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Sedimentological traces of ice-raft grounding in a Weichselian glacial lake near Dukuli (NE Latvia)

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Abstract. A clearly erosional, asymmetrical structure with a large concentration of unsorted clasts (ranging from gravel to boulder size) in its deepest point is present in Weichselian glaciolacustrine, mainly fine-grained sediments exposed in an outcrop near Dukuli (NE Latvia). No traces of currents that were sufficiently strong to be capable to erode the sediments significantly have been encountered in the sedimentary succession under study, and such currents would certainly not have been capable to transport boulder-sized clasts. Neither are traces present of mass movements that could deposit the boulder-sized clasts. The glaciolacustrine setting of the succession, the deep scouring and the high concentration of large clasts must therefore be ascribed to erosion of the lake bottom by the keel of an ice raft that became grounded and gradually melted; the debris that was carried along by the ice raft was released and concentrated at the deepest point of the depression that had been eroded by it.

Keywords: *grounding; ice raft; plough marks; proglacial lake; Weichselian; Latvia*

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INTRODUCTION

Modern climate change results in an increasing rate of iceberg formation. A relatively small number of icebergs and ice rafts become grounded where the seafloor is relatively shallow, for instance in a near-coast setting. Grounded ice rafts still can be moved forwards by winds or currents, leaving a specific trail on the seafloor (scour structures, plough marks), depositing and deforming sediments (Woodworth-Lynas *et al.* 1985, 1991; Eden, Eyles 2001 and references therein).

During the Pleistocene glaciations, similar conditions must have resulted in a large number of icebergs

and ice rafts that drifted away into the world oceans, but also into proglacial lakes (e.g., Dowdeswell *et al.* 2000; Kalm, Kadastik 2000; Yorke *et al.* 2012; Livingstone *et al.* 2015). Traces of the grounding of icebergs and ice rafts have been found at numerous places, sometimes in exposures (Longva, Bakkefjord 1990), but much more commonly by geophysical methods, for instance by echosounding on the southern Spitsbergenbanken in the NW Barents Sea (Zecchin *et al.* 2016). Buried plough marks of locally over 80 m deep that were formed during MIS6 in the Yermak Plateau (northern Svalbard margin) were detected by a variety of geophysical methods; their origin could not be established with certainty,

but Dowdeswell *et al.* (2010) favour the hypothesis of the drift across the plateau of an ice-shelf remnant or mega-iceberg from the Arctic Basin. Gebhardt *et al.* (2011) describe, also on the basis of geophysical methods, scour structures at several depths within the sedimentary succession; they date the oldest ones as Early Pleistocene, and later ones as Middle and Late Pleistocene. They ascribe probably the same structures as those described by Dowdeswell *et al.* (2010) to iceberg armadas which they supposed to have been trapped in sea ice. Belderson *et al.* (1973) describe plough marks discovered by side-scan sonar in the north-eastern Atlantic. Belderson and Wilson (1973) and Freiwald *et al.* (1999) describe plough marks of 5–8 m deep that occur along the western flank of the Sula Ridge; they ascribe them to an ice mass that affected even deep coral communities at the time when the last Fennoscandian Ice Sheet disintegrated.

Scouring may occur over large distances in so-called grounding-zone wedges if the interaction between melting icebergs and irregular shelf topography is suitable (O'Brien *et al.* 1997; Batchelor, Dowdeswell 2015). This may lead to a zone with specific sediments related to the grounding activity (McGlannan *et al.* 2017). Touching the seafloor may facilitate capsizing of an iceberg of which the con-

figuration (mainly width/height ratio) has become unstable (Wagner *et al.* 2017); in turn, this may lead to specific concentrations of ice-rafted debris in the form of dumpstones (see also Pisarska-Jamrozý *et al.* 2018) or dump structures (Thomas, Connell 1985).

Although plough marks have been described frequently from northern polar areas (e.g., Dowdeswell, Bamber 2007), such structures are also well-known from the southern hemisphere. Examples from the North Falkland Basin have been described by Brown *et al.* (2017), who date the structures as Last Glacial Maximum (22–20 ka) or later. Obviously, grounding is also known from modern times in the Antarctic region (e.g., Grosfeld *et al.* 2001; Luckman *et al.* 2010; McGlannan *et al.* 2017); this grounding activity may affect the local biosphere significantly (Gerdes *et al.* 2003; Gutt, Piepenburg 2003).

In addition to the icebergs that are set free in the world's oceans, smaller ice masses (ice rafts) are also set free in proglacial lakes that are reached by land-ice masses. This must beyond doubt also have been a common process during (and shortly after) Pleistocene glaciations (Eden, Eyles 2001). It is only logical, considering the much smaller extent and depth of such lakes in comparison with full-marine settings, that such ice rafts must have undergone grounding

