rarely been described, among others by Woodworth-Lynas and Dowdeswell (1994), Bennett et al. (1996), Mokhtari Fard and Van Loon (2004), and Ampaiwan et al. (2009). Descriptions of dumpstones that originated in a glaciolacustrine setting are even rarer; they are commonly considered as an important indicator of an ice-contact calving margin (e.g., Cowan et al., 1997; Yorke et al., 2012), and are typical of ice-contact lakes (Brodzikowski and Van Loon, 1991).

The process responsible for the deposition of such sediments is commonly called a "dumping event" (Dowdeswell and Murray, 1990). Following this usage, we adopt the term "dumpstones" to indicate such types of deposits. They form the main subject of the present contribution and will be described and analysed in a following section.

SEDIMENTARY AND STRATIGRAPHICAL CONTEXT

The glaciolacustrine deposits under study are exposed in a coastal cliff near Dwasieden (Germany), on Rügen, an island in the southwestern part of the Baltic Sea (Fig. 1). The deposits form part of a Saalian and Weichselian succession; the deposits on which we focus here have been dated by OSL as Weichselian (Steinich, 1992; Krbetschek, 1995; Ludwig, 2006; Ludwig and Panzig, 2010).

The Weichselian Glaciation in Northern Germany is divided into three main phases (Liedtke, 1981), viz. (1) the Brandenburgian Phase, between 24 and 20 ka (Heine et al., 2009; Kenzler et al., 2015, 2017), (2) the Pomeranian Phase,

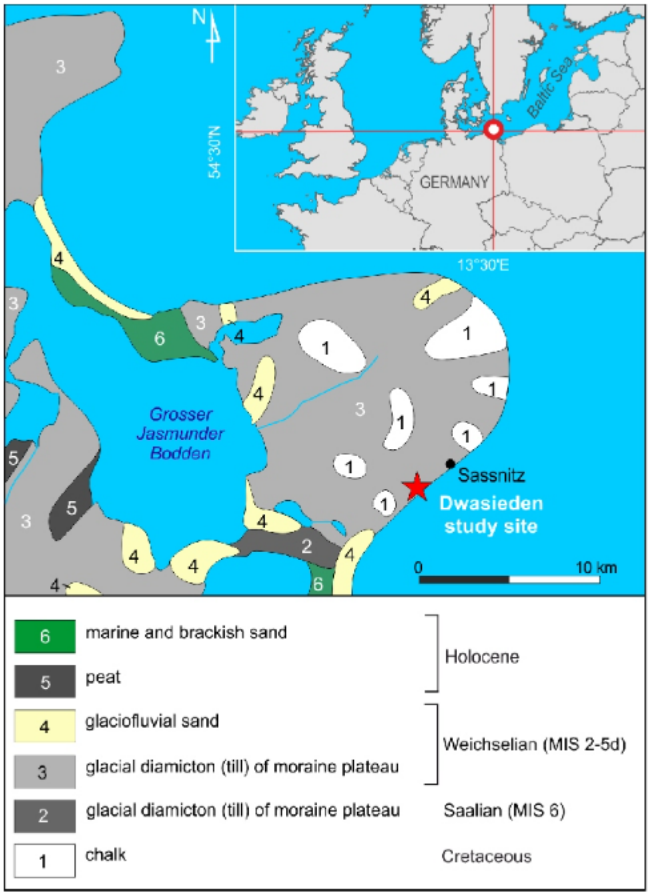

Fig. 1. The study site at Dwasieden in its geological setting

between 20 and 16 ka (Litt et al., 2007; Heine et al., 2009; Lüthgens and Böse, 2011; Lüthgens et al., 2011; Rinterknecht et al., 2014), and (3) the Mecklenburgian Phase, approx. 16–15 ka (Kaiser et al., 2009; Küster and Preusser, 2009; Rinterknecht et al., 2014) or up to 14–12 ka in the case of the Angermünde-Chojna subphase of the Mecklenburgian Phase (Pisarska-Jamroży, 2013).

