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Research Article

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Ice-crevasse sedimentation in the eastern part of the Głubczyce Plateau (S Poland) during the final stage of the Drenthian Glaciation

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Abstract: Glacial sediments in the eastern part of the Głubczyce Plateau, at the Krowiarki site, were studied. Two units were distinguished within the sedimentary succession. The lower unit is composed of mainly sandy sediments with diamicton interbeds, the upper unit of very fine silt and clay sediments that exhibit rhythmic lamination in parts. Based on the textural and structural features of deposits, local deformations and palaeoflow directions, it was found that the sediments had been deposited within an ice crevasse, which was initially open and functioned as an ablation flow artery. The sediments were deposited in the form of a small fan dominated by sheetflows. Glacial tills were also redeposited on its surface. In a later phase, the crevasse was blocked. As a result, it was filled with water, leading to the development of a crevasse lake in which low-energy deposition dominated. The crevasse style of deposition indicates that, in the final stage of glaciation, the marginal part of the ice sheet was in a stagnant phase. This conclusion applies to the part located on the southern side of the watershed of the eastern Głubczyce Plateau. The probable reason for the stagnation of the ice sheet was the distinct loss of ice supply above the local topography barrier due to the decreasing thickness of the ice sheet in the studied area.

Keywords: glaciomarginal zone, stagnant ice, ice sheet dynamics, lithofacies analysis, older Saalian, Sudeten Foreland

1 Introduction

Research on glacial landforms deposited in various types of depressions within stagnant ice, lake crevasses, kettle holes, etc. has a very long tradition, and to this day, the subject arouses great interest in researchers [e.g. 1–3]. This is primarily because these landforms play an important role in the reconstruction of former glaciations, particularly with respect to the phases of the decay of ice sheets in areas where they became inactive. In understanding this sedimentary environment, characterised by great variability in the conditions and course of deposition [4–7], an important role is played as well by research on contemporary glacial systems [e.g. 8–10].

Glacial landforms of this type are very well preserved and documented in many areas of Poland, especially those glaciated during the Weichselian and Warthanian Glaciations [e.g. 11–21]. They are also known from areas located further south, such as the forelands of the Sudetes Mountains [e.g. 22,23] and Polish Uplands [e.g. 24,25], which were glaciated during older glaciations; however, the degree of recognition of glacial landforms is generally much lower there. One of these areas is the Głubczyce Plateau in the foreland of the Eastern Sudetes, where this study was conducted.

The Głubczyce Plateau is composed largely of glacial sediments; however, the glacial relief in this area is poorly preserved. This is mainly the result of strong defragmentation of the plateau in the post-glacial period induced by fluvial and related processes, which were very intensive in the foremountain area. In addition, the plateau is covered with younger loess sediments, deposited mainly during the Vistulian Glaciation [26,27], which mask the older relief. As a result, the development of glaciation in the studied area is poorly understood. It is known that during the Drenthian (older Saalian) Glaciation, the plateau was covered by the Upper Odra ice lobe, formed within the central part of the Racibórz Basin (Figure 1a) located further north [28,29]. The direct depositional effect of its advance is a till [30–32], which, especially in the northern part of the plateau, forms a continuous bed of considerable thickness, locally reaching more than 20 m [cf. 33,34]. The issue of sedimentation in the glacimarginal zone has been presented in very few papers. Its relatively best-known aspect is the stage of maximum glaciation and the first phase of the ice-sheet recession.

