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The evolution of a Weichselian proglacial lake in NW Poland as revealed by static penetration tests

Jędrzej Wierzbicki[1], Renata Paluszkiewicz[2] & Ryszard Paluszkiewicz[2]

[1] Department of Geotechnics, Poznań University of Life Sciences, Piątkowska 94, 60–649, Poznań, Poland; e-mail: jw@up.poznan.pl & Institute of Geology, Adam Mickiewicz University, Maków Polnych 16, 61–606, Poznań, Poland
[2] Institute of Geoecology and Geoinformation, Adam Mickiewicz University, Dzięgielowa 27, 61–680, Poznań, Poland; e-mail: reniach@amu.edu.pl, paluch66@amu.edu.pl

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Abstract

The lithology, structure and geophysical characteristics of the glaciolacustrine clays deposited in the Wierzchowo proglacial lake were determined using static penetration tests (CPTU) in combination with standard lithological measurements. The deposits are divided into four lithological units (R1 to R4) on the basis of overconsolidation. Units R3 and R4 are separated by mass-flow deposits.
The depositional conditions history of the lake result represent four phases: (1) an initial (low-energy) phase with the deposition of the rhythmically laminated sediments of units R1 and R2, which are divided by an erosional interval; (2) a phase of non-deposition with some desiccation structures and extended consolidation of sediments; (3) the main phase characterised by deposition of the rhythmically laminated sediments of unit R3; and finally, (4) the youngest phase, which represents alternations of deposition and erosion. The results show that sedimentation in the Wierzchowo proglacial lake was less continuous, and that the depositional processes were more complex than in the neighboring Złocieniec glacial lake.
Keywords: glaciolacustrine deposits, varves, overconsolidation, CPTU method, Pomeranian Lakeland, Poland

1. Introduction

According to research carried out over 30 year ago (Maksiak & Mróz, 1978), the area around Złocieniec and Wierzchowo in the Pomeranian Lakeland (NW Poland) formed a vast proglacial lake during the Pomeranian phase of the Weichselian glaciation. The Wierzchowo and Złocieniec sites were interpreted as parts of the same glacial lake, i.e. with similar sedimentary conditions and deposits (Maksiak & Mróz, 1978; Kłysz, 1990). It was found only later, on the basis of drillings, that the glaciolacustrine deposits of the Złocieniec and Wierzchowo glacial lakes are separated by glaciofluvial deposits (Paluszkiewicz, 2004) and that the Wierzchowo site may constitute an individual proglacial lake basin. The area of Złocieniec has already been investigated in detail in order to determine the sedimentary conditions of its rhythmically laminated deposits (Paluszkiewicz, 2004).

The previous studies provide too little data, however, to describe the evolution of the Wierzchowo lake. Its deposits have now been investigated by means of a detailed lithology description and by geoengineering studies based on static penetration tests (CPTU).

Geoengineering tests such as CPTU are not commonly applied and have consequently rarely been described for the purpose of lithostratigraphical studies, especially in the case of glaciolacustrine deposits (Sully et al., 1988; Mayne, 1991, Mayne & Kulhawy, 1991, Lunne et al., 1997).

The present study was aimed at determining the depositional conditions of the glacial lake in order to reconstruct its evolution. The detailed characteristics of the Wierzchowo glaciolacustrine deposits, located in the neighbourhood of the glacial channel of Lake Wąsosze, have provided the data for this reconstruction.

2. Geomorphology and geology of study area

The area of the Wierzchowo proglacial lake is located in the southern part of the Drawsko Lake District (a part of the Western Pomeranian Lake District). The Drawsko Lake District is a morphologically diversified area (with altitudes ranging from 100 to 238 m a.s.l.) covered in most places by till. Numerous end moraines and glacial channels are present, as well as dead-ice depressions. In the middle part of the area, an end-moraine ridge occurs, often exceeding 200 m a.s.l. According to Keilhack (1901, 1930), Galon & Roszkówna (1967), Karczewski (1994) and others, this zone represents the maximum extent of the Pomeranian phase of the Weichselian glaciation.

