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THE ROLE OF BLOCKS OF DEAD ICE IN THE DEPOSITION OF LATE GLACIAL SEDIMENTS IN A LARGE VALLEY: A CASE STUDY FROM THE VISTULA RIVER VALLEY IN THE GRUDZIĄDZ BASIN, NORTH POLAND

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Abstract

The paper describes the processes associated with sediment deposition in the presence of large blocks of dead or stagnating ice. The study examines a large valley depression in the Grudziądz Basin (lower Vistula Valley) which formed part of the area covered by the last glaciation. A detailed description of the glaciolimnic landforms arising in that depositional setting was prepared along with a record of their structural and textural variety and their paleogeographical implications are discussed. It is concluded that the whole terrace system of the Grudziądz Basin was mainly formed in the presence of dead ice.

Key words

lower Vistula River valley • dead ice landforms • kame terraces • lithofacies analysis • Quaternary • Northern Poland

Identification of the problem

The origin and development of kame terraces is an old and widely discussed problem in the sedimentological and glaciological literature (Flint 1971; Brodzikowski & van Loon 1990). Kame terraces are mainly associated with mountain settings (Pisarska-Jamroży et al. 2010), currently glaciated areas (Evans 2005), or with fairly small river valleys and subglacial channels (Andrzejewski 1994), which are common in the area of the last glaciation. In this last case, buried or live ice was undoubtedly formerly present. Until now, however, the literature available contains no information about kame terrace forms in large valleys (at least of the size of the Odra or Nemunas) in the area of the last glaciation except in the case of the lower Vistula. It is probable that they are usually simply described as glaciofluvial terraces. There may be many reasons for such a situation. In many areas the type of glaciation generally did not favour their development. In North America vast proglacial lakes dominated and were subsequently drained through valley breakthroughs (Teller et al. 2002). A similar mode of deglaciation was present on the East European Plain (Valchik et al. 1994). Meltwaters were also drained by broad spillways, which were common from Poland to the British Isles (Mojski 2005).

Therefore the lower Vistula River valley, below the Fordon gap near Bydgoszcz, has an exceptional position in this former glacial land system.

Here the drainage route could only have taken an alignment perpendicular to the ice sheet snout forcing the meltwater to be transported by either a northerly or southerly route. The development of proglacial lakes lasted for a much shorter time because the valley form inherited from the times before the last glaciation was much lower than the surrounding morainic and outwash plains. Such a low position favoured the quick draining of such lakes. However, in this situation, kame terraces developed. Rapid removal of meltwater protected blocks of dead ice from quick degradation. In addition the accumulated mineral cover isolated ice blocks from the impact of the warming climatic conditions.

Discussion on the kame terraces in the Grudziądz Basin has a long history, lasting over 100 years. Many researchers thought they are ordinary glaciofluvial terraces. Hence the objective of this paper is to present the geomorphological and sedimentological evidence for the presence of vast blocks of dead ice in the reach of the Lower Vistula Valley studied. Kame terraces of relatively large rivers in recently glaciated areas have so far received fairly limited attention. However, they might be a widespread phenomenon taking into account the fact that most of the Eurasian and American rivers within and slightly beyond the area of the last glaciation went through a stage of sometimes large proglacial lakes and probably an extensive phase of development of fields of dead ice in valley settings (Teller et al. 2002; Astakhov 2006; Rosentau et al. 2007; Lyså et al. 2011). It is to be hoped that similar forms in other big valleys within the range of the last glaciation will be the subject of reports in the future.

Geological setting

The lower Vistula River valley is a polygenetic form (Wiśniewski 1990; Starkel 2001) composed of some reaches which developed in different periods of geological time. The relief of the upper part of the Vistula valley has been developing without hindrance since the retreat of the South Polish glaciations (i.e. Cromerian Complex) several hundred thousand years ago. The middle reach has been developing for a slightly shorter period of time but at least for 125 thousand years since the termination of the Middle Polish glaciations (i.e. Warthian). The present day outlook of the lower section of the Vistula valley only originated after the retreat of the last ice sheet which took place at different times between 17 and 15 ka BP (Mojski 2005; Marks 2012). The time within which the valley took its form was several times shorter than in the case of the middle and the upper Vistula valley segments. The detailed course of events was complicated in nature and depended on the advances of the ice sheets in individual phases of the main Weichselian Stadial.

The lower Vistula reach can be subdivided into two parts: the southern one upstream from Bydgoszcz and the northern one downstream from Bydgoszcz. In the south a complex system of ice margin spillways (pradolinas) developed (for details see Niewiarowski 1968; Wiśniewski 1990; Molewski 2007; Weckwerth 2011, 2013). In the north, spillways running parallel to the margin of the ice did not have a chance to form. The outflow could only pass southwards or northwards, either through vast fields of stagnating or dead ice or cascades of proglacial lakes. Such a situation is typical of many fragments of the east Baltic rivers, such as the Nemunas or Dvina (Valchik et al. 1995; Dvareckas 1998) and for the Odra River (Liedtke 2003).

There are many indications that the origin of the present-day terrace system took place in the presence of blocks of dead ice. The Grudziądz Basin is a geological unit distinguished by the particularly strong amassing of such landforms and sediments.

On the basis of the investigations carried out by the Royal Prussian Geological Survey (Jentsch 1901, 1909a, b; Jentsch & Schucht 1909; Sonntag 1919) it was considered that many proglacial, ice-dammed lakes existed in the lower Vistula valley. One of them was formed in the Grudziądz Basin. It should be remembered that this opinion was formed at the onset of 20th century, when many concepts and terms of glacial geology were not well defined and established. In the present terminology glaciolacustrine terraces should be considered as kame terraces.

Investigations carried out by Galon (1934) indicated the presence of many terraces: terrace Vc (61-59 m), terrace Vb (55-54 m), terrace IV (45 m), terrace III (38-35 m), terrace II (31-26 m) and two floodplain levels (terraces Ia and Ib at altitudes of 26-23 m and 25-22 m). What is important is that just at the northern mouth of the Grudziądz Basin the number of terraces is reduced to only two (I and II). In order to maintain clarity, the geomorphological system of terrace designation was used in this paper. This means that the lowest terrace has the Roman numeral I and the highest one – XI. While from the geological point of view this is not correct, it has a historical justification.

Galon (1968) tried to link these levels in a genetic manner with the terrace system in the Toruń-Eberswalde Spillway. As a result, the previous designations were changed into the following: terrace IX (61 m), VIII (55 m), VII (50 m), VI (48 m), V (38 m), IV (30 m), III (27 m), II (25 m) and I (22 m). Following this, the cartographic image of the terraces was significantly improved by Drozdowski (1974, 1979). Drawing an analogy with the investigations of the Brda (Galon 1953) and Drwęca River valleys (Niewiarowski 1968), it is assumed that the proglacial outflow at levels XI-IX was southbound. In the Fordon Gap, at levels VIII-VI, there was a bifurcation at which the river was partly directed to the Noteć-Warta Spillway towards the west and, partly, to the north. The lower terraces evolved only with the postglacial northern flow of the Vistula river.

The model of relief development established by Galon became complicated due to Drozdowski. The investigations by Drozdowski (1974, 1979, 1982, 1987) resulted in the statement that there were kame terraces and dead ice disintegration forms on the slopes of the valley. In the opinion of Drozdowski (1974) the Grudziądz Basin originated owing to glacial erosion during the Świecie Glaciation. Blocks of dead ice blocks persisted here beneath the coverage of morainic debris until the next, main stage of the Weichselian Glaciation. After its recession the basin had already been revealed due to melting out of buried ice blocks by the end of the Late Glacial period. These findings were supported by the results of the dating of biogenic sediments from the Fletnowo subglacial channel and Rudnickie Lake which indicate that analysis is needed relating to the whole terrace system but that the floodplain had already come into being before Allerød (Drozdowski & Berglund 1976; Drozdowski 1982). Drozdowski's observations were later confirmed on the sheets of Detailed Geological Map of Poland (Butrymowicz 1981; Maksiak 1983) and by the current author's study in the Świecie Basin (Kordowski 2005).

Of key significance to the understanding of the development of the lower Vistula valley is the issue of the assumed bifurcation. This is a common phenomenon (not to be confused with rivers anastomosing) in delta and fan settings but not in ordinary valleys. The confusion occurs most probably because some factors and events were not taken into consideration during the development of Galon's (1968) traditional model of terrace development. As is explained later, these new factors should be: (i) the origin of the large reaches of thelower Vistula valley fragments, which had already been developed before the main Weichselian Glaciation (see Makowska 1979, 1980, 1986; Brykczyński 1986; Marks & Pavlovskaya 2003), and (ii) the presence of blocks of dead ice during the formation of the terrace system during the upper Weichselian deglaciation.

Study area and research methods

The Grudziądz Basin is part of a large gorge running across till and outwash plains of the Frankfurt-Poznań and Pomeranian Phases. Buried valleys exist along its length which are linked to the Holsteinian and Eemian interglacials (Drozdowski 1982, 1986, 1992) and the Middle Vistulian (Wysota 2002). Glacial oscillations left many blocks of dead ice in this area.

Detailed geological and geomorphologic mapping was done in two test areas in the southern and south-western parts of the basin (Fig. 1). The results are presented in Figures 2 and 3. The fieldwork also consisted of hand-made borings and outcrop analyses together with sediment sampling. Sedimentological analyses comprised the determination of granularity and genetic interpretation of sediments, their internal structures and analysis of directional features (orientation of sand laminae).