The lowermost diamicton in the cliff section, directly below the glaciolacustrine sediments under study, was deposited during the Saalian Glaciation (MIS 6), whereas the overlying diamicton, directly above the glaciolacustrine deposits, represents the Brandenburgian Phase of the Weichselian Glaciation (MIS 2; cf. Kenzler et al., 2015, 2017; Pisarska-Jamroży et al., 2018).

METHODS

The various deposits of the section under study have been investigated sedimentologically, distinguishing a number of lithofacies that have been coded following Miall's (1978) classification, with a slight modification introduced by Zieliński and Pisarska-Jamroży (2012). All lithofacies symbols are explained in the figure captions.

The grain size of the deposits is indicated according to the Udden-Wentworth scale (Udden, 1914; Wentworth, 1922). Despite the fact that the IRD include the full spectrum of grain sizes, we focused in the field on macroscopically recognizable IRD. The orientation of the long axes of elongated gravels and boulders as well as the orientation of striae on pebble-sized clasts have been measured.

THE DUMPSTONES AND DROPSTONES

As far as we are aware, no dumpstone deposits suggesting two phases of dumping have been described before from a Weichselian proglacial lake. Here, we describe some characteristic examples of dumpstones and dropstones from the cliff section at Dwasieden.

DESCRIPTION

The Weichselian glaciolacustrine deposits in the cliff section contain significant quantities of outsized clasts in the form of dumpstones and dropstones at several locations and at different levels (Fig. 2). The glaciolacustrine succession overlies a glacial diamicton (till) and is also overlain by a glacial diamicton (lithofacies Dm in Figs. 3 and 4); the lower diamicton is 1–1.5 m thick and was deposited as a subglacial traction till during the Saalian Glaciation, whereas the upper one is up to 2 m thick and also represents a subglacial traction till, which was, however, formed during the Brandenburgian Phase of the Weichselian Glaciation (cf. Kenzler et al., 2015, 2017).

The clasts representing IRD in the glaciolacustrine deposits are up to 0.8 m in size and consist predominantly of Scandinavian granitoids (Fig. 3). Moreover, two clasts with glacial striae on some of their surfaces (Fig. 3E) are clear evidence of a glacigenic origin. Due to the random occurrence of the clasts, the orientation of the glacial striae on the two clasts does not provide any reliable information about the direction of the source area, the transport direction of the ice, or the depositional process. The hosting glaciolacustrine deposits are 1.5 m thick and consist of deformed and horizontally-laminated silts and fine sands (Fig. 2). The coarser clasts are irregularly distributed in a 20 m long and commonly some 10 cm thick lenticular layer; they form occasionally clusters of boulder-sized and smaller particles within this layer, and are occasionally covered by a thin drape, in such a way that the hosting layer has locally an exceptional thickness that is roughly equal to the visible vertical size of the boulders (Fig. 3).