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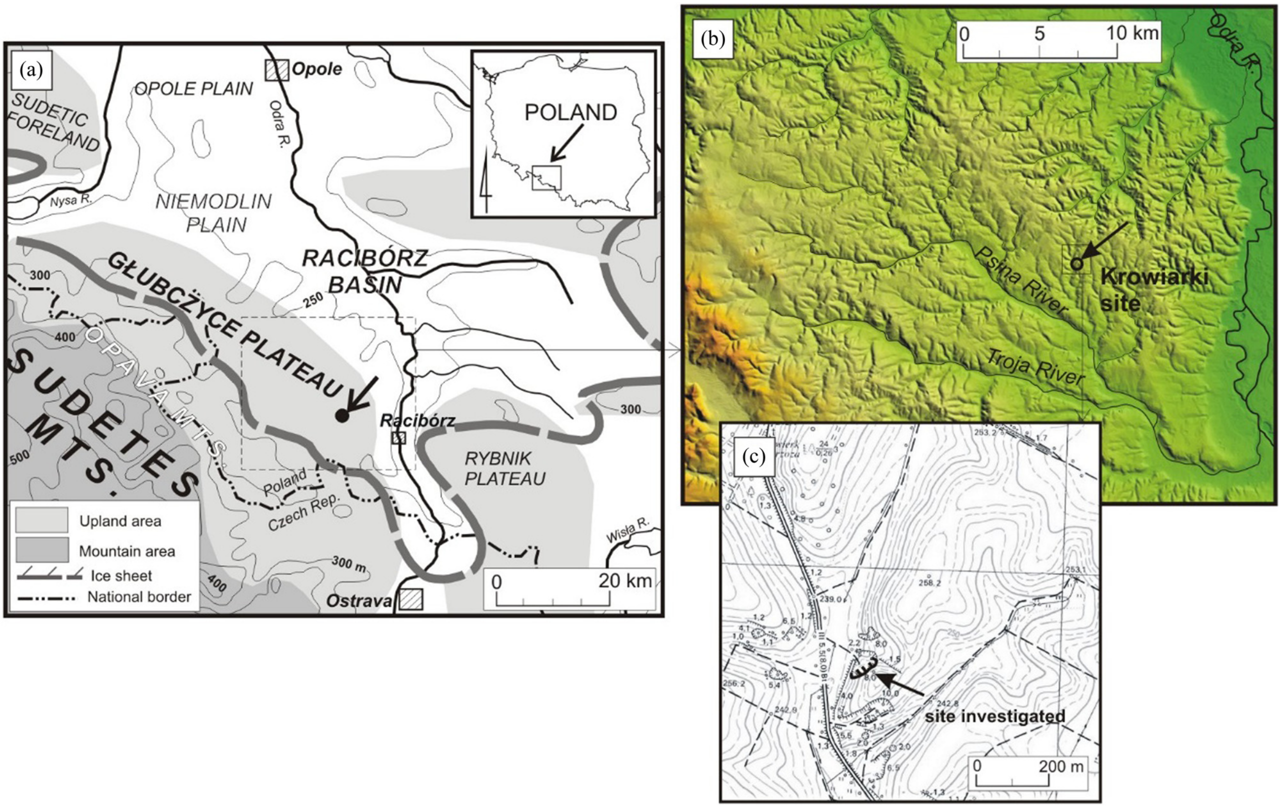

Figure 1: Location and the relief of the study area. The maximum extent of the Scandinavian Ice Sheet is marked by grey dotted lines.

Small marginal fans passing laterally into the valley sandurs were deposited at that time. Fluvioglacial streams used the morphological depressions of the Prudnik, Troja or Psina River valleys, oriented parallel to the ice-sheet margin [35–38]. Much less is known about the final stage of glaciation, during which the ice sheet retreated from the studied area. Some information about sedimentation processes in this period can be found in sediment succession at the Krowiarki site located in the eastern part of the plateau, about 15 km north of the maximum extent of the ice sheet. The purpose of this research is to reconstruct the sedimentary environment of the deposits at the Krowiarki site and to identify the dynamic state of the ice sheet in the final phase of glaciation. The glaciogenic deposits in the NW vicinity of the village of Krowiarki were briefly described over fifty years ago by Jahn [35]. Unfortunately, most of these exposures no longer exist.

2 Regional setting

The Głubczyce Plateau is a hilly area in the foreland of the Eastern Sudetes with altitudes of 260–280 m a.s.l. and relative altitudes up to 50 m (Figure 1b). The Quaternary sediments that built the plateau are underlain by fine-grained Miocene sediments of varying thickness, which cover older, mainly Palaeozoic, locally Mesozoic rocks [31,36]. During the Drenthian Glaciation, the plateau was almost completely covered by the ice sheet. The remainder of the advance of the ice sheet is a nearly continuous bed of till which lies directly on the Miocene sediments, and locally, older glacial series or river sediments [31,33,39]. The till is locally covered with glaciofluvial sediments. On the valley margins, these form more continuous covers, while on the hilltops, they exist in isolated patches. Glacial sediments occur on the terrain surface relatively rarely, due to the overlying loess, which forms a continuous cover [e.g. 30].

The Krowiarki site is located in the eastern part of the Głubczyce Plateau, at a distance of about 8 km from the edge of the Odra River Valley, near the main watershed of the plateau, which extends from the area of Racibórz NW towards Głubczyce (Figure 1b and c). The surface of the plateau in the watershed zone reaches 260–265 m a.s.l. to the SW, and it inclines gently towards the Psina Valley. The site is located in the upper section of one of its tributaries, flowing S from the watershed.

An exposure of glacial deposits is located in the southern part of the longitudinal hill continuing from the central watershed and characterised by an NNE-SSW orientation. At the SW edge of the hill is a small isolated hillock about 250 m a.s.l. in altitude. The exposure, located on the northern side of this hillock, is characterised by an SW-NE orientation. The wall of the exposure is 8 metres high and 35 m wide; its top reaches 245 m a.s.l.