Impact of dead ice on the relief and sediments in the Grudziądz basin and its vicinity

The impact of blocks of dead ice upon the relief and sediments in the study area is recorded by the presence of four types of landforms: (i) ice-crevasse forms on the valley floor, (ii) kame terraces on the valley slopes, (iii) kettle holes within the fluvial and fluvioglacial (outwash) terraces and (iv) a recreated subglacial channel dissecting the recent terrace system.

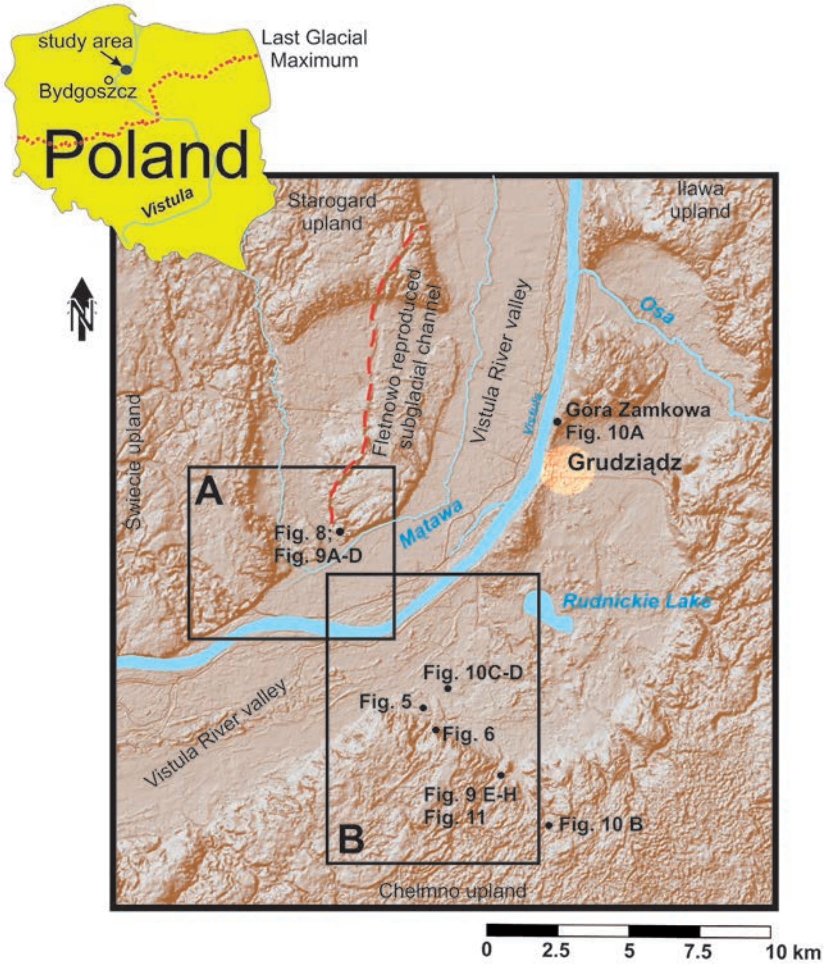


Figure 1. Shaded relief map of test areas in the Grudziądz Basin.

Ice-crevasse forms

The most appropriate example of ice-crevasse landforms in the Grudziądz Basin is the Gogolin site (Figs. 3, 4 and 5). It is a single form but relevant for further consideration as a source of information regarding the genesis of the Basin. Currently it is ca. 2.5 km in length. Its eastern part is buried beneath the sands of the former fluvial fan of the Młynkówka therefore its original length might have been much greater. Its maximum relative height is ca. 10 m. The form follows the alignment of the crevasse and is composed of separate ridges with a length from several dozen metres up to 700 m and a width of 20-150 m. They run straight in the SSW-NNE direction. The form is built up from an at least 10 m thick succession of fine sands with horizontal lamination and sporadic diamictic layers or, perhaps, lenses (Figs. 4 and 5). The top is slightly transformed to a depth of ca. 1 m due to Aeolian processes. Diamictic sands, diamictons, silts and diamictic silts occur at the base.

The presence of horizontal lamination in fine-grained deposits indicates tranquil water conditions and the domination of low-energy laminar flow. The geomorphologic features of the form analysed leave no doubt that it is of ice-crevasse origin. Originally, following geological maps, this sequence of landforms was marked as a dune (Jentsch 1901, 1909b; Maksiak 1983) but sedimentological analysis permits one to establish that Aeolian activity affected only the uppermost part. Moreover, the morphology of the presently

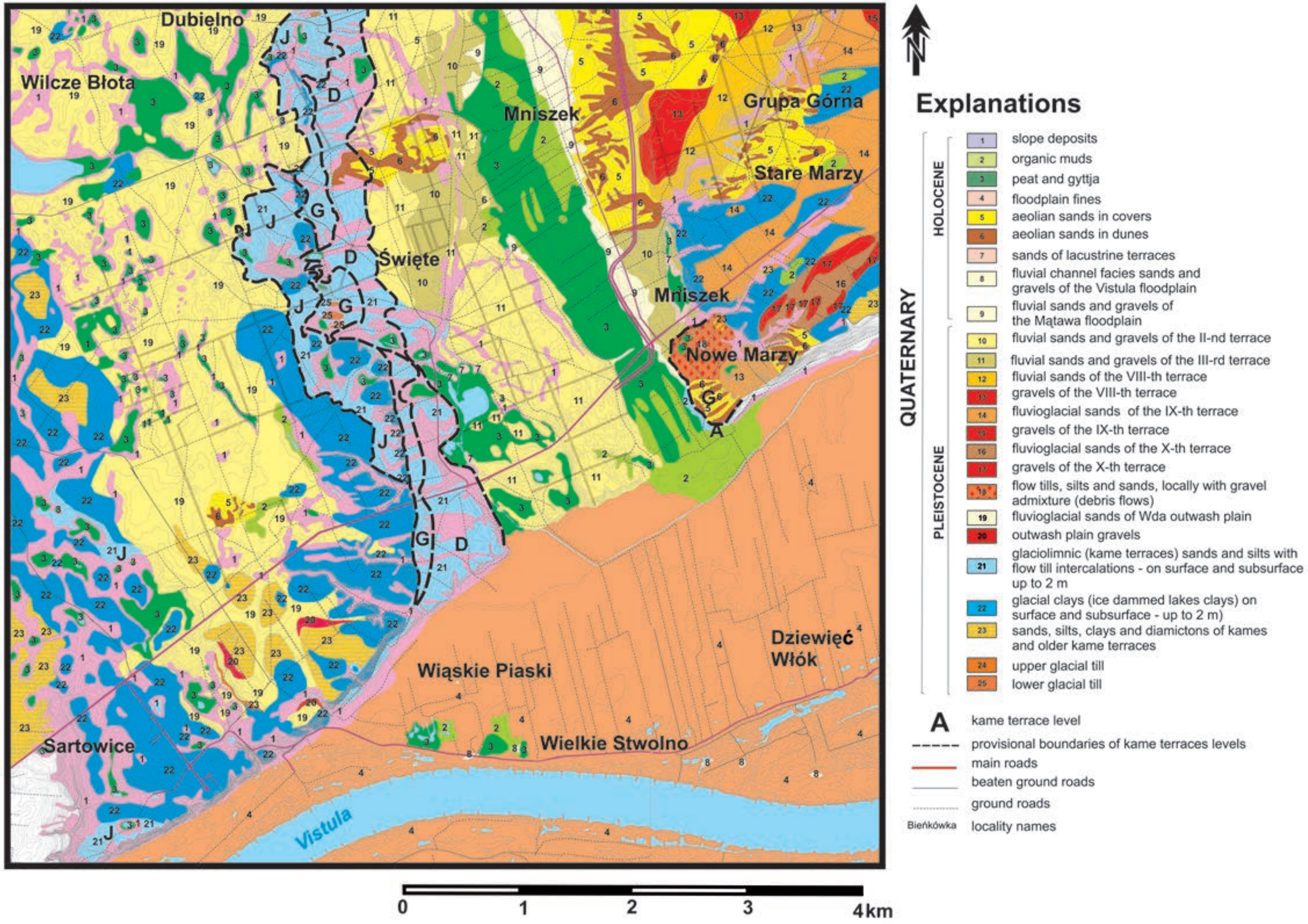


Figure 2. Geological map of the south-western part of the Grudziądz Basin. Detailed location in Figure 1.