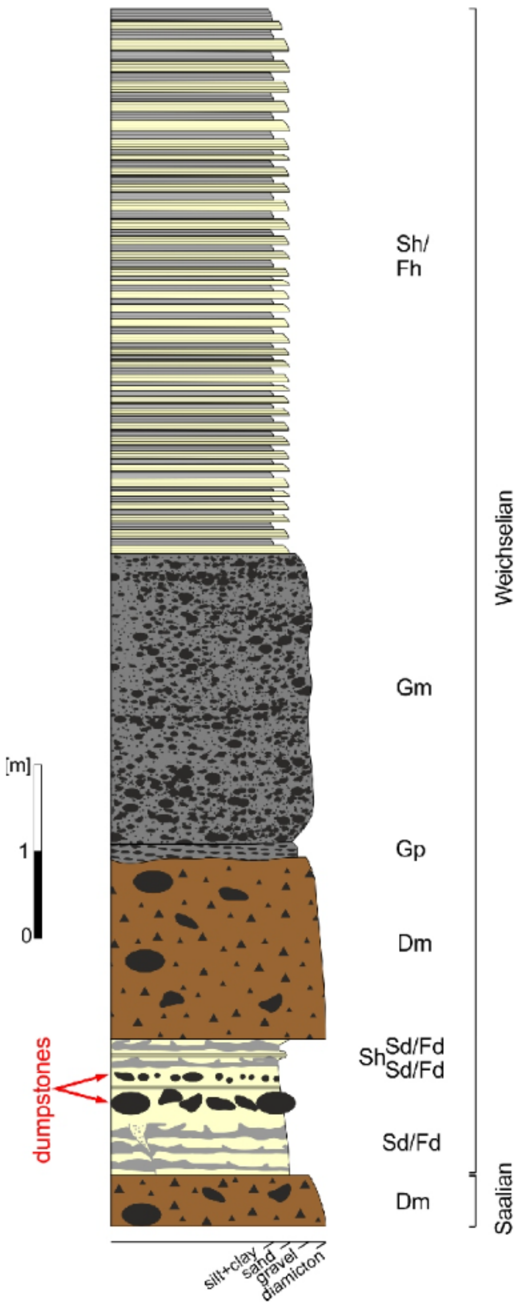

Fig. 2. The succession in the cliff section in Dwasieden on Rügen Island, showing the position of dumpstone deposits within glaciolacustrine sediments

Dm – massive diamicton, Fd – deformed fines, Fh – horizontally-laminated fines (silt + clay), Gm – massive gravel, Gp – planar cross-stratified gravel, Sd – deformed sand, Sh – horizontally-laminated sand

In addition to the clusters, some boulders occur as isolated outsized clasts (Fig. 3C – see the clasts on the left side of the photo). These are present below the above-mentioned lenticular layer with boulder clusters but still within glaciolacustrine deposits. Also in this lower level, however, some clusters of outsized clasts are present, forming lenses that are up to 1.5 m long; the clasts concentrated in these clusters show

Fig. 3. Boulder-sized dumpstones in the Dwasieden glaciolacustrine deposits

A–**D** – horizons of large dumpstones; **E** – glacial striae on the surface of some gravel-sized dumpstones; explanations as on Figure 2

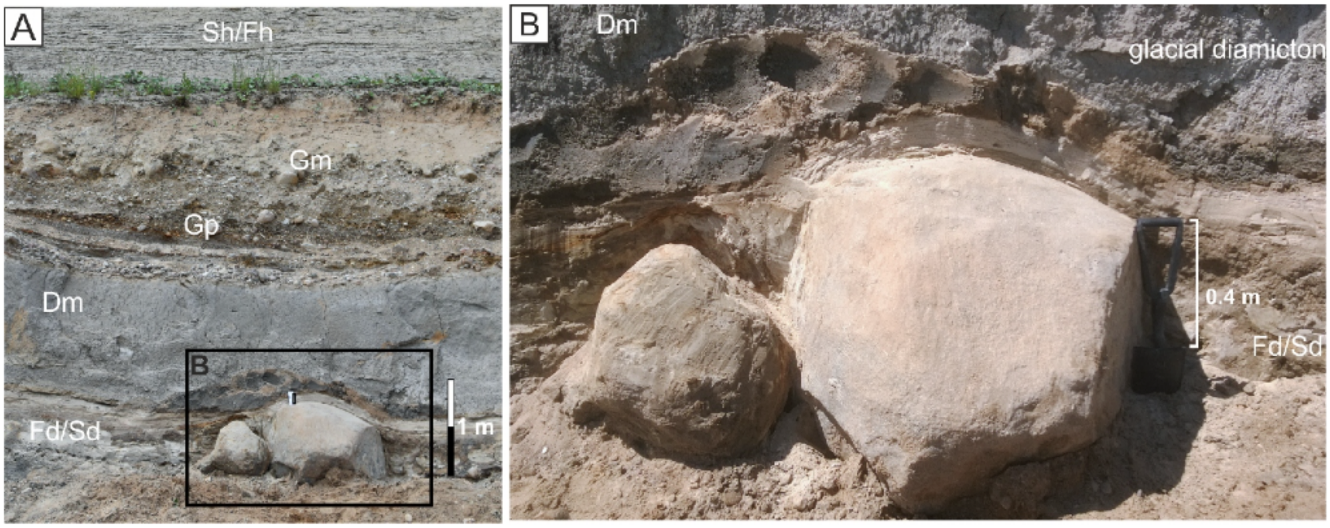

Fig. 4. Dumpstones within fine-grained sandy, thin, curved layer draped by sandy sediments

Explanations as on Figure 2

grain-to-grain contacts (Figs. 3A–D and 4). The long axes of most of these clasts are oriented parallel or semi-parallel (Fig. 3C) to the lamination but some elongate clasts (with length/width ratios ranging from about 1.5 to about 2) are positioned almost perpendicular to the lamination (Fig. 5A, B).