3 Methods

The exposure was described and logged. A standard sedimentological analysis of deposits is the main method used in the present study. Detailed observations of textural and structural features form the basis of the reconstruction of the ancient sedimentary environment. Lithofacies description is based on Miall's [40] code with modification. A twofold division of depositional units was used, with designated lithofacies and facies associations. In the facies association code, lithofacies with a low frequency of occurrence are given in brackets. Palaeoflow directions have been estimated based on cross-bed measurements. The results are depicted as rose diagrams.

4 Results

4.1 Description of sediments

Two units have been distinguished (Figure 2): Unit 1, which includes the lower and middle parts of the sedimentary succession, is composed of gravelly sandy and diamictic deposits and Unit 2, which constitutes the upper part of the succession, is much more fine-grained and built mainly from silty-clayey deposits. A similar succession, i.e., the co-occurrence of predominantly sands and clays, was also recorded by Jahn [35] within former sand pits located in the vicinity of Krowiarki.

4.1.1 Unit 1

4.1.1.1 Sands and gravelly sands

Three lithofacies associations were distinguished, based mainly on variability in the grain sizes of the sediments (Figure 2). On the WSW side of the exposure, all lithofacies are inclined at an angle of several degrees, while in the central part, they lie sub-horizontally.

The lower lithofacies association Sh, SGh, (Sl, St), observed within the SW and central parts of the exposure, is composed mainly of medium-scale beds of coarse-grained sands Sh and gravely sands SGh with horizontal stratification (Figures 2 and 3a) and horizontally stratified sandy gravels with thicknesses of several centimetres are slightly less frequent. Rare lithofacies of sands with low-angle planar cross-stratification Sl and trough cross-stratification St occur occasionally; these are usually thin beds (up to 10 cm), and their lateral extent is small. The second facies association Sh, Sr, SFh is much more fine-grained and about 2.5 m thick, forming fining upward succession. Medium-grained sands with horizontal stratification Sh occur in its lower part; these are overlain by fine-grained sands with ripple cross-lamination Sr accompanied by thin lithofacies Sh, over which silty sands with horizontal lamination SFh occur (Figure 2). The upper facies association of Unit 1 is 1.5 m thick and composed of coarser-grained deposits, characterized by the occurrence of gravelly sands with low-angle cross-stratification SGl and horizontally stratified sands Sh, as well as several gravel lithofacies with the same structure Gh (Figure 2).

Due to the small number of lithofacies with cross-stratification in the studied section, only a few measurements of palaeoflow direction were made, indicating palaeoflows towards NE.

4.1.1.2 Diamictons

Diamictons form irregular beds occurring alternately with sandy deposits. Three thick beds of diamicton, with thicknesses of 0.5–2 m, were found. The two lower beds separate the two lower lithofacies association of Unit 1, reaching their greatest thickness in the extreme SW part of the exposure and becoming thinner towards the central part, where they wedge out within the sands (Figure 3c). In the marginal part of the exposure, these diamicton beds are inclined at an angle of several degrees towards the NE, the same as the underlying gravelly sandy deposits, while in the central part of the section, they occur in a sub-horizontal position. The third thick bed of diamicton occurs at the top of Unit 1 and continues for a greater distance than the lower beds. However, it also thins towards the NE. Moreover, thin and irregular diamicton lenses, with thicknesses up to 30 centimetres and up to several metres wide, are also visible in the exposure, especially in the middle facies