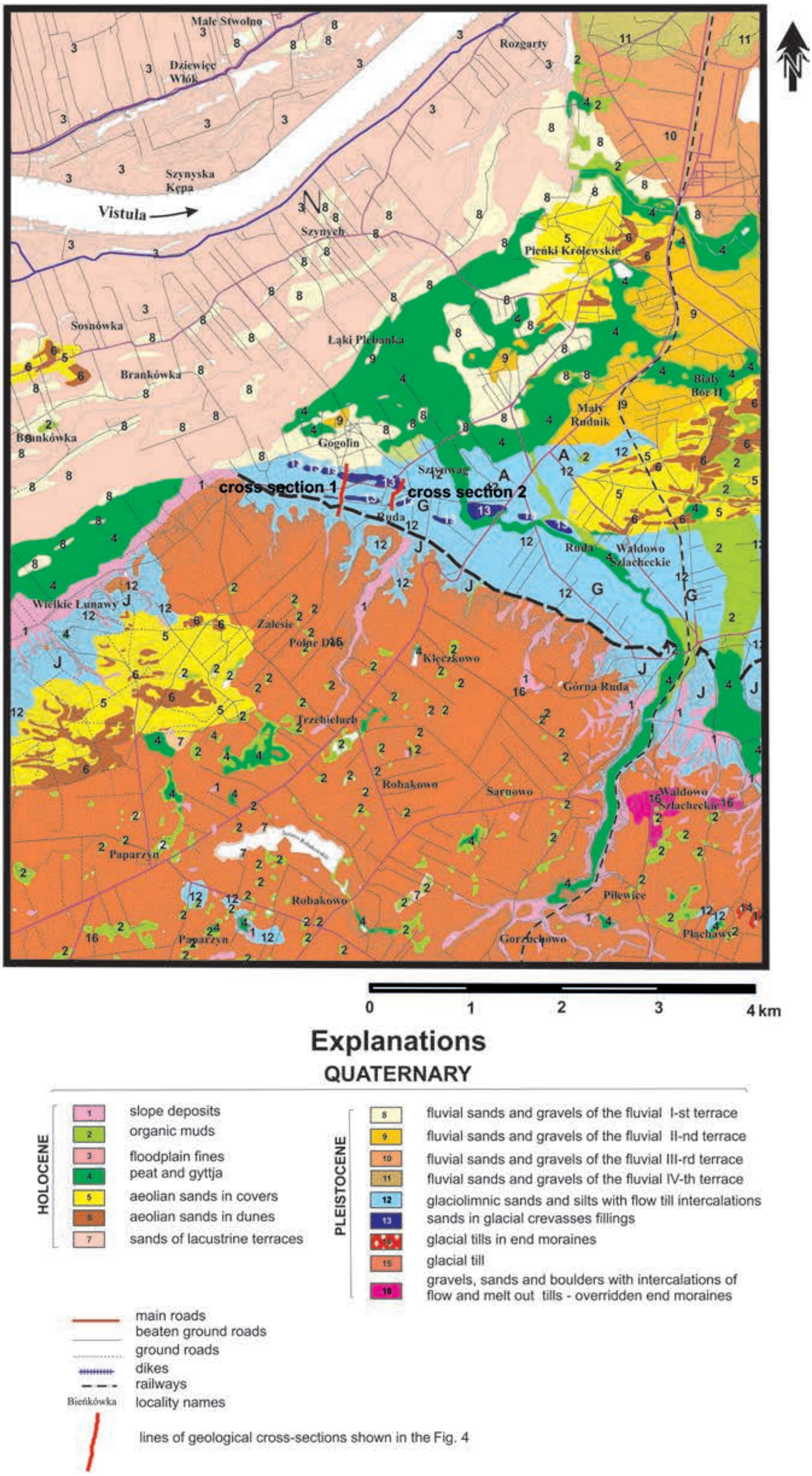


Figure 3. Geological map of the southern part of the Grudziądz Basin. Detailed location in Figure 1.

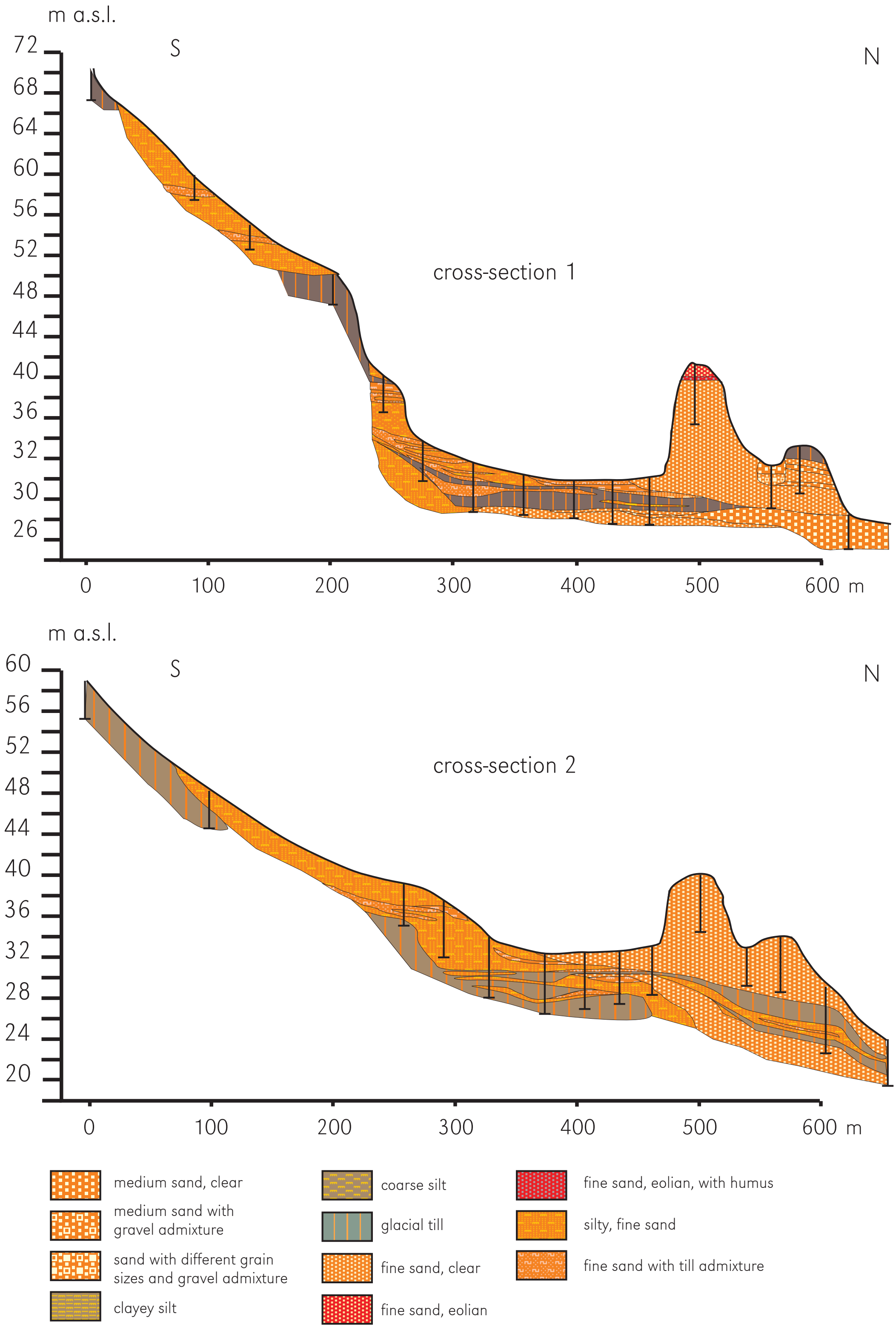


Figure 4. Cross-sections through the ice-crevasse hill in Gogolin. Cross section locations shown in Figure 3.