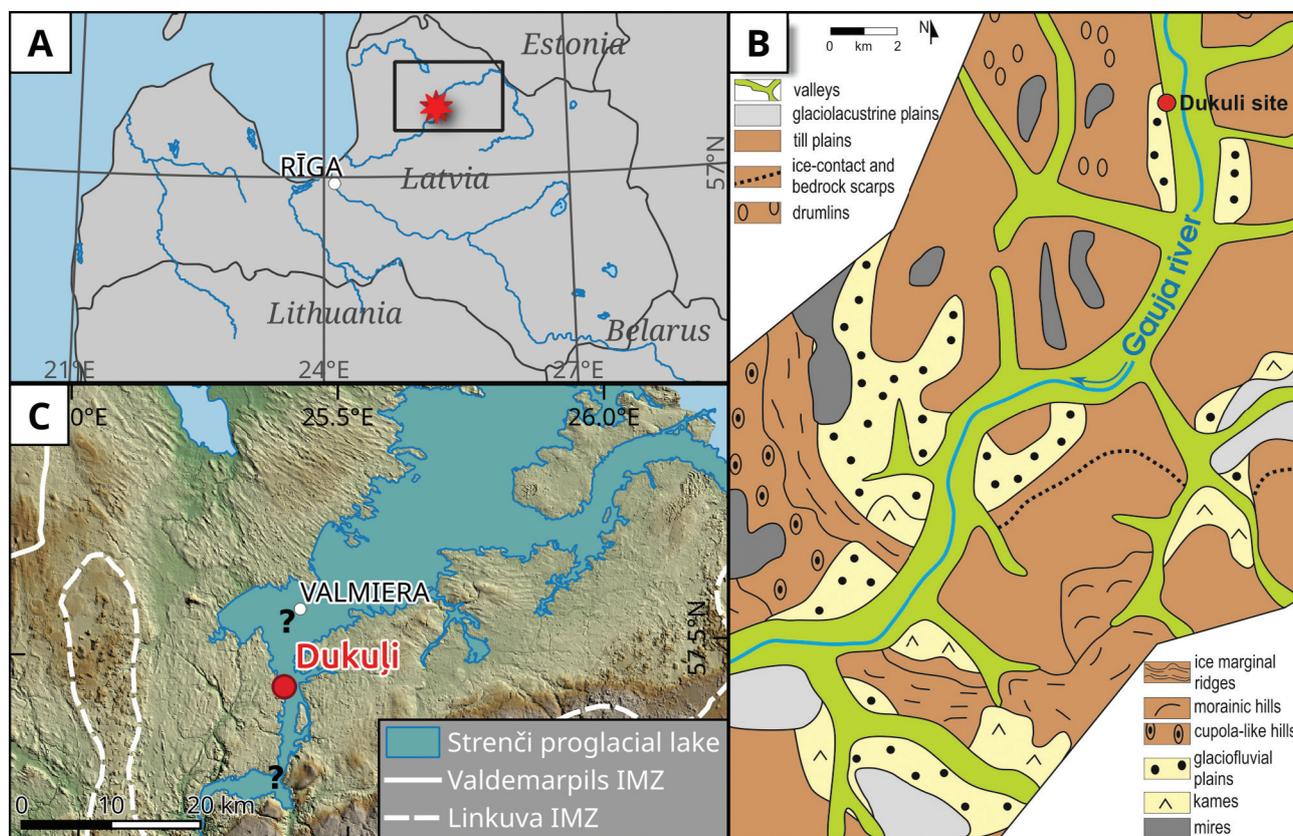


Fig. 1 Location maps. A: Location of the study site in Latvia. B: The Dukuli site along the Gauja River in its Quaternary geological setting. C: Location of the study site and the proglacial Strenči Lake (modified after Nartišs 2014). The exact configuration of the Strenči Lake south-west of Valmiera is unknown (indicated by question marks). Ice marginal zones (IMZ) after Zelčs *et al.* (2011)

much more frequently than their marine counterparts. Yet, relatively few field descriptions of features resulting from grounding ice rafts in a glaciolacustrine setting are available (e.g., Thomas, Connell 1985; Mokhtari Fard, Van Loon 2004; Winsemann *et al.* 2008). Eden and Eyles (2001); they point at a high potential of improper identification of ice scouring/grounding sedimentary structures, especially if they are accompanied by mass-flow deposits consisting of ice-rafted debris released from the melting ice.

The present contribution deals with a well-developed grounding structure of an ice raft in a Weichselian proglacial lake that was situated near the present-day town of Valmiera in NE Latvia (Fig. 1A), within the valley of the Gauja River (Fig. 1B). It is suggested that this study can help deepen the insight into this feature that must have occurred fairly frequently during the Pleistocene and shortly afterwards, particularly during phases of ice retreat; this feature is, however, still poorly known.

SEDIMENTARY CONTEXT OF THE GROUNDING STRUCTURES

The grounding structure and the related sedimentary characteristics (including soft-sediment deformation of the bottom sediment of the lake in which the ice raft grounded) were exposed (Fig. 2) in a scarp formed by lateral fluvial erosion in the outer bend of a meander (57°27'46"N, 25°23'17"E) of the Gauja River (Fig. 1). The sediments form part of river terrace III (Āboltniš 1971). The succession at this site (Fig. 3; see Krievāns, Rečs 2014) consists mainly of late Weichselian fine-grained glaciolacustrine sediments with occasional ice-rafted debris and dropstones from the Fennoscandian Shield. Some of these dropstones are completely weathered to such a degree that they have physically turned into a mass of crumbles in which even escape structures could originate (Van Loon *et al.* 2016a). In addition to the mainly fine-grained lacustrine sediments in the succession, some more silty/sandy sediments of glaciofluvial origin interfinger, which points to lateral lithofacies shifts that must be ascribed to fluctuations in the lake level, probably resulting from different intensities of ice melting – and thus of meltwater discharge – in the course of time. The overall depositional environment has previously been interpreted as an oxbow lake and as floodplain members (Āboltniš 1971), but recent studies have proven its glaciolacustrine origin (Krievāns, Rečs 2014). It is not yet clear, however, whether the site was a part of the nearby Strenči proglacial lake (Āboltniš 1971; Nartišs 2014) (probably a river-lake) or represents a separate proglacial lake.