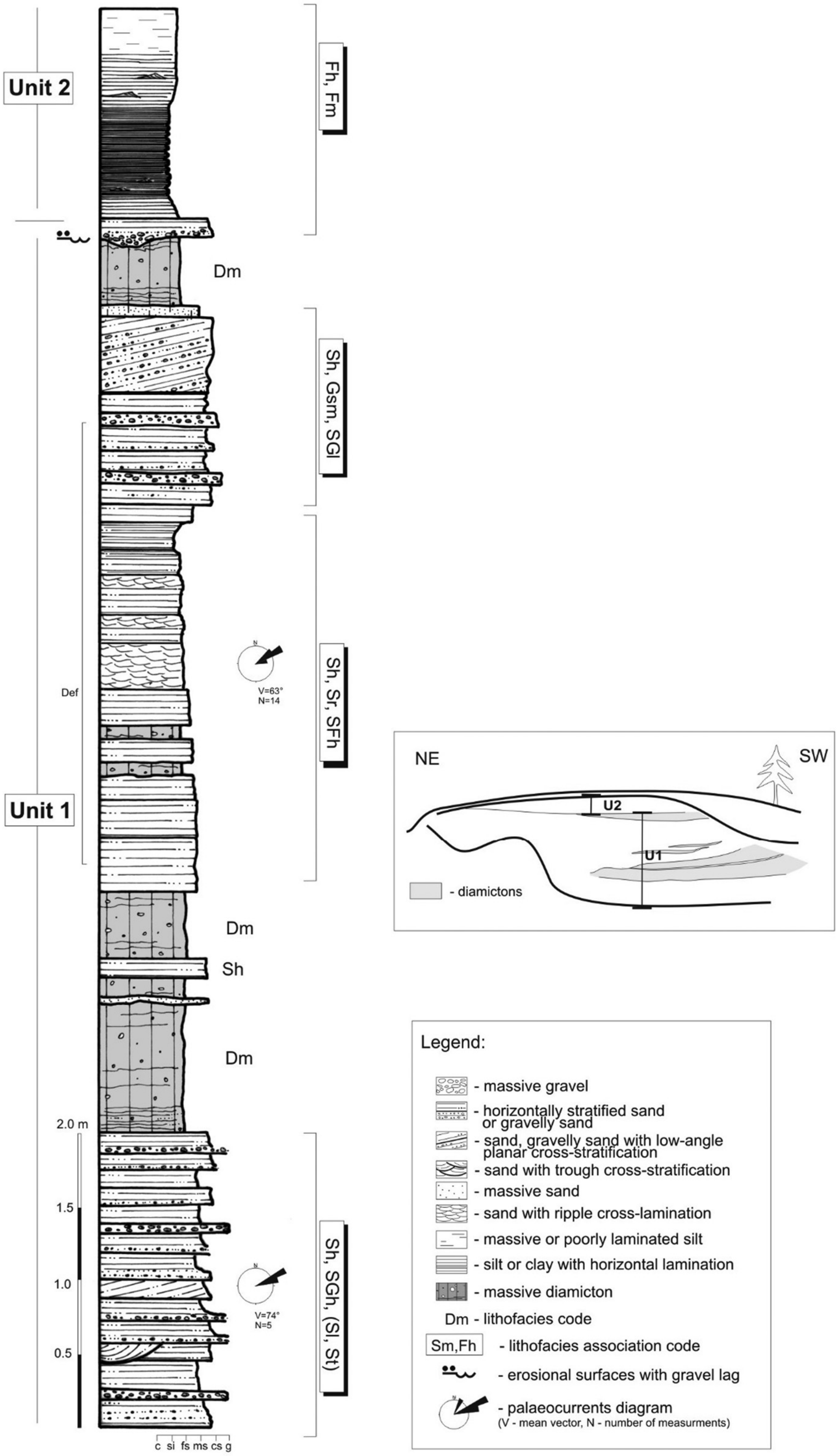

Figure 2: Sedimentary log of the ice-crevasse succession at the Krowiarki site.

association of Unit 1. The diamicton is composed of a sandy-silty matrix characterised by a brown colour. The concentration of gravel clasts, with Scandinavian crystalline rocks among them, is usually small. The diamictons are usually massive. An exception is the lower diamicton bed, characterised locally by a laminar