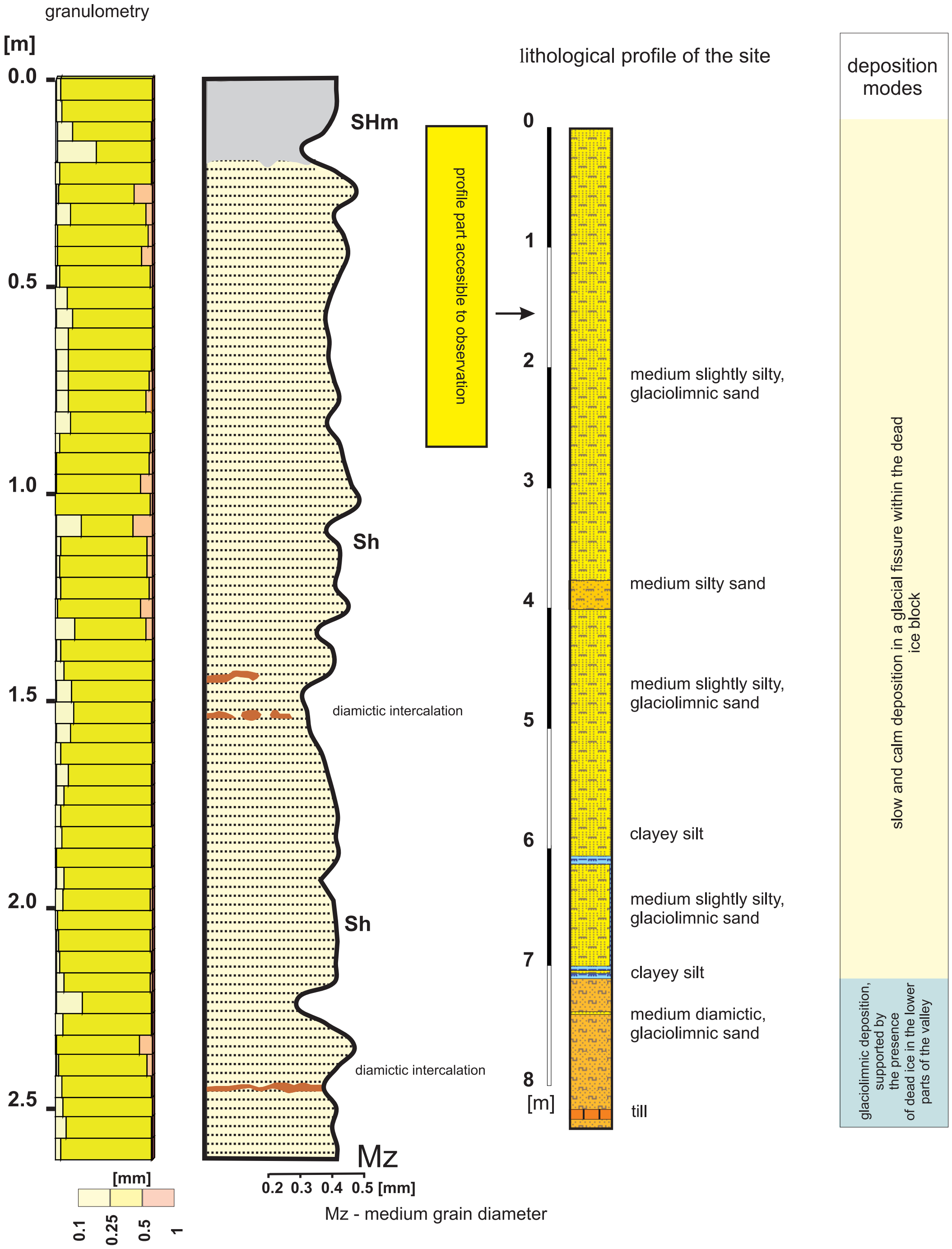


Figure 5. Sedimentary succession of the ice-crevasse form in Gogolin. The Sh lithofacies dominates in that part accessible to observation. Outcrop coordinates: 53°28’58.73’’N, 18°40’10.67’’E, altitude 43 m.

existing dunes in the study area is different from the example described above.

Kame terraces

Kame terraces are a common feature in glaciated areas. They are defined as the forms developing between substratum elevations and ice masses which force meltwaters to flow along the ice margin (Flint 1971; Jopling 1975; Klimaszewski 1981). Sometimes they are also called lateral kames (Karczewski 1971). In lowland areas they are common on the slopes of subglacial channels. Glacial depressions are also favourable areas for their occurrence. According to lithology, kame terraces are subdivided into glaciolimnic with a dominance of clays and silts, and glaciofluvial with a dominance of sands (Bitinas et al. 2004). In practice the majority of kame terraces have a much more complex origin.

In the southern part of the Grudziądz Basin there are two kame terrace sedimentary successions separated by glacial till of the last glacial advance. So far, there have been few observations of the older, buried terrace sediments which consist of laminated silty sands with dropstones (Fig. 6). Towards the glacial till plateau they change gradually into glaciofluvial sediments.

The most fully developed system of kame terrace levels in the study area occurs in the vicinity of Święte locality (Fig. 2). Level J is placed at 70-72 m with a width of 200-400 m; level G at 40-60 m with an average width of 100 m, maximum 400 m; level D at 35-40 m with a width of approximately 800 m on the left side of the valley and 1.5 km on the right side. Level A is the lowest with a height of 30-35 m and a width of over 1 km (partly buried by alluvial fans of small rivers entering the Grudziądz Basin). In the majority of cases there are no distinct edges between the levels which gradually merge into each other. This phenomenon is caused by the sequential processes of erosion on the valley slopes and subsidence due to the melting out of buried slices of dead ice, so the absolute height of levels may vary slightly in different parts of the Basin.

Internal structures of kame terraces

Over a dozen lithofacies of kame terraces were identified during fieldwork, the schematic geomorphologic and stratigraphic position of which is shown in Figure 7. The TL datings taken from a depth of about 2 m indicate that the sediments on the terrain surface were deposited during the Pomeranian Phase of the Weichselian Glaciation. The following lithofacies can be distinguished:

Fine, silty, horizontally laminated ***sands with dropstones SFh+dpsn*** (*dpsn – dropstone, S – sand, F – fines, h – horizontal stratification*). They were found in the small, deep valley of the Młynkówka River dissecting the 60-70 m high edge of the present Grudziądz Basin. This lithofacies package is ca. 2 m thick and lies beneath the last glacial till (Fig. 6). Their presence in the study area shows clearly that fairly deep water bodies formed in front of the snout of the advancing ice sheet depending on the local topography. These sediments are interpreted as deposited in a relatively deep water lake because the lamination would not have come into being in a reservoir undergoing thermal or wind mixing. Gravel clasts were rafted in from icebergs during the summer season. The sandy-silty texture of this lithofacies suggests that it was a lacustrine environment proximal to the ice masses, which were the source of clastic material (Sturm & Matter 1978).

Matrix-supported massive diamictons Dms (*D – diamicton, ms – matrix supported*). There is evidence for these at the foot of the valley slopes where they make beds of up to 6 m thick. The measurements of the orientation of the clasts showed a chaotic, multimodal azimuth pattern as well as a dip pattern. At the top, below the bioturbation zone, small sandy lenses with a diameter of up to 1 cm were observed. This diamicton is interpreted as flow till redeposited as dense cohesive flow filling up the crevasse at the contact between the valley slope and ice margin (cf. Zieliński & van Loon 1996). Noteworthy is the very low position of these sediments, almost at the level of the floodplain, which may indicate they were formed in deep ice crevasses.

Massive silts and clays Fm (*F – fine (clay+silt/s), m – massive*) *with occasional water escape structures.* There is evidence for these in numerous sites (Fig. 9A). Most often this lithofacies has been noted in the upper parts of the sedimentary successions. They reach a thickness of 0.5 m. As a rule, they do occur in bioturbation zones, therefore their primary structure is generally lost. They are interpreted as deposited from dense suspension during the rapid waning phases of floods. The conditions favourable to such deposition most

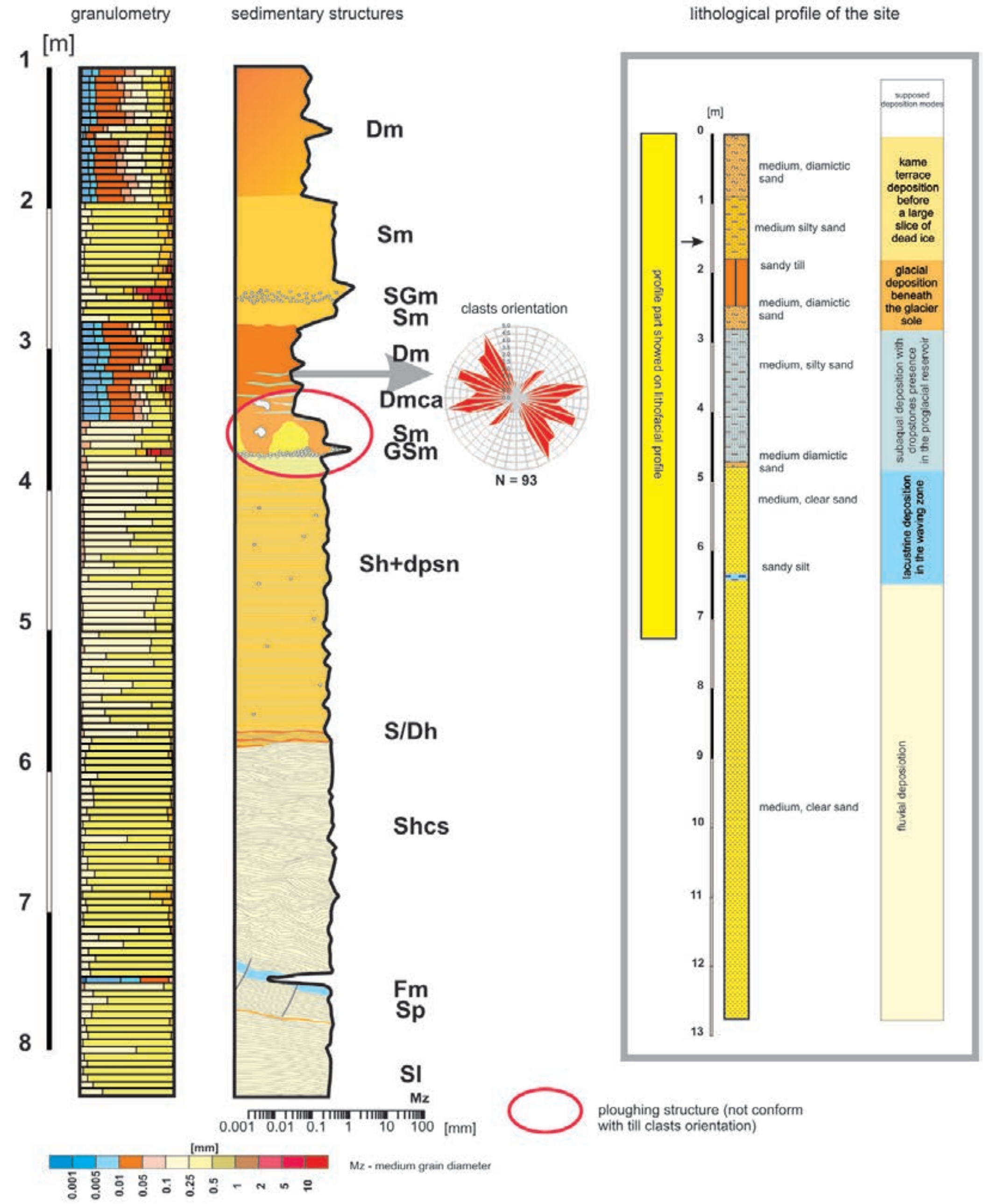


Figure 6. Sedimentary log of the kame terrace in Wałdowo Szlacheckie – horizontally laminated sands with dropstones beneath the till. Outcrop coordinates: 53°22'29.43''N, 18°43'1.47''E, altitude 70 m.

probably took place during periodic damming and draining of meltwaters as a result of mass flows from the valley slopes or blocks of dead ice.