The southern part of the Drawsko Lake District is less morphologically diversified, and is up to 160 m a.s.l. The Wierzchowo proglacial lake in the foreland of the Pomeranian phase end moraine forms a flat plateau which reaches 130–135 m a.s.l., and which is covered by glaciolacustrine deposits.

The exposure of the Wierzchowo glaciolacustrine deposits is located in the scarp along Lake Wąsosze, at its south-eastern end (Fig. 1). Lake Wąsosze is located in a glacial channel of approx. 0.5–1 km wide, at its northern end reaching the Złocieniec proglacial lake. Several ditches were dug in the central part of the scarp of an abandoned brick-yard pit.

According to archive data (Geological documentation 1977, unpublished), the glaciolacustrine succession in the Wierzchowo area is not thicker than 10 m. A unit of fine- to medium-grained glaciofluvial sands occurs below these glaciolacustrine deposits. Depressions in the surface of the sands are filled with silty sand, which indicate most probably the initial phase of the evolution of the glacial lake. The sedimentary succession of the glacial lake consists of two units, viz. (1) a varved clay overlain by (2) a massive silt. The varved clay varies considerably in thickness (4–11 m), whereas the overlying massive silt is 1–1.5 m thick. The varved clay is commonly the most prominent, particularly in the NE part of the lake area. The SW part is characterised by a thick silt unit.

3. Methods

Static Cone Penetration Tests (CPTU) were performed according to the standard procedure, described in detail by Lunne et al. (1997) and Schnaid (2009). The tests were performed to a depth of 15 m, and recorded the cone resistance (q_t), sleeve friction (f_s) and induced pore pressures (u_1 and u_2) (Fig. 2). The results allowed to characterize the soil behaviour according to the classification diagrams of Robertson (1990). Based on the interpretation by Wierzbicki (2002), it was also possible to assess the overconsolidation ratio (OCR), as well as numerous sediment characteristics connected with their shear strength and susceptibility to deformation.

The OCR has been defined by Casagrande (1936) as the ratio between the maximum effective value of the vertical component of geostatic stress, found at any time in a given subsoil point, and the present effective value of the vertical component of geostatic stress. The OCR index does, however, not always reflect changes in strength parameters unambiguously, as these are generated as a consequence of the overconsolidation process. This results from several postdepositional processes that effect the behaviour of the subsoil (Crawford, 1986; Locat et al., 2003).