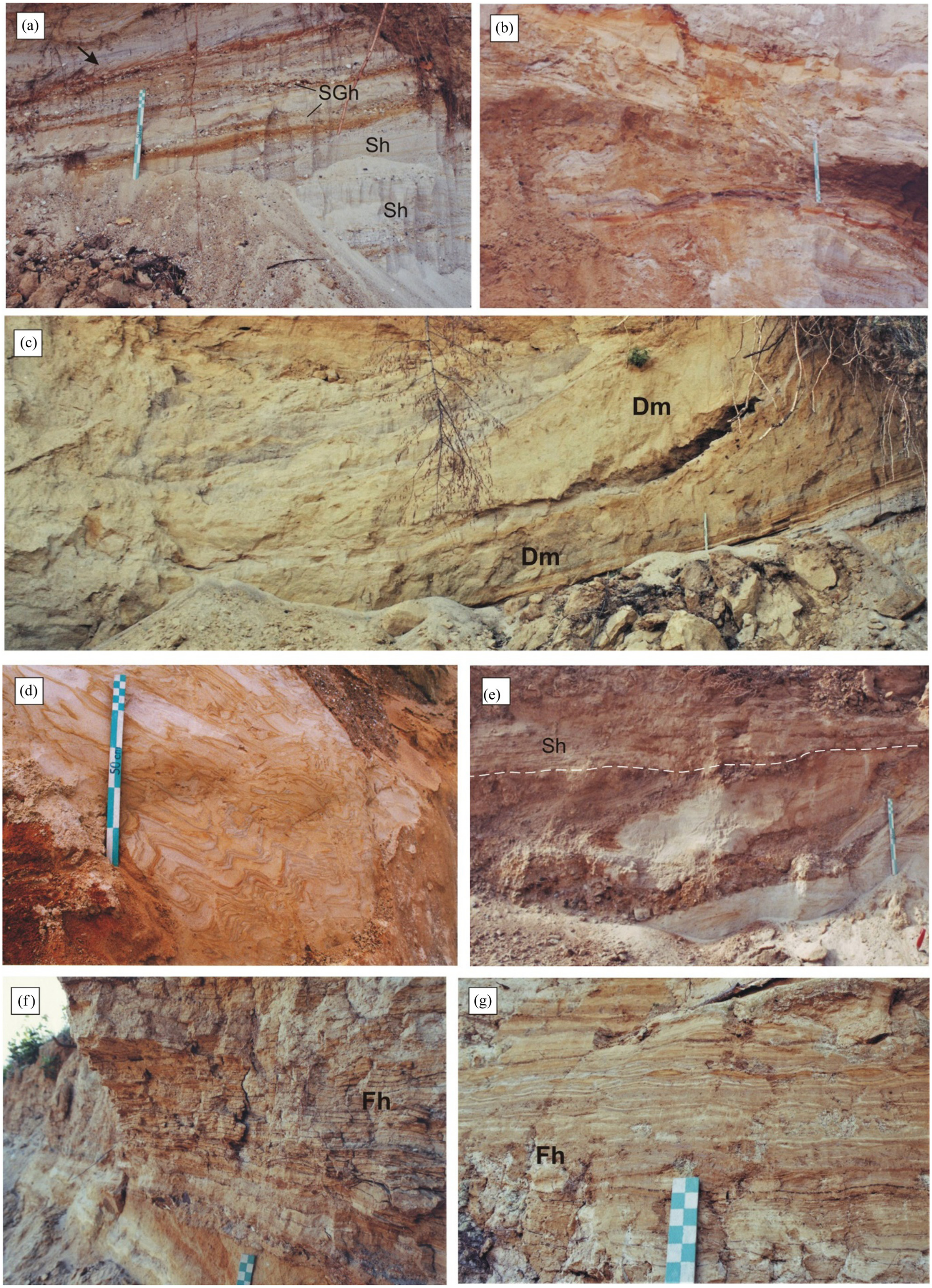

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Figure 3: Sediments at the Krowiarki site: (a) sands and sandy gravels of the lower association of Unit 1. An arrow indicates single bed of sand with cross-stratification. See that cross laminae are inclined to the left, i.e. towards NE direction. Scale – 50 cm. (b) Deformed sediments of Unit 1. Lower facies association is visible in the lower part of the photo. Above occur sands of the middle facies association. The diamicton bed is brown colour. (c) Thick diamicton beds of Unit 1 within marginal SW part of the exposure. Their thickness become thinner to the left. (d) Mosaic structure of deformed sediments of Unit 1. Numerous differently oriented faults are visible. (e) Package of deformed sands and gravels, which is erosively cutted and upbuilt with sub-horizontal sands. Erosive surfaces are marked by a dotted line. (f) Rhythmic succession of silts and clays of the lower part of Unit 2. The thickness of silty laminae is variable and locally irregular. Brown clay laminae are very thin. (g) More coarse-grained silty and sandy-silty laminae within middle part of the Unit 2.

structure resulting from the presence of numerous laminae and lenses of sands within the diamicton. The lower surfaces of diamicton beds are usually flat, but in some places, they are deformed. At the top of the upper diamicton bed, a thin layer of discontinuous sandy gravel lag is developed.

4.1.1.3 Deformation structures

The sediments of Unit 1 contain numerous deformations, usually taking the form of inclined faults with displacements from centimetres to several decimetres, observed especially in the central and NE parts of the exposure within sediments of the second and third facies associations of Unit 1. Normal high-angle faults dominate. A few individual reversed faults were also observed. The latter indicate slight displacement of sediments in different directions, but mainly towards NE, i.e. opposite to the direction of the ice-sheet movement. Locally, deformations form a dense network of several fault systems with various angles of inclination, resulting in the obliteration of the original structure of the sediments; instead, they resemble a mosaic of patches (Figure 3b and d). Deformed sediments within Unit 1 are eroded locally in the outer part of the hill. Horizontal beds with no signs of deformation occur above this erosive surface (Figure 3e).