Low-angle cross and horizontally stratified gravel and gravelly sand Gh, GSh, Gl, GSl. (*G – gravel, S – sand, l – low-angle cross-stratification, h – horizontal stratification*). These are found at the contact zone between the till plain and kame terraces in their uppermost sections (Fig. 8). The thickness of gravelly sets reach up to 1.5 m.

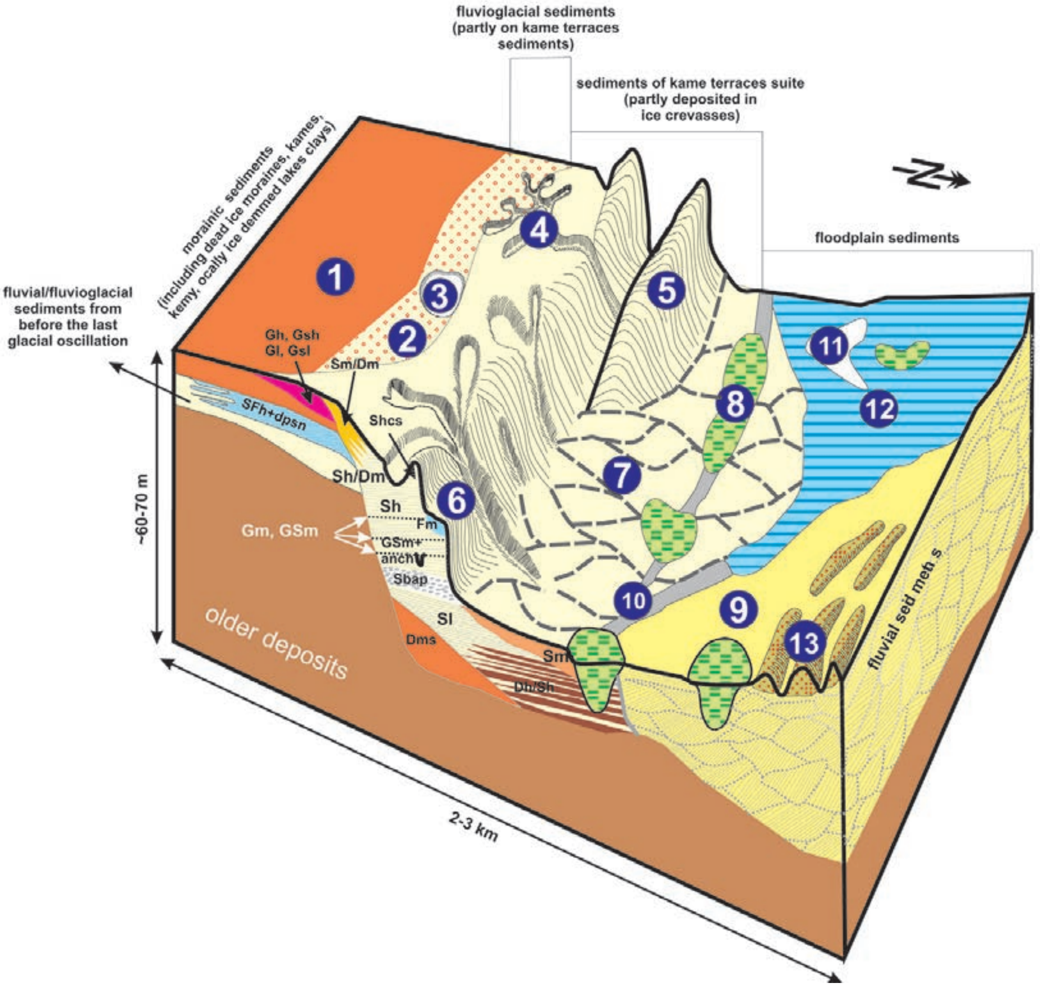


Figure 7. Model of kame terraces in the Grudziądz Basin. 1 – till plain (morainic plateau), 2 – fluvioglacial terrace, 3 – kettle hole, 4 – gully, 5 – ice-crevasse form, 6 – kame terrace, 7 – proluvial fans of redeposited sediments of kame terraces, 8 – peat fen in a kettle hole, 9 – fluvial terraces, 10 – meltwater routes, 11 – terrace remnants within the recent Vistula floodplain, 12 – Vistula floodplain, 13 – dunes. Further explanations in the text.

Laterally, towards the central parts of the valley, they change into finer sediments, mainly fine and medium, horizontally stratified sands. They are interpreted as the record of the initial phase of the development of the kame terrace in the highest topographic positions with intensive meltwater discharge. This lithofacies is deposited in the highest energy conditions observed in the study area.

Massive gravel and gravelly sand Gm, GSm. These lithofacies are thin, barely reaching several cm to a maximum of over a dozen cm. Despite only being weakly visible, normal gradation is noticeable. Massive gravel is interpreted as a channel lag in a fluvial sedimentary environment and marks rapid run-off of the reservoir water within the kame terraces, most probably as a result of the unlocking of outflow due to the melting of walls of dead-ice.

Medium sand with ball-and-pillow structures Sbap (*bap – ball-and-pillow structure*). These sets are of a thickness of up to 1.5 m (Fig. 9D). Individual ball-and-pillow structures reach several cm in diameter. All the disturbances have a plastic nature, devoid of faults. Considering the inclination of the underlying beds these structures may have been formed on a slope of between ten and twenty degrees. The range of the horizontal shift is difficult to estimate because of the limited space

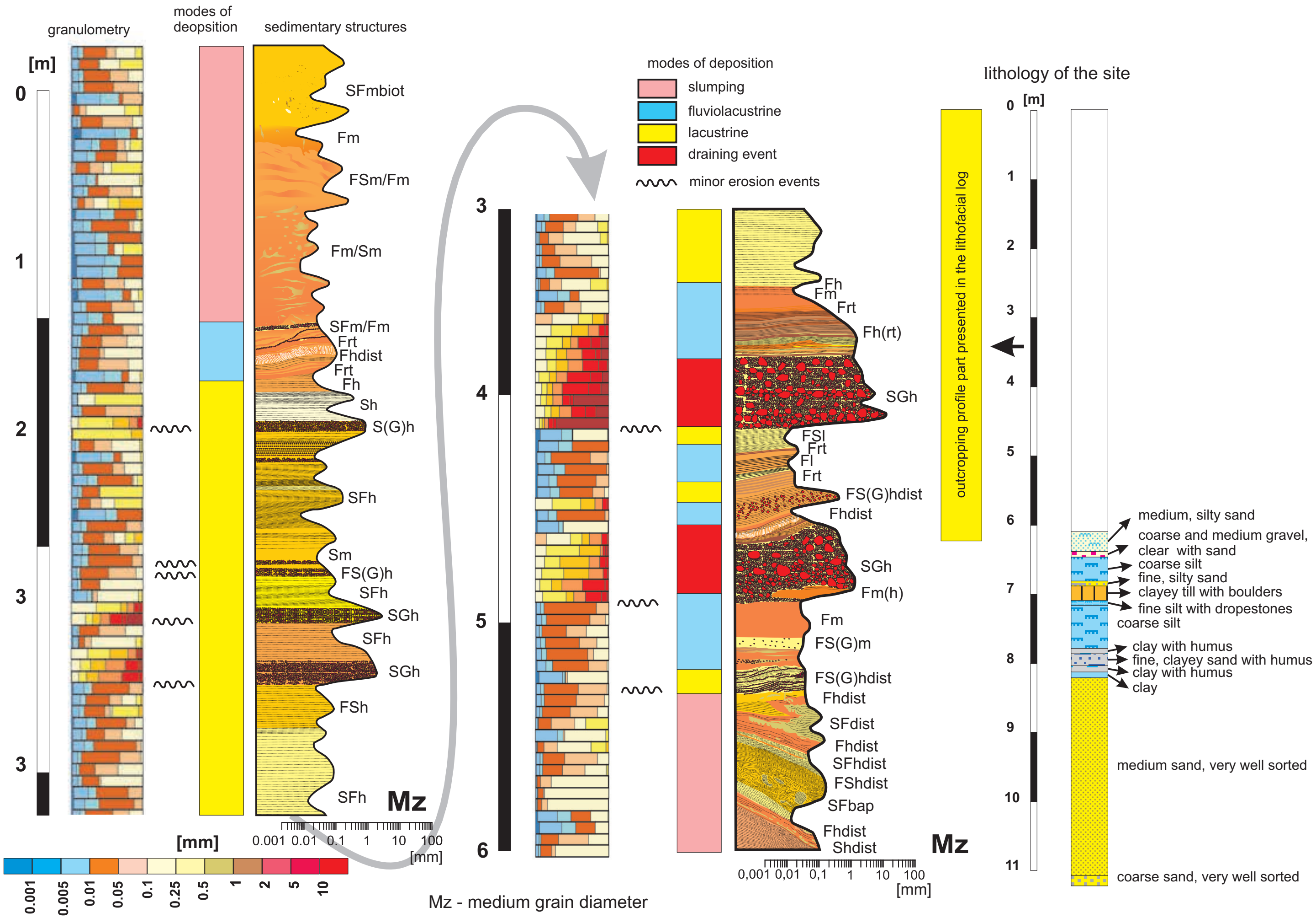


Figure 8. Kame terrace sediments in Nowe Marzy with traces of abrupt drainage marked by gravel lithofacies. The proven thickness of kame terrace sediments in this location exceeds 11 m. There are also lithofacies of glaciolimnic deposition and debris flows. Outcrop coordinates: 53°27′36.61′′N, 18°37′37.73′′E, altitude 36 m.