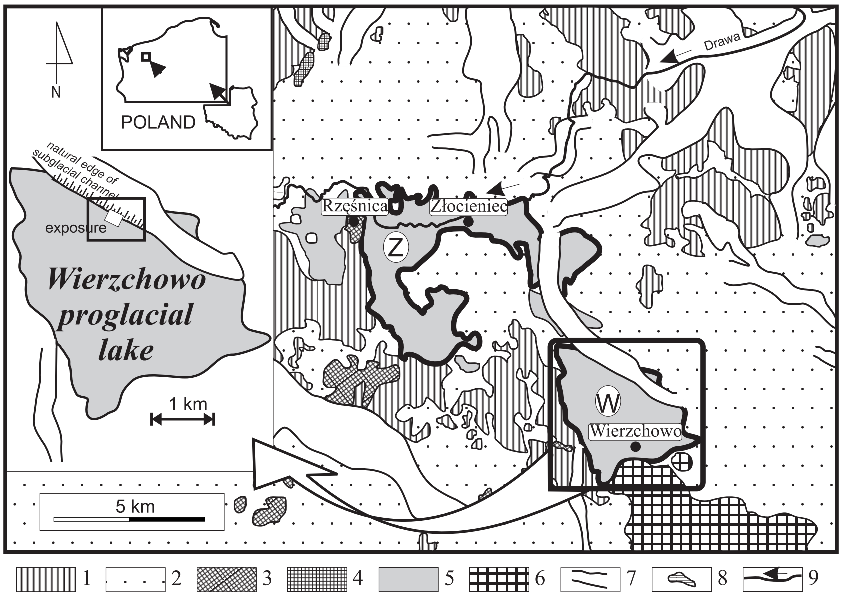

Fig. 1. Lithological and geomorphological setting of the Wierzchowo proglacial lake (modified after Kłysz, 1990).
1 – till of Pomeranian phase, 2 – glaciofluvial sands and gravels, 3 – end moraines of the Pomeranian phase of maximum extent, 4 – recession end moraines, 5 – glacial lakes, 6 – areas of the Pomeranian phase (after Kłysz, 1990), 7 – glacial troughs, 8 – lakes, 9 – rivers.

As shown by Wierzbicki et al. (2006), the assessment of the overconsolidation ratio profile may reflect the depositional and erosional stages within a sedimentary profile. A sudden change within the OCR profile, evaluated on the basis of CPTU, indicates (even in the case of further similar lithology) a change in conditions (for example, changes in groundwater level or loading/unloading of the subsoil).

Grain-size analyses have been based on the soil texture (following a classification widely used in environmental sciences, among others the classification developed by the United States Department of Agriculture system (Das, 1985). According to this classification, eight grain-size groups were distinguished and their percentages are calculated for the entire population of 26 samples. The calcium-carbonate content was also analysed, using a Scheibler apparatus.

4. The glaciolacustrine succession

The glaciolacustrine succession is up to 13 m thick. The top of the underlying sandy deposits is situated at a depth of 14.5 m (Figs 3 and 4). The glaciolacustrine succession starts with a layer of medium-grained, massive sand which is characterised by strong consolidation (as found by CPTU testing).

Varves build the majority of the succession (Paluszkiewicz, 2004), which consist of alternating light and dark brown-grey laminae. Medium silt tends to dominate in the lower, light-coloured varve lamina (0.006-0.02 mm) (Fig. 3). Finer fractions are also present in considerable amounts, with over 24% of fine silt (0.002-0.006 mm) and 21% of colloidal clay (<0.002 mm). Coarser fractions of over 0.02 mm occur in small amount. The light laminae are characterised by 10–20% of colloidal clay and the content of silt is some 10% higher than in the dark laminae, which contain over 24% of colloidal clay, with a maximum content not exceeding 30%. In both types of laminae, the sandy fraction makes up to 4%. The calcium-carbonate content is slightly (approx. 3–5%) higher in the light laminae (which contain 13–20%) than in the dark laminae. The succession is not homogenous, however, and can be subdivided into several units. The subdivision of this glaciolacustrine succession is based on both a lithological analysis and geoengineering tests. Units R (rhythmites – varves) and S (deformed varves) were described in detail (Figs 2 and 3).

Although the whole succession of the R units is lithologically similar, it can be subdivided into three parts on the basis of its geoengineering properties and parameters, such as cone resistance (q_t), friction ratio (R_f) and overconsolidation ratio (OCR) (Fig. 2). All subunits (R_1, R_2, R_3, R_4) show some differences in the abovementioned parameters. R_1 is 3 m thick and has all characteristics of varves. R_2 starts with