4.1.2 Unit 2

The upper part of the sedimentary succession is composed of fine-grained silty-clayey sediments with a thickness of about 1.5 m (Figure 2). The lower 50 cm constitutes a rhythmic succession consisting of light-beige silt beds with a thickness of 0.5–3 cm, occurring alternately with much thinner (approx. 2–3 mm) dark-brown clay laminae (Figure 3f). An admixture of fine-grained sands was observed in the lower parts of some silt laminae, which, as a result, are characterised by distinct normal grading. These fine-grained sediments are mostly horizontally laminated; however, several lithofacies of silt with admixtures of fine-grained sands are characterised by ripple cross-lamination. Their thicknesses do not exceed 3 cm. In the remainder of the unit, sediments become slightly more coarse grained. Clay laminae disappear, and silty-sandy laminae and lenses appear among the silt deposits (Figure 3g). Towards the top of the profile, the rhythmic structure is less noticeable and the deposits become more and more massive.

4.2 Interpretation

The lithofacies of horizontally stratified sand Sh, gravelly sand SGh and gravel Gh of the lower lithofacies association Sh, SGh, (Sl, St) were deposited by shallow currents under upper-stage plane-bed conditions. The domination of lithofacies with horizontal stratification and their tabular shape and large lateral extent suggest deposition from sheetflows [cf. 41–44]. Secondary rare lithofacies of sand with low-angle planar cross-stratification Sl were derived from low-relief washed-out bed forms that had been locally deposited during waning flood stages. These forms are also correlated with sheetflow conditions [45–47]. Textural variation in lithofacies reflects the short-term changing dynamics of flows resulting from the variable intensity of ablation. Accessory and rare lithofacies St are cut-and-fill structures associated with concentrated small streams that developed during a phase of decreasing flows.

The second, more fine-grained facies association Sh, Sr, SFh was also deposited from sheetflows, but in conditions of lower energy. Medium-grained sands with horizontal stratification Sh represent the upper plane bed configuration, but the successive lithofacies Sr and SFh are associated with the progressively decreasing energy of currents, i.e. co-sets derived from ripple marks Sr reflecting the lower part of the lower flow regime and silty sands SFh from decaying flows and deposition from suspension. Similar sandy-silty associations, related to sheetflows, have been observed quite frequently in distal fan environments [cf. 41,48–50]. The upper lithofacies association of Unit 1 indicates an increase in current energy and conditions of flows similar to those from the lower facies association. The sandy-gravelly texture and horizontal or low-angle stratification of sediments indicate that deposition took place again in shallow, dynamic sheetflows in super-critical or transient conditions.

The diamicton beds of Unit 1 are flow tills. This interpretation is supported by, among others, the varied thickness, limited extent and lateral wedge-out of tills within sandy sediments. The diamictons were transported as cohesive flows of ablation material from the ice sheet surface [cf. 51–53]. The debrites, following deposition, were accompanied by local washing, as reflected in sandy interlayers or erosive pavement on their tops.

The deformation within the lower Unit 1 indicates that the sediments were locally dislocated after deposition. This process occurred especially within the marginal part of the hill. The severely obliterated structure and mosaic character of the deposits and at least a few overlap fault sets suggest that deformations developed during at least a few episodes. Domination of steep normal faults resulted from the sub-vertical displacement of sediment packages. This indicates that the substrate was unstable, which may in turn suggest deposition on the ice contact. The presence of small reversed faults indicates locally more complex field stress within sediments. Although this type of deformation is a common feature of ice-marginal landforms connected with active ice [54,55], the orientation of the observed reverse faults, opposite to the direction of the ice-sheet movement, makes this interpretation rather unlikely [cf. 21,56]. Similar deformations could be generated also by mass flows within underlying sediments [56]. However, the occurrence of reverse faults, including in the part of the succession where flow tills are absent, suggests that this was not the main triggering factor and that their formation should also be linked with the processes of sediment subsidence and dislocation during the melting of buried ice. A similar conclusion results from the NE palaeoflow directions, which also suggest that sediments were deposited in the supraglacial system rather than immediately in front of the ice-sheet margin.

The fine-grained texture of Unit 2 sediments indicates a significant change in the sedimentary environment. Silty clays were deposited mostly as a result of settling of fine-grained suspensions within the water column. The water was deep enough for the sorting of suspensions to occur, suggesting the development of a lake water body. The silt-clay rhythm of the lower part of the unit resembles a varve record typical of the limnoglacial environment [e.g. 57–59]. The laminae of silts represent periods of more intense sedimentation, whereas clay laminae were deposited from remnants of the finest suspensions during the period when the lake was not fed with ablation discharges. Rare thin silty-sandy lithofacies with ripple cross-lamination indicate that low-energy traction currents travelled episodically across the bottom of the basin. Their co-occurrence with clay laminae may also suggest low-energy turbidite currents. The same origin for many more silty clay rhythms cannot be ruled out, as suggested by the fact that some silty laminae are enriched in the sand in their lower parts and are characterised by distinct normal grading. The successively more coarse-grained nature of the sediments within the upper part of the unit and the gradual disappearance of the laminar structures indicate an increased supply of sediments over time and increasingly less stable sedimentation conditions within the lake.