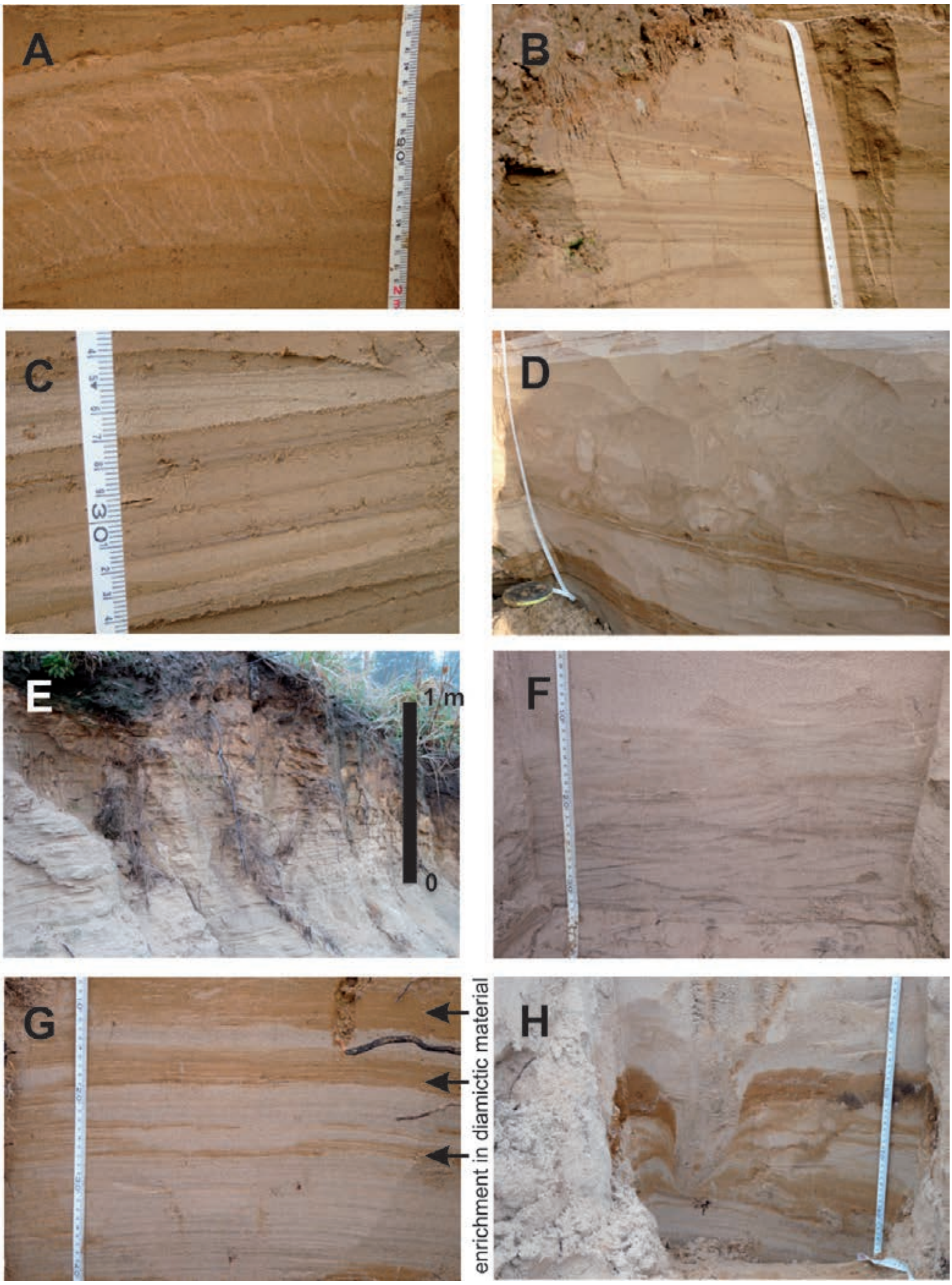


Figure 9. Details of some lithofacies of kame terraces in Nowe Marzy (A-D), outcrop coordinates: 53°27’36.61’’N, 18°37’37.73’’E, absolute height 36 m a.s.l. and details of some lithofacies of kame terraces in the Ruda outcrop (E-H); coordinates 53°23’35.28’’N, 18°41’35.65’’E, altitude 40 m.

A – hydrofractures associated with water escape under increasing pressure through accumulated porous sediments; B – glaciolimnic lithofacies, sandy-silty rhythmites deposited from turbidity currents; C – laminated sand and silt; rhythmic arrangement of sand and silt laminae reflects short-term cycles of ablation; D – ball-and-pillow structure in silty medium and fine sands indicating local fluidisation on the slightly inclined slope of the reservoir floor; E – horizontally laminated sand, the most common lithofacies; F – sediment of the shallow, marginal part of the lake; deposition of these structures was induced by wave and current action; G – horizontal stratification with enrichment with diamictic material from a moraine source; H – iceberg grounding structure ca. 80 cm deep; the central part of a trough 1.5 m long and 50 cm wide.

in the outcrop. Nevertheless taking into consideration that these structures were destroyed during a longer transportation and, for instance, transformed into Sh/Dm, Sm/Dm lithofacies, the distance of the shift would be estimated at the most to be a dozen metres. The structure originated as a result of a plastic flow of highly fluidised silty-sandy material, most probably due to the sudden raising of the water level in the depositional basin on the relatively steep bottom of the water reservoir (Owen 2003) or due to collapse of the supporting ice walls.

Fine, medium, horizontally and subhorizontally laminated sand Shl with occasionally laminated silt. This is a dominating lithofacies in the kame terraces making up ca. 2/3 of the volume studied (Figs. 9B, C, E and G). The sets revealed in outcrops are up to several m thick (probably over a dozen). This sediment type was probably deposited from laminar flows following the daily discharge rhythms of thawing meltwater.

Fine and medium horizontally laminated sands with diamictic intercalations Sh/Dm (*D – diamicton*). These occur in places where the kame terrace sediments were deposited in ice crevasses without a direct contact with the slope of the morainic plateau. Diamictic laminae appear at intervals of few or several cm and are up to 1 cm thick (Fig. 9G). These lithofacies originated due to shallow laminar flows with some input of glacial material from the distant ice masses (Syverson 1998). Variations of these lithofacies are ***fine and medium sands with diamictic intercalations Sm/Dm.*** Such sets reach a thickness of up to 2-3 m (Fig. 10C). They probably originated in a process of alternating sliding/slumping of glacial sediment due to melting out of the supporting walls of dead ice blocks and, in some cases, undercutting of the valley slopes combined with redeposition of material and segregation over a relatively short distance of up to several dozen m.

Fine and medium, massive sand Sm. These reach tens of cm in thickness. There is no internal gradation within the beds of the sediment. Due to their relatively large thickness, the sediments should be treated as deposited from gravitational non-cohesive flow moving short distances in a subaqueous setting and induced by subaqueous landslides.

Fine and medium, ripple laminated sand Sr (*r – ripples*). Ripple lamination is fairly commonly encountered in kame terrace sediments. The sets reach several dozen cm. They are accompanied by sand of a lenticular structure. In some cases this lithofacies is quite similar to a small-scale hummocky cross stratification. As a rule, ripple structures represent current-derived forms. All the features mentioned indicate that the development of these structures took place within the shallow shore zone of a water body with abundant tractional flows (Allen 1982).

Fine and medium sand with wavy and lenticular lamination Slent (*lent – lenticular*). Lenticular lamination is found in the upper parts of the successions, in packages up to several dozen cm thick (Fig. 9F). Individual lenses are up to 5 cm thick and up to 20-30 cm long. In the case of the Vistula valley, lenticular and wavy lamination implies high water turbidity and mixed deposition from traction and suspension over sporadically moving individual ripples and wrinkles of pure sand indicating a temporary increase in water flow energy in the shore depositional system. After the water level increased, ripple lamination and individual sandy wrinkles developed in the sedimentary sequences.

Disturbed laminated sand Sdist (*dist – disturbed*). Disturbance zones were noticed at over 100 m distance in an outcrop in Górna Grupa. The depth of this zone reaches over a dozen m. The inclination of laminae imitates the slope gradient and locally is over 40-45 degrees. The sequence is partially slightly undulated due to the force of gravity acting on the sediment mass with an undulation radius of several dozen cm. The disturbances were probably caused by the plastic flow of oversaturated sandy sediments due to melting and the disappearance of supporting ice walls. Their primary structure seems to have been horizontal lamination or low angle cross lamination. Among the disturbed structures ***pure sand and gravelly sand within the iceberg grounding structures Sm+anch, GSm+anch*** (*anch – anchor structure,* Figs. 9H, 11) can be observed. Only one example of a structure was observed which was approximately 30-40 cm wide and 60 cm thick. The length of the structure was 1.5 m. There is no layer of gravels and increased sand diameter at the bottom of this structure, which excludes the possibility of genesis by current erosion. The lack of coarse-grained infill suggests that it cannot be a structure derived from fluvial erosion (Winsemannn et al. 2003).