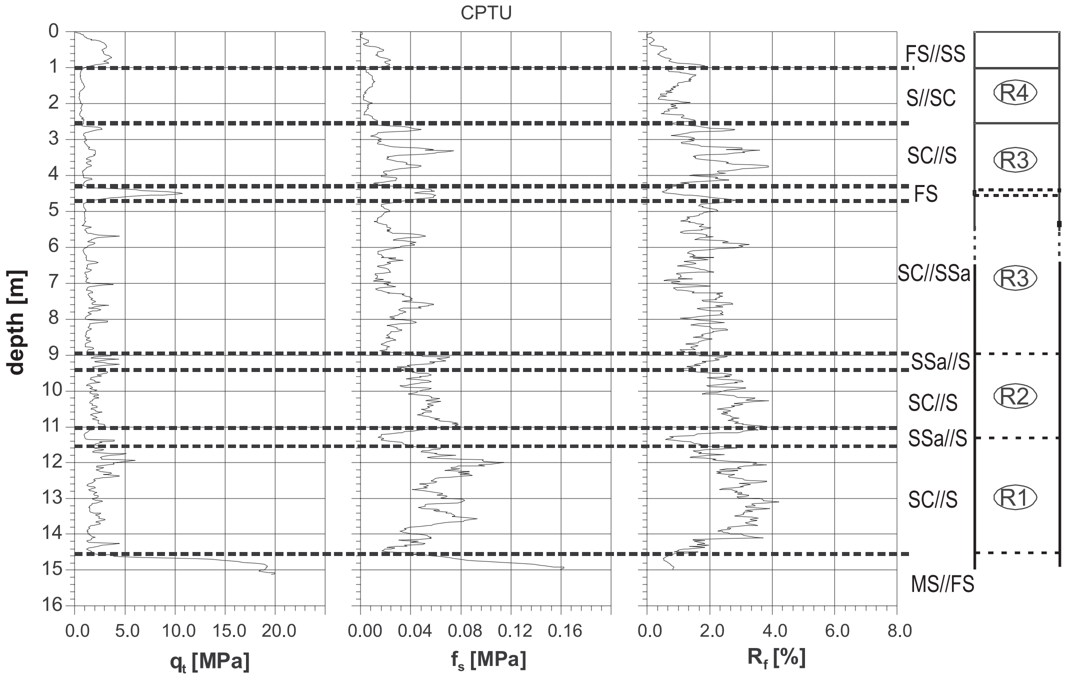

Fig. 2. The static probing (CPTU) profile and the lithofacies.
SC – silty clay; S – silt; SSa – sandy silt; SS – silty sand; FS – fine sand; MS – medium sand; R – rhythmically stratified units, S – deformed units; R1, R2, R3, R4, S1, S2 are subunits CPTU parameters: q_t – recording cone resistance, f_s – sleeve friction, R_f – friction ratio.

a sandy silt layer of 30 cm thick and grades into typical varves for the next 2 m. According to the CPTU results, the sediments of R_1 and R_2 show a significant (almost 40%) increase in overconsolidation compared to the upper part of the glaciolacustrine succession. In R_1 the thickness of the primary laminae is more or less constant (approx. 1 cm), whereas a considerable variation in the laminae thickness occurs in R_2 (approx. 1–3 cm). Fine and silty sands show vague ripple cross-lamination (Fig. 5). The sediments of R_3 consist lithologically of alternating light and dark laminae. On the basis of CPTU probings, it may be assumed that R_3 is the thickest unit (over 6 m). The grain-size distribution of the light laminae does not differ significantly from that of the light laminae in the other R units. Slight differences occur, however, with respect to the mean contents of colloidal clay in the dark laminae: the rhythmically laminated sediments dark laminae within R_3 have a lower mean content of the finest fraction (15–20%). On the other hand, the content of coarse silt increases by a similar value in R_3. Sandy laminae occur as well within the silty clay laminae of R_3. In its lower part, sandy laminae are several centimeters thick, occasionally up to 10–20 cm, but their thicknesses are variable (sandy laminae tend to thin out). The overconsolidation within R_3 is significantly less than in the lower part of the succession but still higher than in the youngest part of R_4.

Units R_3 and R_4 are separated from one another by unit S_1 (Fig. 3), which lies in between in a distinctly discordant position. A characteristic feature of S_1 is the presence of folded varves in some places, changing laterally or vertically into disrupted clasts of laminated clay or pebble-sized rounded clasts of massive clay in a silt matrix. Some clay clasts occur in laminated silt layers. The overlying deposit is the varved silt of R_4, which is thinnest of all R units with its maximum thickness of 1.5 m; this unit shows the lowest overconsolidation of the entire succession. The uppermost part of the glaciolacustrine succession is represented by unit S_2, which shows characteristics similar to those of S_1.