5 Discussion

5.1 Crevasse origin of the deposits

Numerous sediment deformations characterised by an increasing degree of deformation towards the outer part of the hill are most likely the result of the loss of the stability of the sediments due to the disappearance of the ice abutment [cf. 60,61]. Their presence suggests that deposition of the sediments took place in ice-contact, most likely in an ice crevasse. Deformation of sediments in the outer parts of hills is one of the main criteria for the identification of kame-related genesis for glacial forms [62,63]. The ice crevasse as a site of deposition of sediment is also indicated by directional data showing palaeoflows towards NE, i.e. almost opposite to the direction of ice-sheet movement. This interpretation is also confirmed by the local presence of sub-horizontal beds with undisturbed structures above deformed sediments that are erosively cut. These beds were most likely deposited during a later episode between the partly deformed sediments forming the nucleus of the filling of the crevasse and the receding ice wall.

The structural and textural features of the sediments of Unit 1 indicate that they were deposited in the form of a small fan. This is supported by the dominance of tabular lithofacies with horizontal stratification reflecting shallow sheetflows (Figure 4a), which usually dominate in the environment of small alluvial fans [cf. 41,47,64,65]. Debrites of glacial flow till were also deposited on the fan surface. The till melted out on the

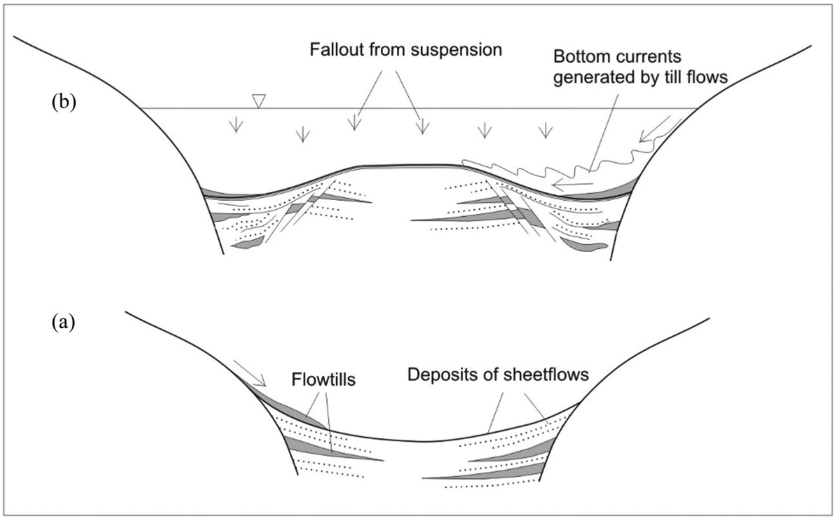

Figure 4: Model of the ice-crevasse succession development. (a) Deposition from sheetflows and gravity flows within open crevasse and (b) development of lake within the crevasse and deposition from suspension and bottom currents.

ice-sheet surface and episodically flowed into the crevasse in which the fan was developed. The more fine-grained nature of the sediments within the second lithofacies association of Unit 1, which reflects much lower energy flows, may have been the result of a periodic loss of fan water and sediment supply. Subsequently, in this part of the crevasse, mass flow began to play a slightly greater role. Fan deposits, along with accompanying flow tills, are very common elements of crevasse successions. Many examples of kames containing these types of deposits have been described by Terpiłowski [16], among others.

The silty-clayey sediments of Unit 2 indicate that, following a period of fan deposition, the crevasse was blocked and filled with water (Figure 4b). As a result, the character of the deposition changed, becoming limnoglacial. The rhythmic sequence of sediments at the bottom of the unit undoubtedly reflects the cyclical variability of material supply to the water and a condition of very low energy. However, it could not be clearly determined whether these rhythms represent annual cycles of change in the intensity of ablation or shorter cyclicity. Due to its small size, the lake was characterised by a high level of sensitivity to dynamic instability, associated with the potential for sudden changes in the depth and size of the water supply. For these reasons, it seems less likely that annual cycles could have been recorded in such conditions. The same conclusion results from the supposition that some rhythms may be related to bottom currents. In this case, subsequent sediment rhythms could be initiated by gravitational mass flows in marginal parts of the crevasse, which induced small turbidity currents travelling across the lake bottom. Nevertheless, annual cyclicity cannot be completely excluded. Within a small pond, deposition of such low energy would suggest a very restricted supply of sediment for a longer time. However, the morphology of the crevasse bottom, which may have been extremely variable due to melting-out and progressive recession of the crevasse walls, may also have played an important role here. As a result, the bottom within the central part of the crevasse may have constituted a small, flat elevation. Thus, the described sediments may have been deposited at the bottom at this higher level (Figure 4b). In this situation, more dynamic depositional episodes may have been concentrated in the marginal depressions, which constituted morphological traps for sediments in the outer parts of the crevasse.