The larger clasts penetrate and deform (locally in a fairly chaotic way) the underlying silty and sandy laminae; in particular in the direct vicinity of the largest clasts, the laminae are strongly deformed (Figs. 4 and 5). The laminations immediately below the grains are down-warped, and the laminae are laterally truncated (Figs. 3C and 5). In contrast, laminae overlying the clasts are gently curved, draping them, commonly with some deflection (Fig. 4B). This type of boundary contact between IRD and the host sediment has been called "bedding contact" by Thomas and Connell (1985).

INTERPRETATION

The glaciolacustrine silty and sandy sediments in the lower part of the Dwasieden cliff were deposited in a lake at the front of the ice. The different grain sizes must be ascribed to the settling of silt with an admixture of clay particles that were widely dispersed via interflows and underflows, in combination with sands that were probably derived from inflowing meltwater from the nearby ice sheet (cf. Smith and Ashley, 1985; Best et al., 2005; Pisarska-Jamroży, 2013).

The occurrence of particles with strongly different (much larger) sizes than the lacustrine host sediments indicates a completely different depositional mechanism. The only feasible interpretation of the local deposits with boulders is that these were formed as dumpstones, derived from ice rafts that tumbled over and released all particles that had been set free on their surface due to melting. This interpretation is supported by the fact that the laminae above the pebbles and boulders are thinner than the laminae at their sides: the autochthonous sedimentation was less on top of the clasts that stuck out above the sedimentary surface of the lake. The same is visible for the outsized clasts that are present at a lower level, and that show a similar thinning of the drapes that cover them (cf. Thomas and Connell, 1985). There is no evidence of plough marks and squeezing-up (sediment prows) around the clasts that might suggest subglacial traction or melting-out processes (cf. Jørgensen and Piotrowski, 2003). Most of the boulder-sized, rounded and subrounded dumpstones were deposited parallel or semi-parallel to the bedding. This suggests that they were not re-oriented in the water column, in contrast to the smaller (pebble-sized) clasts, at least as far as they are elongated, showing a relatively high length/width ratio of at least approx. 2 (Figs. 5 and 6).

The dumping of clasts from ice rafts in the proglacial lake at Dwasieden apparently took place in at least two phases, as can be deduced from the two exposed levels that contain dumpstones and dropstones. These two levels are separated by silty and sandy sediments without large clasts, pointing at a break in the deposition of IRD.

DISCUSSION

Four main processes are commonly held responsible for the formation of dropstones and/or dumpstones: (1) biological rafting, (2) ice rafting, (3) flotation, and (4) projectiles (see Bennett et al., 1996). Biological rafting can be excluded for the Dwasieden deposits because of the climate during the Weichselian Glaciation. Flotation can also be excluded, as only small grains (up to 25 mm) can float on water due to surface tension (Syvitski and Van Everdingen, 1981). Projectiles are almost exclusively linked to volcanic activity (volcanic bombs) or astronomical processes (meteorites), and the composition of the clasts at Dwasieden does exclude such an origin. It can thus be stated with certainty that the dumpstones and dropstones at Dwasieden were released from melting ice rafts. According to Houmark-Nielsen and Kjær (2003), the study area was covered by a glaciolacustrine basin between 33–23 ka; this seems consistent with the palaeogeographical study by Anjar et al. (2012). This lake could be reached occasionally by ice rafts carrying IRD (see Hambrey, 1994).