The sediments must have been affected by numerous earthquakes, as indicated by the nearby (Valmiera) pres-

ence of a succession of also late Weichselian with seven seismites, all formed in a geologically short time span (Van Loon *et al.* 2016b). As will be detailed below, it can well be that some of the earthquakes influenced the development of the structure in the section under study.

THE GROUNDING STRUCTURE

The structure under study here is situated in the middle of the fine-grained succession of proglacial lacustrine sediments described above (Figs 2–3).

Description

The structure gives at first sight the impression of a channel-like incision with a lag deposit in the form of a large concentration of clasts up to several decimetres long (Fig. 4). The channel-like structure is about 2 m wide and about 1 m deep (more precise dimensions cannot be given because of significant spatial variations in width and height). The top part of the channel-like structure has been eroded away, thus preventing establishing its original depth. This erosional surface,



Fig. 2 Overview of the study site near Dukuli in the bend of the Gauja River, showing the uncommonly sandy upper part of the infilling of the scoured depression, and the uncommon concentration of coarse clasts at the left side of the bottom of the depression. The entire succession outside the structure consists of fine-grained sediments (mainly silt, some silty clay, clayey silt and silty sand)

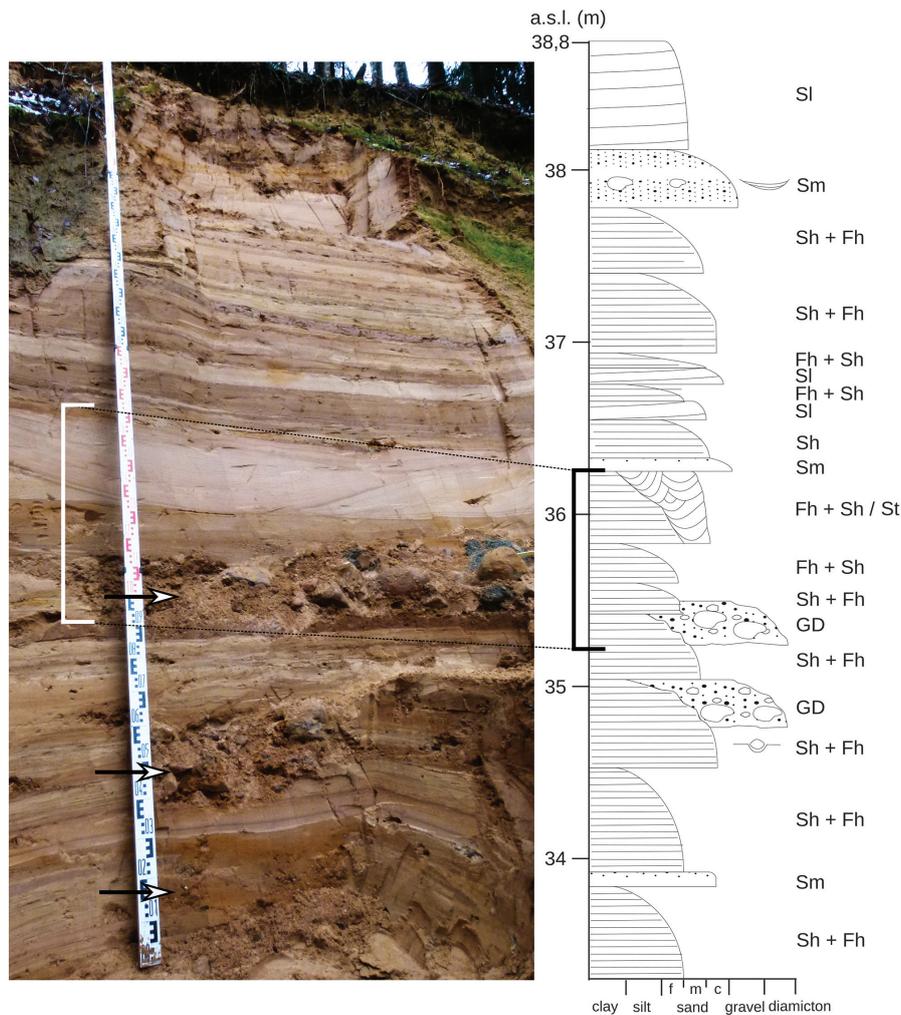


Fig. 3 Sedimentary log of the study site (modified from Krievāns, Rečs 2014). The part of the sedimentary succession included between the ‘brackets’ forms the infilling of the structure under study. The horizontal arrows mark levels with ice-rafted debris

which is one of the few examples present in the outcrop, extends also in the sediments outside the channel-like structure. In the deepest part of the structure, a large concentration of clasts is present; the largest clasts, which are subrounded to well-rounded, have longest axes of around 20 cm. These clasts form the coarsest part of the ‘channel’s’ infilling that consists further mostly of unsorted fine-grained sediments with, inside the channel-like structure, an admixture of sand and gravel (like a glacial diamict; interpreted as “supraglacial diamict” by Krievāns, Rečs 2014). This diamict forms a wedge, thinning towards the left (Fig. 4), to die out completely after about 1.5 m. This wedge is overlain by the same fine-grained sediments as present below, above and beside the structure, but this sediment is locally strongly deformed. Moreover, it is, as far as present within the channel-like structure, much less regular than the sediment outside the structure. The sediment in the channel-like structure is, in turn, overlain by the ‘normal’ fine-grained, horizontally-laminated glaciolacustrine sediment upward from

the top of the channel-like structure, thus becoming a normal part of the glaciolacustrine succession.