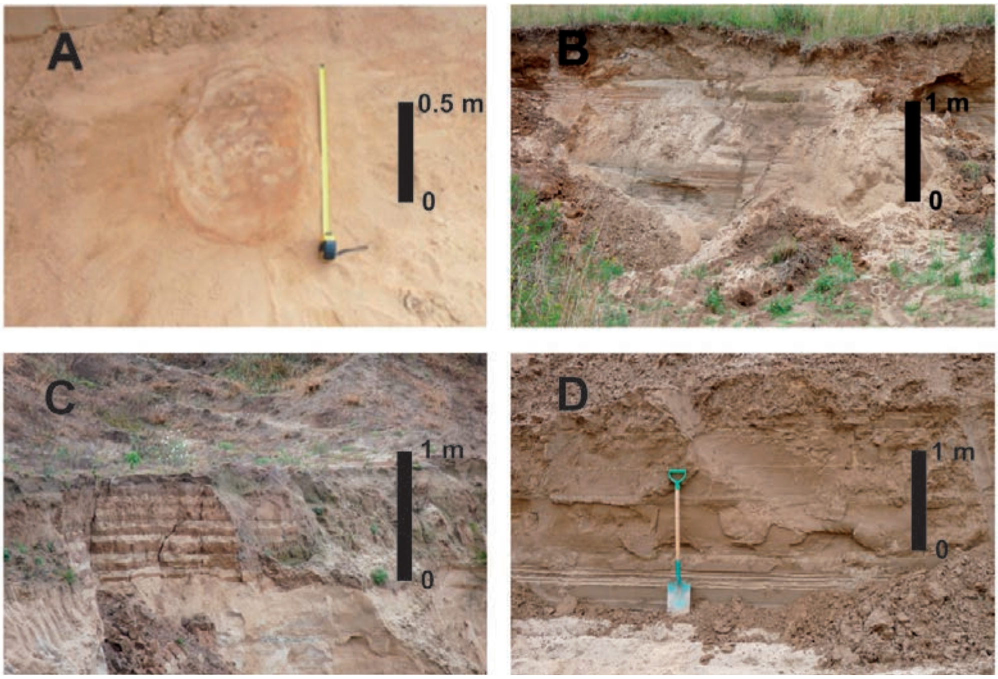


Figure 10. Details of some lithofacies of kame terraces in the southern part of the Grudziądz Basin.

Continuation: A – glacial till block within sandy deposits of a kame of a thickness of about 4 m. The block has a diameter of 0.5 m. Due to the lack of opportunity for slumping to occur, this is proof of the existence of floating icebergs; outcrop coordinates: 53°29′42.12′′N, 18°44′57.25′′E, altitude 65 m; B – sandy-silty-gravelly rhythmite in the vicinity of Błędowo. This is one of the highest geomorphological positions occupied by kame terrace sediments from the earliest stages of the deposition; outcrop coordinates: 53°22′31.17′′N, 18°45′8.94′′E, altitude 88 m; C – sandy-diamictic rhythmite in Gogolin; outcrop coordinates: 53°24′10.11′′N, 18°40′57.43′′E, altitude 28 m; D – laminated glaciolimnic diamicton in Gogolin. Many sandy intercalations are visible in the basal section. Outcrop coordinates as in C.

Horizontally laminated diamicton and sandy diamicton with sand intercalations Dh/Sh. Theyse reach a thickness of up to 2-3 m. The thickness of the diamictic layers is irregular – from several to over a dozen cm (Figs. 10B, D). Their granulometric composition is polymodal – sandy-silty-clayey. Sandy intercalations occur in the lower parts of these sets. The presence of a disruption of the sandy layer, taking the form of bows or dishes, is associated with water escape through porous material. Intercalations of sand a few mm to a few cm thick periodically occur in the diamictic material. These lithofacies were derived from small but numerous lakes in places where melting of ice blocks occurred. The sediment underwent short distance transport because its primary polymodal composition is preserved. The absolute dominance of layers in a horizontal arrangement and sporadic occurrence of water escape structures suggest deposition within a fairly deep water body below the wind and thermal mixing zone.

Fine and medium sands with dump structures Sds (*ds – dump structure*). These were identified in Góra Zamkowa in Grudziądz (Fig. 10A). The diamicton block was excavated at the top of a kame and had a diameter of 0.5 m, clearly indicating the existence of icebergs in the lakes dammed by ice masses.

Kettle holes

Kettle holes are a common feature of former glacial landscapes. Their presence is not often mentioned on fluvial terraces, while in the lower Vistula valley these forms are quite abundant on almost all levels of terrace. Their diameter reaches well over 500 m. In the case of Rudnickie Lake it is over 1 km. The depth of organic deposits recorded in their centres exceeds 5.5 m. Their infilling had already begun in Allerød which was proved by the palynological investigations of Noryśkiewicz (2005). Initially, peat was accumulated in them but at the beginning of the Holocene gyttja began to dominate the process.

Reproduced subglacial channel in Fletnowo

The presence of the reproduced subglacial channel of Fletnowo cutting through the southern part of the Starogard Plateau and farther on almost all levels of terrace in the western part of the Grudziądz Basin is one of the strongest pieces of evidence of fluvial and fluvioglacial deposition in the presence of blocks of dead ice. The reproduced segment of the channel within the basin is 10 km long and approximately 100-200 m wide. It consists of many hollows up to 30 m deep. These hollows are filled with slope deposits of at least 3 m thickness. Peat infill occurs only locally on the lowest terraces of the valley. The presence of the subglacial channel indicates that the movement of living ice took place during its formation. The presence of numerous kettle holes along the course of the channel proves that subsequent deposition occurred over the ice. A detailed morphogenesis of this landform requires further intensive investigations.

Discussion

Landforms and deposits linked to the glaciolimnic sedimentary environment occur abundantly in the Vistula valley. They were already mentioned by Skompski (1969) in the Płock Basin. In the Grudziądz Basin they were described in the numerous papers of Drozdowski (e.g. 1974, 1979, 1982). These landforms were also marked on the *Detailed Geomorphological Map of Poland* (Butrymowicz 1981; Maksiak 1983). The influence of blocks of dead ice upon the formation of the terrace system was also described by Kordowski (2001, 2009) in the Unisław and Świecie Basins. Some geomorphological evidence in the tributary valleys of the Wda and Wierzyca may also indicate the presence of dead ice in the Vistula valley. The Wda valley, described by Andrzejewski (1994), has in its lower reach and excluding the floodplain at least 15 levels more than the Vistula valley itself. The Wierzyca valley has developed kame terraces at its contact with the Vistula valley (Błaszkiewicz 1998). The presence of blocks of dead ice indicates that the present form of the valley originated partly prior the last glacial advance.

During the sedimentological investigations, sediments related to the glaciolimnic environment (horizontally laminated fine silty sand with dropstones) were found in a few sites beneath the till of the Weichselian Glaciation. This proves the existence of glaciolimnic reservoirs prior to the advance of the last glaciation. In Kłęczkowo, in the locations of present-day gullies dissected during the construction of the A1 motorway, these sediments occurred as infillings between two glacial tills: below the last glacial till and over the last but one. These intercalations are up to 200 m wide and 3-4 m thick. Hence it may also be supposed that many features of the present-day Grudziądz Basin were formed before the last glacial advance. The kame terrace deposits in the Grudziądz Basin were accumulated in the zones between the dead ice margin and the slopes of the surrounding morainic plateau (see model in Fig. 12). Initially, they were filled with debrites and then with coarse-grained material (massive and horizontally stratified gravels) gradually changing to sandy/diamictic rhythmites and finally to the most widespread facies of laminated sands. An important feature of the kame terrace deposits in the Grudziądz Basin is the rare presence of channelised structures (cross stratifications, which are diagnostic for typical fluvial and fluvioglacial terraces). Horizontal lamination, derived from low-energy laminar flow, is the most predominant depositional structure there. The presence of laminations with dropstones, sets of massive fine and wavy laminations, indicate the existence of local water bodies. In turn, the ball-and-pillow structures and thick sets of massive sands suggest fluidisation and subaqueous landslide development as a result of the abrupt raising of water levels.

Considered as a whole, the diversity of internal structures points to very dynamic oscillations of the level of meltwater reservoirs. The lithofacies presented seem to differ strongly from those discovered in mountainous settings (cf. Pisarska-Jamroży et al. 2010) due to their larger diversity and a strong dominance of low-energy non-channelised internal structures in the finer-grained spectrum of sediments than those described there.

The situation described in the area discussed may indicate that other large valleys in the formerly glaciated parts of the Baltic catchment, within their inherited reaches, may have undergone a similar stage of formation of 'dead ice' relief as that occurring during the decline of the Weichselian Glaciation on the lower Vistula River.