The increase in the grain size and frequency of the massive structure of the sediments in the upper part of Unit 2 probably indicates a disturbance in the dynamic equilibrium within the reservoir which, during the previous period, had enabled rhythmic sedimentation. This was probably due to an increase in the energy of the water supply as a result of more intensive ablation. Within a small basin, this factor, due to turbulence, may have suddenly caused a total change in lake dynamics [cf. 14,66].

The fluvial nature of the sediments in Unit 1 indicates that the crevasse was open and played the role of a meltwater route. Palaeoflow directions within the studied succession indicate that ablation waters flowed into the crevasse from the south-west. Through a system of connected crevasses, they probably reached the ice-sheet margin and outflowed freely to the glacier foreland. Later, despite the progressing widening of the crevasse, drainage was blocked and thus the lake was developed within the crevasse. These processes have been identified in many kame successions [e.g. 4,16]. The development of the lake within the crevasse was probably a local phenomenon. However, the potential for linking Unit 2 with a much larger glacimarginal lake that may have functioned in the ice-dammed upper Odra Valley cannot be completely excluded. Due to intensive ablation during the recession phase, the lake within this main valley of the region may have been quite large [cf. 67,68]. The lower section of the valley of the Psina, a tributary of the Odra, may constitute a vast bay of this dammed lake. If the water in this basin reached a sufficiently high level, then the lower parts of the glacimarginal zone in the eastern part of the Głubczyce Plateau may thus have found itself under water, including crevasses separating blocks of dead ice in the N part of the Psina basin. However, this thesis has not been confirmed. In this situation, glaciolacustrine sediments should make up the upper parts of the glaciogenic successions in a large area of the Psina Valley, but this has not been commonly observed.

5.2 Ice sheet stagnant phase

The crevasse-related origin of the sediments indicates that their deposition generally took place in the zone of stagnant ice margins. However, it cannot be ruled out that the first phase of sedimentation was initiated when the ice still was characterised by a low level of activity [cf. 9,16]. Unfortunately, today's relief prevents more accurate identification of glacimarginal forms, and thus, no conclusion as to whether we are dealing with one or a whole group of similar depositional forms is possible. However, the latter possibility is very likely. In the case of the examined site, it seems that the modern hillslope corresponds more or less to the original margin of the glacial form. However, due to the erosive nature of the morphology of the Głubczyce Plateau and the almost complete masking of the original glacial relief, which, additionally, was greatly transformed during the last glaciation, such analogies cannot be applied to all forms of the terrain.

The site is located on the southern side of the main watershed of the plateau. It seems that this topographical barrier could have led to easy transformation of the marginal part of the ice sheet into a dead-ice field. This relatively low but quite broad transverse obstacle led, during the final stage of the glaciation, to the cessation of the flow of ice above the watershed and the transformation of the marginal part of the ice sheet into stagnant and subsequently dead ice. Perhaps numerous crevasses developed in this most peripheral zone of the ice sheet, constituting paths for the outflowing ablation waters and the space where sediment assemblages were consequently formed. The influence of the topography on the development of kames or other landforms related to stagnant ice has been postulated by many authors [e.g. 12,62,69,70]. In the case under study, this factor also seems to be the most probable, especially since the Upper Odra lobe within the central part of the Racibórz Basin could be continuously supplied by ice, during the ice sheet recession phase as well [32].

6 Conclusions

The sediment succession at the Krowiarki site is a record of deposition within a continually expanding ice crevasse. Initially, this crevasse was open, and the sheetflow deposits and flow-tills were formed on a small fan, which were developed in the marginal part of the crevasse. Later, the crevasse was blocked and filled with water. This crevasse lake was dominated by low-energy suspension sedimentation accompanied by weak bottom currents.

Sedimentation within the ice crevasse indicates that the ice sheet in the SE part of Głubczyce Plateau was in a passive state during the final stage of Drenthian Glaciation, mainly due to the relevant topography, which, once the thickness of the Upper Oder ice lobe had diminished, restricted the potential ice flow to the marginal part of the ice sheet above the local watershed.

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