Both the walls and the bottom of the channel-like structure are irregular (Fig. 4). The sediments to the right of the structure show features that resemble those of the channel-like structure, but less well-developed: there are some erosion structures with irregular walls and a partly diamictic infilling, in combination with soft-sediment deformation structures. In addition, some meter-sized faults with a displacement of only a few centimetres are present. Some smaller faults result locally in a tectonically complex pattern that excludes a regular and stable glaciotectonic or endogenic tectonic force. At the left side of the structure, soft-sediment deformations are common; they include compression-induced folding, as well as some faulting.

Interpretation

The structure cannot represent a channel with a coarse lag deposit. Such an origin can be excluded



Fig. 4 The structure under study showing its clearly erosional boundaries and the clast concentration at the bottom, making it at first sight resemble a channel with a lag deposit

for two main reasons: (1) the environment was, as indicated by the overall fine-grained sediments, far too quiet for streams with an energy high enough to transport decimetre-sized clasts, and (2) only locally some small climbing ripples occur in the surrounding glaciolacustrine sediments, indicating that, even when some current activity was present, the water was so calm that settling of fine sand and silt could take place, dominating over the current activity. Moreover, the irregular shapes of the walls (Fig. 5) cannot be explained by erosion due to a current in a channel. At several places, the walls seem rather to have been affected by lateral pressure, as indicated by soft-sediment deformation structures.

Yet, the structure is clearly erosional. The four main erosional agents are organisms, wind, fluids (commonly water) and ice. Considering the proglacial character of the sediments, large-scale erosional activity related to bioturbation can be excluded. The same holds for wind (wind and wind-induced waves do not produce channel-like erosion structures of this size and shape). As mentioned above, a bottom current would have left recognizable traces, and this holds also for the passage of tsunami-induced currents. Erosion by gravity flows, which might principally have had sufficient power to erode the subaqueous slope over which they ran down, can also be excluded as no gravity-flow deposits are present. Moreover, there are hardly any places in the neighbourhood from where a mass flow could have run down, and possible source sediments with such large clasts are not present at all. This leaves ice as the only possible erosional agent.

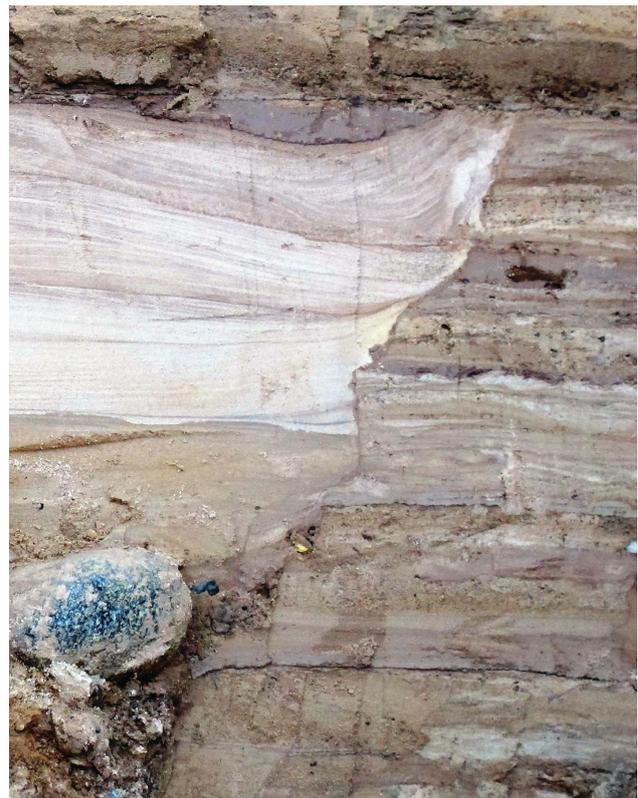


Fig. 5 Boundary of the right-hand wall of the infilled eroded depression, showing irregularities that cannot be ascribed to channelling

Erosion by a glacier can be excluded, as this would have resulted in a much larger-scale feature. Consequently, the erosion must have been caused by ice that did not (or at least no longer) form part of a glacier.

This can only have been an iceberg or an ice raft; the latter seems the most likely, considering the relatively shallow character of the proglacial lake at the time when the structure under study was formed (a fairly shallow character must be deduced from the erosional surface that removed the topmost part of the channel-like structure and the neighbouring sediments; this erosional surface can be explained feasibly only to wave activity; considering the almost complete absence of wave ripples in the sediments, it is likely that the bottom of the lake was situated between the fair-weather and the storm wave base). Ice rafts can erode the bottom sediments of the water body in which they are floating if their keel touches the bottom, leaving plough marks in the bottom (cf. Eyles, Clark 1988). Eventually, this may lead to the fixation (grounding) of the ice raft that subsequently may gradually melt away. The ice raft must, as will be detailed further on, have carried much ice-rafted debris (IRD) with it. This IRD was deposited at the site where the ice raft grounded. The presence of much IRD, partly in the form of large rounded clasts, indicates that the ice raft must have been derived from the Fennoscandian Ice Sheet that eroded, during its advance, much unconsolidated sediment, probably glaciofluvial sediment that was deposited in front of the ice sheet during the same or an earlier Pleistocene glaciation.