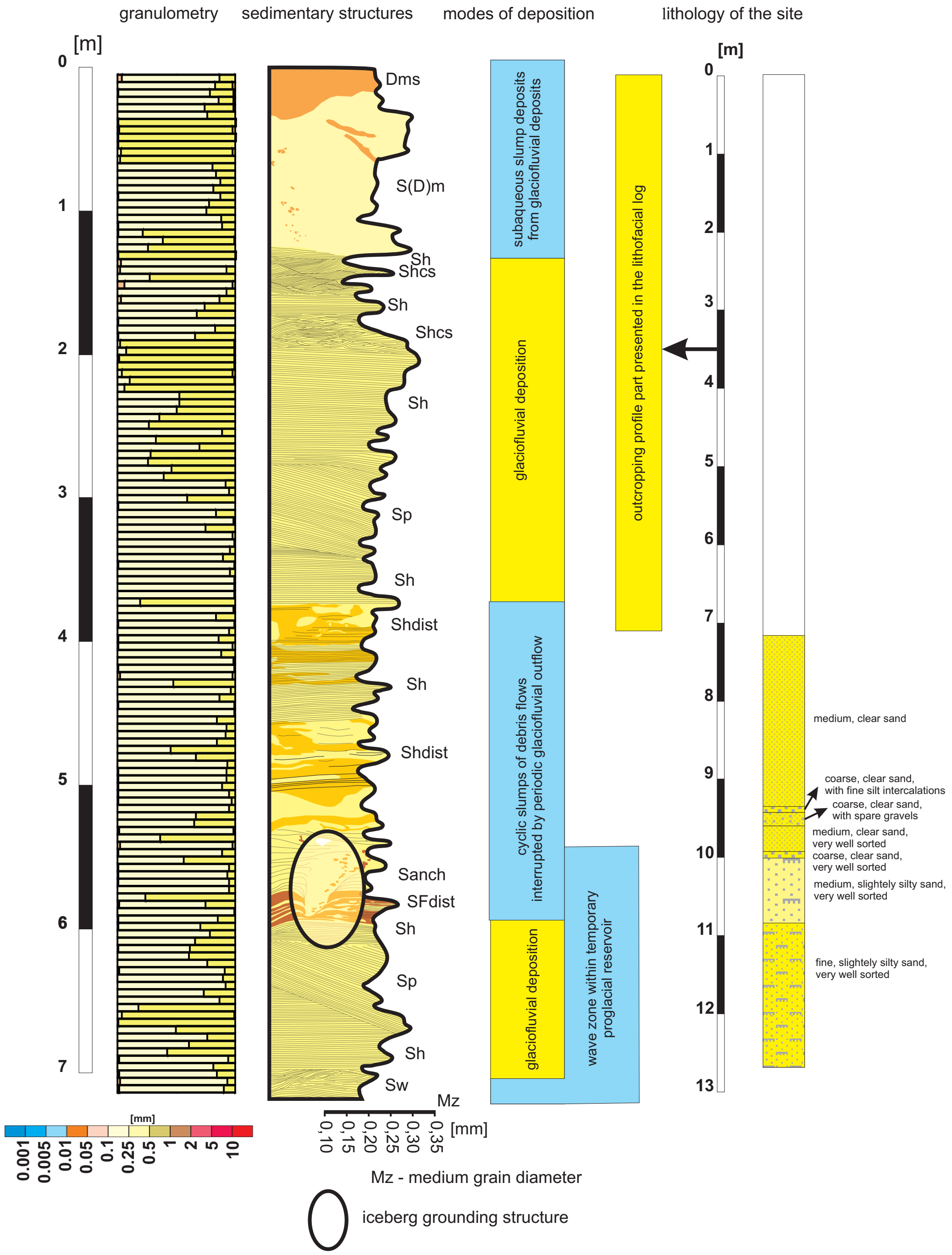
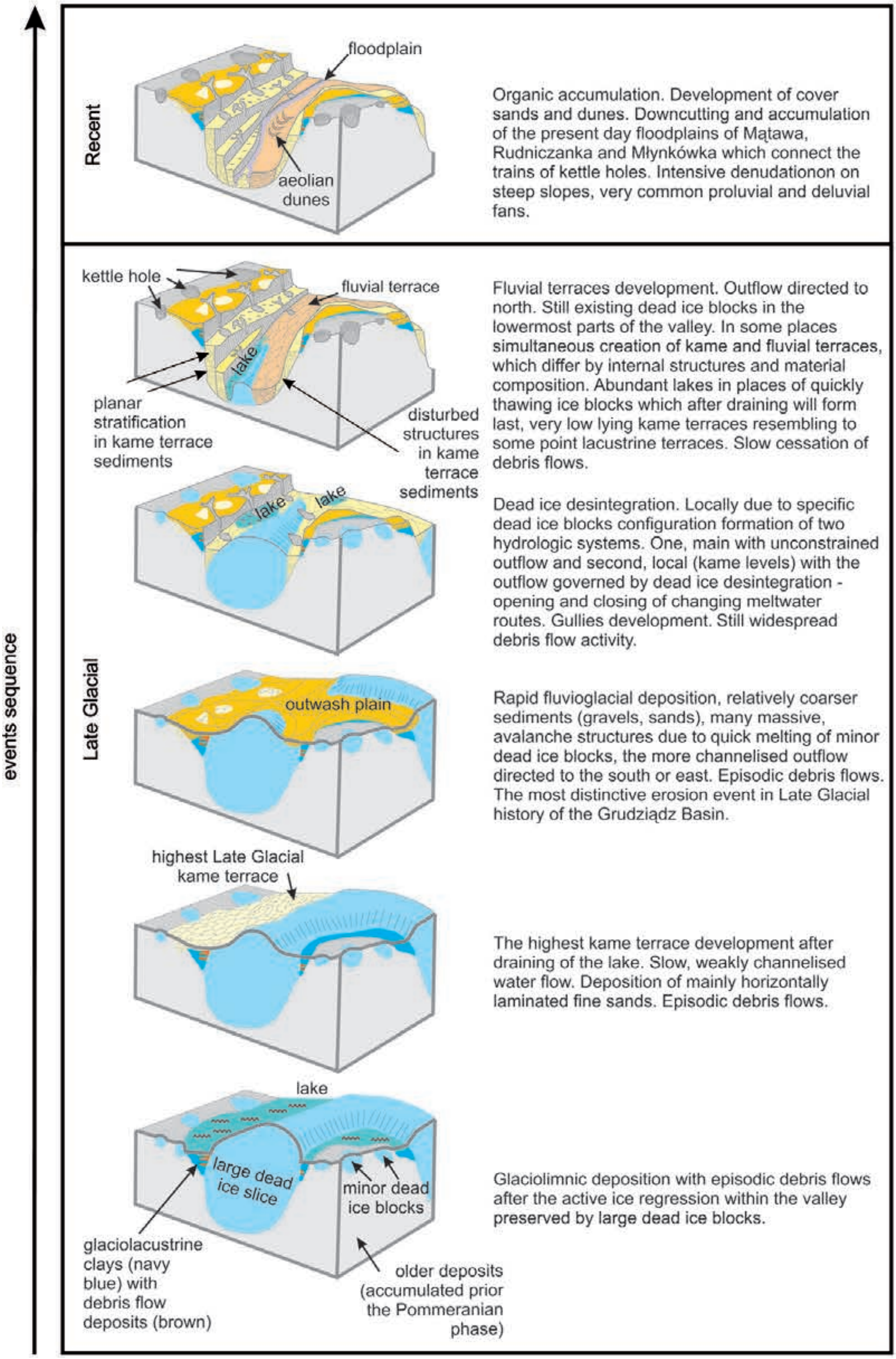


Figure 11. Properties of the kame terrace sediments. The site at Ruda with an example of an iceberg grounding structure. The proven thickness of the kame terrace sediments is almost 13 m. Alternating glaciofluvial, glaciolimnic and sediment slumping lithofacies dominate. Outcrop coordinates: 53°23'35.28''N, 18°41'35.65''E, altitude 40 m.



Organic accumulation. Development of cover sands and dunes. Downcutting and accumulation of the present day floodplains of Mątawa, Rudniczanka and Młynkówka which connect the trains of kettle holes. Intensive denudationon on steep slopes, very common proluvial and deluvial fans.

Fluvial terraces development. Outflow directed to north. Still existing dead ice blocks in the lowermost parts of the valley. In some places simultaneous creation of kame and fluvial terraces, which differ by internal structures and material composition. Abundant lakes in places of quickly thawing ice blocks which after draining will form last, very low lying kame terraces resembling to some point lacustrine terraces. Slow cessation of debris flows.

Dead ice desintegration. Locally due to specific dead ice blocks configuration formation of two hydrologic systems. One, main with unconstrained outflow and second, local (kame levels) with the outflow governed by dead ice desintegration - opening and closing of changing meltwater routes. Gullies development. Still widespread debris flow activity.

Rapid fluvioglacial deposition, relatively coarser sediments (gravels, sands), many massive, avalanche structures due to quick melting of minor dead ice blocks, the more channelised outflow directed to the south or east. Episodic debris flows. The most distinctive erosion event in Late Glacial history of the Grudziądz Basin.

The highest kame terrace development after draining of the lake. Slow, weakly channelised water flow. Deposition of mainly horizontally laminated fine sands. Episodic debris flows.

Glaciolimnic deposition with episodic debris flows after the active ice regression within the valley preserved by large dead ice blocks.

Figure 12. Model development of kame, fluvioglacial and fluvial terraces in the Grudziądz Basin.

Conclusions

The sediments and relief of the lower Vistula River valley in the study area seem to reveal some signs of glacial-derived landforms, only reworked by fluvial processes after the retreat of the last ice sheet (cf. Brykczyński 1986). This is evidenced by i) ice-crevasse forms, ii) kame terraces, iii) abundant kettle holes, iv) reproduced subglacial channels dissecting the whole terrace system. The most important evidence, however, is the existence of kame terraces on the valley slopes.

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Unless otherwise stated, the sources of tables and figures are the author(s), on the basis of their own research.

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