The presence of at least two levels of dumpstones and dropstones suggests that the clasts in the lower level (which contains significantly less IRD than the upper level) were deposited during one phase of iceberg melting, followed by "normal" glaciolacustrine sedimentation; the same or another ice

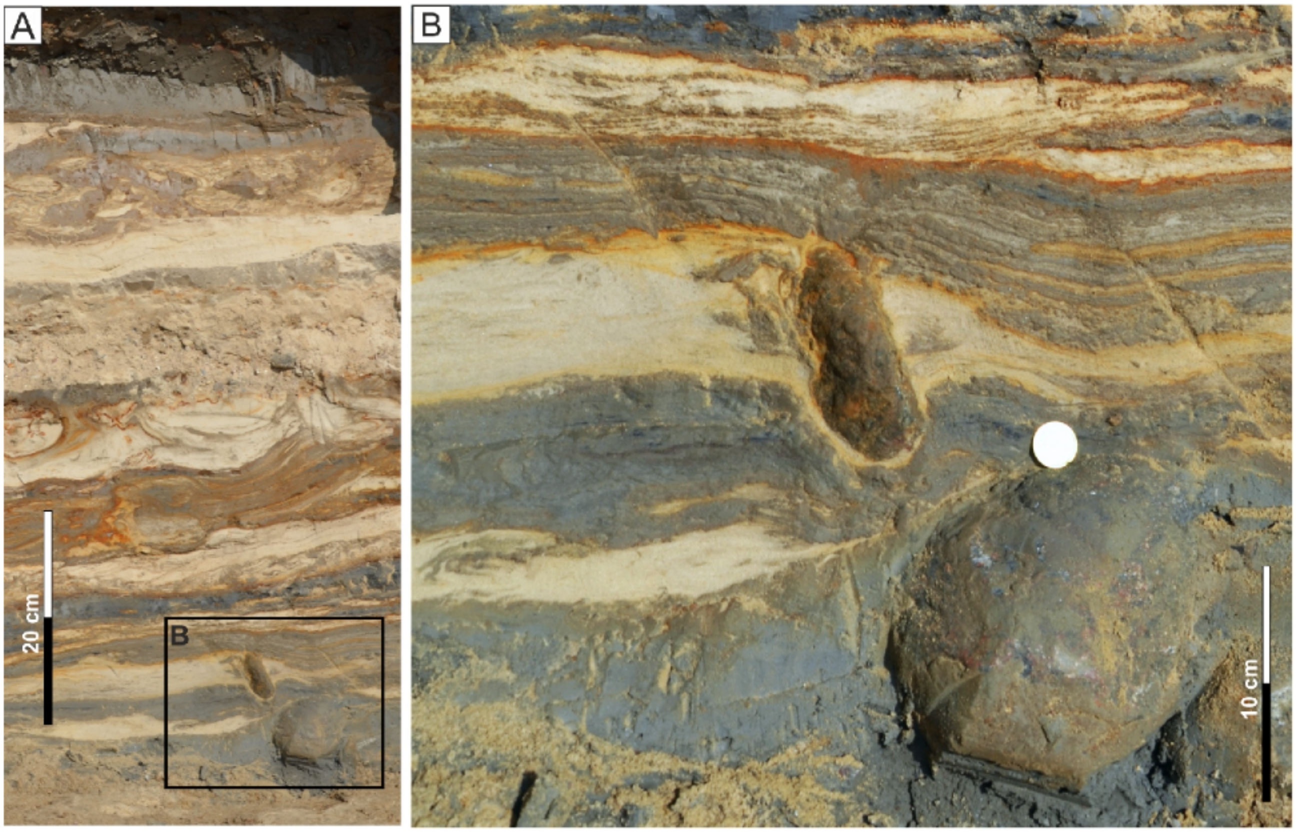

Fig. 5. Dropstones in the glaciolacustrine deposits

A – two dropstones, the lower one quasi-isometric and the upper one elongated;
B – dropstones separated by deformed sandy and silty deposits