Erosion by icebergs and ice rafts as a result of grounding is, as detailed in the Introduction section, well known from present-day polar regions, and some plough marks left by grounding icebergs and ice rafts during or just after Pleistocene glaciations have also been described, though only rarely (e.g., Thomas, Connell 1985; Longva, Bakkefjord 1990; Mokhtari Fard, Van Loon 2004; Winsemann *et al.* 2008). We ascribe the structure under study here also to the grounding of an ice raft, and we will detail below the various processes that were involved, together with the structures that they left.

Scouring

The keel of the ice raft must have touched the bottom while moving, most probably under the influence of wind, as no sedimentary structures indicating a strong current are present. This initially led to the few relatively small erosional structures at the side of the main structure when the keel just bumped slightly against the bottom, but was still able to continue moving, possibly by somewhat changing its orientation. Subsequently, however, the keel penetrated the bottom deeper, and scoured the channel-like structure, which thus should be considered as representing a more or less transverse section through a plough mark.

The irregular character of the subvertical wall at

the right-hand side of the plough mark (Fig. 5) must be ascribed to the irregular shape of the ice raft. Although the topmost part of the bottom sediment must have been unfrozen, due to the thermal impact of the lake water in which the ice raft moved, the pore water in the deeper sediment may have been frozen due to the presence of permafrost. It may also be that, if these deeper sediments were initially still unfrozen, the sediment that became in direct contact with the keel of the ice raft after the grounding took place became temporarily frozen. Whatever the cause may have been, the sediments that were in contact with the deeper part of the ice raft must have been frozen, as can be deduced from the fact that the walls of the scoured structure show overhanging places. Most probably the shape of the wall represents a cast of the side of the ice raft.

It cannot be established from a single vertical outcrop in which direction the ice raft moved; it might have been more or less perpendicular to the exposed surface, but it might also have been at an angle, so that the visible width of the plough mark does not represent the width of the raft's keel. As examination of the plough mark was limited to a natural outcrop, no distinct traces (e.g. ridge and groove microtopography) could be identified in the sediment to reconstruct the direction of raft movement accurately.

Ice-raft wobbling

When a solid object is situated on the bottom of a water body and can – either or not occasionally – be reached by waves, it starts wobbling. This process is the main cause of the burial, in part or in whole, of ships that sink in a shallow lake or sea. The process has been exemplified in a geological context by Van Loon and Wiggers (1975), who described how large peat blocks that sank a few centuries ago to the bottom of the (then) central lagoon in The Netherlands, were responsible for their own burial by wobbling that eroded the sediment below them.

It is most likely that also the ice raft responsible for the structure under study underwent such wobbling. This may have been a slight movement only, but the mass of the ice raft must have exerted a significant pressure to the sediments under and beside the raft. This is shown by the frequent deformations that are present in the glaciolacustrine sediments, exclusively in the immediate surroundings of the plough mark.

The folds and faults indicate compression, which must be ascribed to pressure exerted by the ice raft either during wobbling, or while freely moving in the eroded depression and bumping occasionally against the wall. This is very well comparable with the deformations described by Van Loon and Wiggers (1975) from the surroundings of the wobbling peat masses.

When the ice raft gradually melted away, it will eventually have become released from the surrounding sediment wall, but relatively deep parts of the irregular bottom may for some time still occasionally have touched the bottom, thus still enabling wobbling. This might explain some other deformations in the sediments surrounding the plough mark.

Sedimentation of ice-rafted debris

When the ice raft had grounded, it was doomed to melt away by thermal subsrosion (melting of the ice due to exposure to above-zero material, i.e. water) of the subaqueous part and by solar irradiation affecting the subaerial part. The large concentration of decimetre-scale clasts in the deepest part of the plough mark and the ‘tail’ of diamictic material at its left-hand (Fig. 4) side suggest that the release of ice-rafted debris (IRD) from the ice raft was sudden. Considering the mixture of pebble-sized clasts and silty grains in the ‘tail’, it is most probable that the IRD that had concentrated on the subaerial part of the ice (under the influence of solar irradiation) formed some kind of debris flow on the ice surface and plunged down into the lake; the coarsest sediments reaching the bottom flowed to the lowest point of the plough mark, where space had become available because of the thermal subsrosion of the keel of the ice raft (melting of the keel must have occurred due to the above-zero temperature of the ambient wa-

ter). Both the release of unsorted IRD from the melting ice and the occurrence of a debris flow were responsible for the extremely badly-sorted sediments that infill the wedge-shaped erosion structure. The debris-rich tail of the debris flow followed and filled up the remaining space at the deepest point. The occurrence of clast clusters and scattered clasts higher up in the structure indicates that the ice raft continued to melt, thus occasionally setting free the remaining mineral debris. Considering the scarcity of these dropstones, the ice raft was not very large anymore.