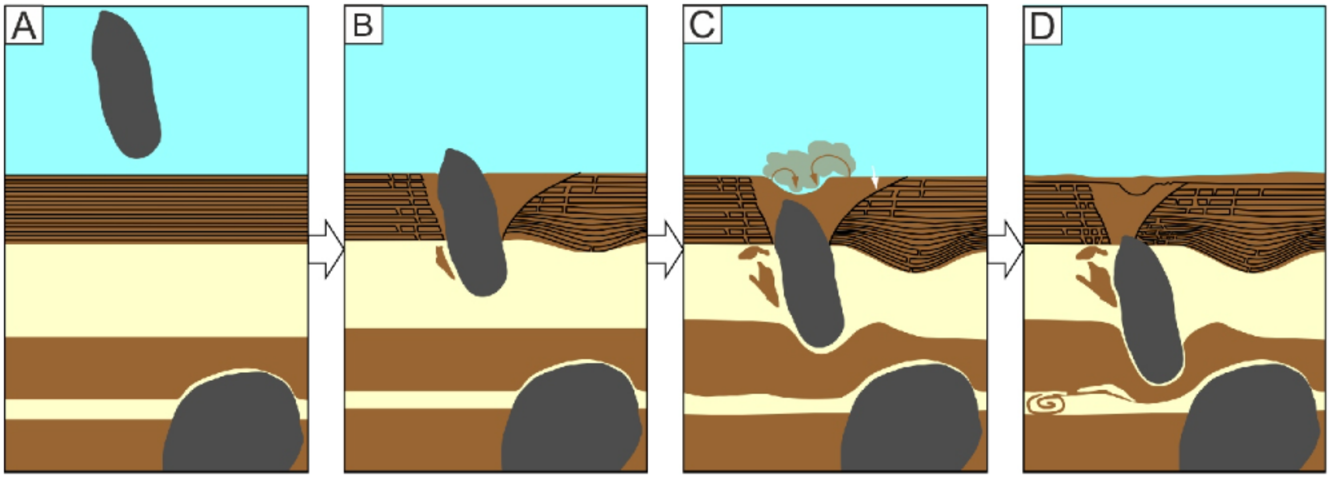

Fig. 6. Schematic model of a dropstone falling through the water column (A), the dropstone penetrates and deforms the bottom sediment (B), causes resuspension of sediments (C), and development of soft-sediment deformation structures (D)

Compare with Figure 5

raft subsequently probably gradually became unstable, eventually tumbling over and dumping its sediment load as dumpstones in a stratigraphically higher layer (Fig. 3C).

Most cobble- and boulder-sized clasts are aligned more or less parallel to the laminae of the host sediment, which suggests according to Benn and Evans (1998) that the bottom sediment was soft and mostly unable to hold the falling elongated clasts in the vertical position that they might have taken during their fall through the water column. Some examples of vertically positioned clasts are, however, present (Fig. 5). On the other hand, no deformation structures have been found, indicating that clasts hitting the bottom fell over, or that they followed a somewhat tortuous pathway during their fall (as do leaves falling from a tree) and hit the bottom at an angle. It thus must be deduced that the clasts that were not exceptionally flattened most likely had insufficient time during their fall through the water column to obtain the vertical position that would have given the least resistance. This, in turn, might indicate that the lake was relatively shallow (probably a few to maximally about ten meters), which would explain why only one ice raft (possibly two) could reach the Dwasieden site, melt, and drop their sediment load.

The sedimentary surface hit by the settling clasts must have been water-saturated and still unconsolidated, because water-escape structures are absent in the sediments below and immediately beside the large stones; such structures would certainly have originated in compacted sediments after a large clast had fallen on the bottom, considering the sudden increase in pore-water pressure that the falling clast would have caused (cf. Domack and Lawson, 1985; Knudsen and Marren, 2002).

CONCLUSIONS

The following conclusions can be drawn from this study.

1. The Dwasieden area was covered by a lake during MIS 2; boulder- sand cobble-sized IRD released from ice rafts in this lake, occasionally in the form of dumpstones, are embedded in the fine-grained glaciolacustrine deposits.

2. Lack of escape structures below and alongside large dropstones or dumpstones indicates a non-consolidated state of the bottom sediments when the dropstones or dumpstones were deposited.

3. A bed-parallel position of flattened and/or elongated clasts suggests a relatively shallow depositional environment.

Acknowledgements. We thank M. Kenzler and W. Wysota, for valuable suggestions that improved the quality of our contribution. The study has been financially supported by a grant for the GREBAL project (No. 2015/19/B/ST10/00661) from the National Science Centre Poland.

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