The large clasts in the debris-flow deposit were much heavier than the silty sediments underneath. Because the bottom sediments in direct contact with (or nearby) the ice keel were most probably temporarily frozen (see the Scouring and the Discussion sections), this will not immediately have led to loading. However, when the ice raft had melted away, the sediments became thawed under the influence of the ambient lake water. The heavy load of the boulder-sized clasts then consequently resulted in – relatively gentle – loading into the underlying glaciolacustrine sediments.

Filling of the plough mark

It is interesting to note that some irregular sediments are present at the base of the eroded depression, even below the coarse dumpstone (Fig. 6). This must be ascribed to starting sedimentation of ice-rafted de-

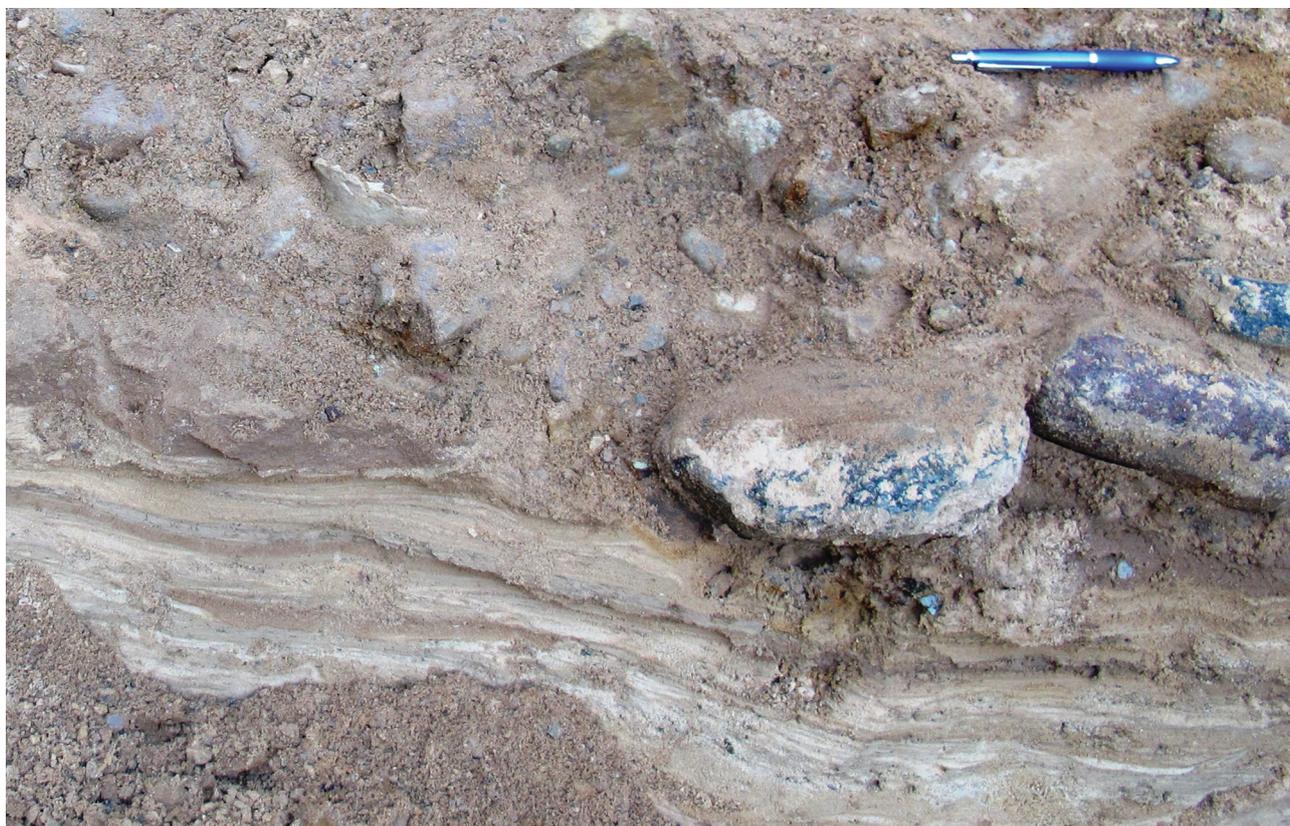


Fig. 6 The lowermost infilling of the eroded depression, consisting of irregular laminae of badly sorted ice-rafted debris, indicating sedimentation under the melting and wobbling ice raft

bris when the ice started to melt. The below-dumpstone sediment is badly sorted and coarser than the unaffected glaciolacustrine deposit, indicating that the material cannot have been derived from the lacustrine succession, but must have been settled from the melting ice. The wobbling of the ice raft caused an unquiet micro-environment, which explains the irregular character of these lowermost infilling sediments.

When the grounded ice raft had completely melted away (or possibly: when the ice raft had been set free because of melting of the grounded keel, and had floated away from the grounding site), a depression was left in the lake bottom. It served as a trap for the particles that still were being transported over the bottom of the lake. This resulted in much thicker and less 'quiet' layers of sediment than in the rest of the succession. The fact that several layers with distinct characteristics (mainly regarding the grain size and the sedimentary structures) are present indicates that the sedimentary infilling was not a continuous process but took rather place in phases (Fig. 7), probably associated with seasonal variations in runoff. This is consistent with the overall sedimentary succession, in which layers/laminae with different grain-size characteristics (though all fine-grained) prevail.

Ongoing sedimentation

After the plough mark had become filled up completely, normal lacustrine sedimentation took over on top of the infilling (Fig. 2), forming an entity with the surrounding sediments. The sediments on top of the infilling consist, like those under and alongside the infilling, of alternating clayey silts and silty clays, with some admixtures of fine sand. This implies that the grounding of the ice raft was just a one-time event that interrupted the local sedimentation only for a while.

DISCUSSION

The succession, in which the erosional structure under study is present, consists almost exclusively of fine-grained sediments, i.e. mainly silts and fine sands. The sedimentary structures (rare local small-scale current ripples but mainly low-energy horizontal lamination) indicate a low-energy environment where settling from suspension dominated, with separate events of currents capable of eroding up to sand size clasts. There are no channels or other structures that indicate high-energy currents. This makes the erosional feature under study a phenomenon that



Fig. 7 Top part of the infilling, showing a limited number of successive phases of rapid infilling of the depression after the ice had melted away. The sediments are coarser (fine sand) than the average (mainly silty) lacustrine sediments which explains the sedimentary structures that indicate transport and deposition by traction currents, rather than settling from suspension. The layers are much better sorted and finer-grained than the ice-rafted debris in the depression, which indicates that they should be considered as autochthonous lacustrine sediments

must be ascribed to temporary and locally exceptional conditions. Obviously, a major question is whether the structure under study can be explained in another way than by grounding of an ice raft. Considering the fact that the environment was a glacial lake (taking the geological context into consideration, it was with almost absolute certainty a proglacial lake), only few processes may be held responsible for the presence of deep erosion structures. As mentioned above, channelling can be excluded on the basis of the absence of bottom currents with a sufficiently high energy. The environment was unsuitable for animals that could dig deep holes in the bottom and, moreover, no macrofossils have been found in any of the glaciolacustrine sediments of this site. Erosion by floral remains, for instance the stem of a tree, can be excluded for the same reasons. Deformation of the subaqueous sediments after subaerial exposure under the influence of periglacial conditions can also be excluded as no structures that indicate such conditions (e.g. frost fissures or ice wedges) are present in the part of the sedimentary succession under study. Truly exceptional events such as the impact of a bolide or a meteorite cannot be held responsible either, considering the lack of traces of a sudden local heating, and because of the shape of the walls of the erosion feature. Since no other processes can result in erosional depressions in the bottom of a proglacial lake, the only feasible process is the grounding of an ice raft. A similar conclusion was reached on the basis of similar arguments by Eyles and Clark (1988), who describe a sediment-filled depression with characteristics that are in many respects comparable to the one under study here (see their Fig. 10, including thrust and normal faults, large load casts, and folds alongside the incised feature), except that their structure does not contain a concentration of IRD.

Another point to be discussed is the irregular, sub-vertical shape of the walls of the scoured structure. It is unlikely that the uppermost glaciolacustrine sediments were frozen before the ice raft arrived, even though permafrost will have been present in this proglacial area, so that the deeper lacustrine sediments will have contained frozen pore water and thus will not have acted as an unconsolidated sediment. The temperature of the water will have been high enough – even if only slightly above 0 °C – to thaw the pore water in the uppermost sediment layers, just like the active layer of the subaerially exposed sediments will probably have thawed during summer time. The irregular character of the subvertical wall at the right-hand side of the plough mark (Fig. 5A) may be due, as explained above, to the irregular shape of the eroding ice raft. Similar blocky and irregular walls have been observed in contemporary iceberg scours (Woodworth-Lynas *et al.* 1991). Because of

the sub-zero temperature of the ice, the pore water in the sediments close to the ice must have become frozen. This explains why, when the ice raft melted or drifted away, the irregular shape (with some small overhanging parts) of the wall could survive for some time. After the melting of the ice raft, the sediments alongside the depression must have gradually thawed again, so that this water-saturated sediment could slide down. This cannot have continued for a long time, because a depression like this in a glacial lake with a high sedimentation rate forms typically a sediment trap. The uncommonly thick sets of relatively coarse (though still fine sandy) sediment that fill the top part of the depression above the dumpstone deposit are evidence that this sediment trap was filled up quickly. Consequently, the filling up may have taken place before the sediment, especially at the right-hand side of the structure, became unfrozen. The irregular shape of the wall, including some slightly overhanging parts, could thus be preserved.

In short, the processes that successively led to the erosional structure and its infilling can be modelled (Fig. 8) in the following way: an ice raft arrived at the study site in a proglacial lake and grounded with its deep keel (Fig. 8A). Due to wind activity, the ice raft started wobbling, thus deepening the erosional depression, while melting subaerially because of exposure to the sunshine, so that debris accumulated at its top (Fig. 8B). The ongoing subaerial melting and subaqueous subsidence caused an unstable configuration, so that the ice raft tumbled over, releasing the accumulated debris on its upper surface, which fell down to form a dumpstone (Fig. 8C). When the ice raft had completely melted or had drifted away, traction currents deposited sandy material in the trap formed by the eroded depression (Fig. 8D). After the depression had completely been filled up, an erosional phase took place, possibly by storm-induced waves, that eroded part of the lacustrine bottom sediments, including the topmost sediments that filled the depression (Fig. 8E). Later ice rafts left dropstones in the lacustrine sediments that continued to accumulate (Fig. 8F).

CONCLUSIONS

A Weichselian proglacial lake was gradually filled with fine-grained sediments that point at low-energy conditions, and in a water body that was sufficiently quiet or, less likely, deep enough to make clay and silt particles settle from suspension. No sediments or structures suggesting higher-energy currents are present in the glaciolacustrine succession.

The ongoing sedimentation was interrupted by the grounding of an ice raft that not only eroded a depression into the water-saturated fine-grained sediments, but that also probably wobbled after grounding, de-

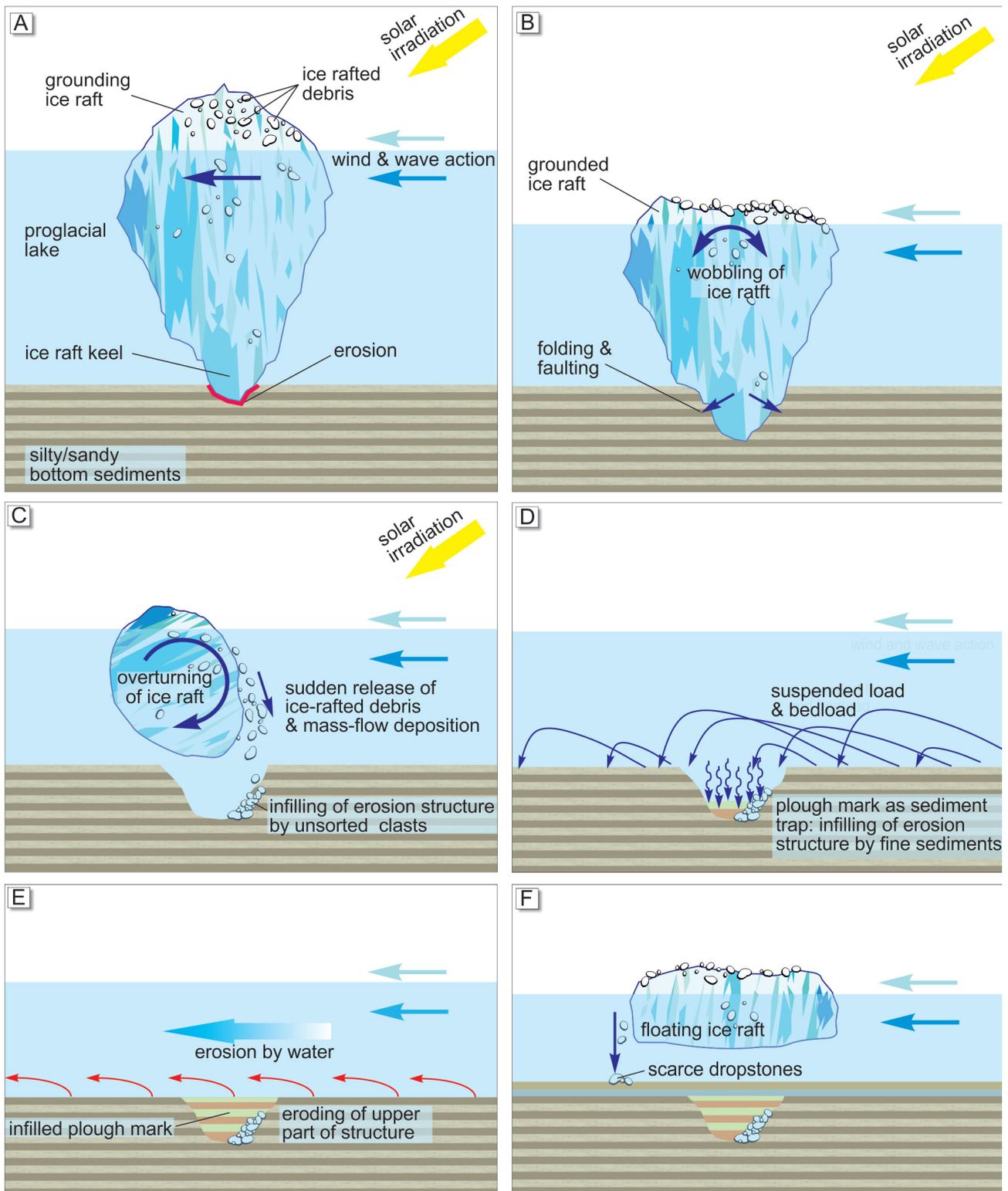


Fig. 8 Model showing the origin of the structure under study. A: An ice raft becomes grounded. B: Wobbling causes the ice raft to deepen its erosion pit; the top part of the ice raft melts so that debris accumulates at its surface. C: Subaerial melting and subaqueous subrosion cause the ice raft to become unstable. It tumbles over and a dumpstone consisting mainly of the debris that was set free at the ice surface is formed. D: After the ice raft has melted away or drifted away, a depression is left in the sedimentary surface; it becomes filled by material supplied by traction currents. E: After the depression has been filled with sediment, an erosion phase removes the top part of the lacustrine sediments, including the topmost sediments that filled in the depression. F: Later ice rafts pass and leave dropstones in the still accumulating lacustrine succession

forming the sediments in the walls of the depression. Whether the depression forms part of an elongated feature so that it represents a long plough mark could not be established (by lack of a 3-D exposure), but this seems most likely considering data from literature about modern grounding features.

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