Both R_1 and R_2 are deformed by numerous postdepositional normal faults (Fig. 6). These faults displace the sediments at either sides from several to several dozens of centimeters, and they dip 70–80°, mostly towards the SE;

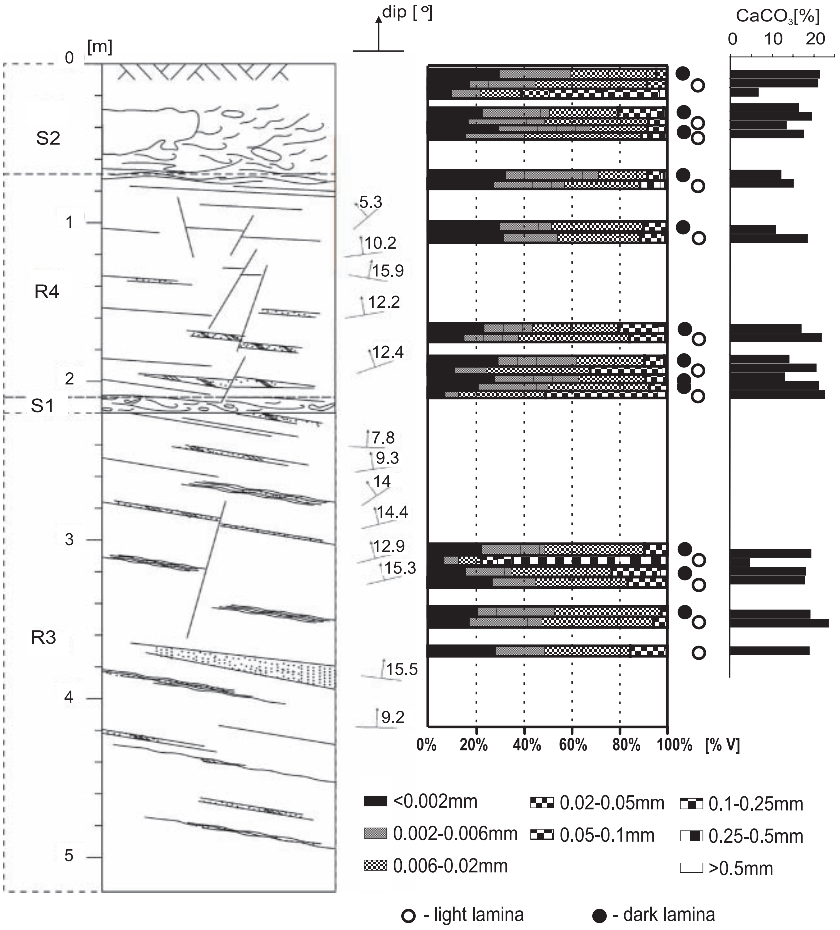

Fig. 3. The lithological profile with dip direction and dip value of the laminae, grain-size, and $CaCO_3$ content (%).

faults with an opposite dip direction have, however, occasionally been found in the neighbouring area, thus resulting in typical horsts. The downthrow of these faults usually is approx. 1 cm, with a maximum of 2 cm. The horst structures are most common within unit R_1. Faults systems have neither been found in the overlying R_3 and R_4 units, nor in the plastically deformed sediments of S_1 and S_2.

5. Discussion

The Wierzchowo succession represent typically glaciolacustrine rhythmic deposits, with light-coloured laminae characterised by a relatively high content of silt and sand, and dark laminae with more clay (cf. Harrison, 1975; Ringberg, 1979, 1984; Eyles & Miall, 1984; Brodzikowski & Van Loon, 1991; Paluszkiewicz, 1996).

The R units can be assumed as typical rhythmites, deposited under low-energy conditions (cf. Błaszkiewicz & Gruszka, 2005; Rubensdotter, 2006). The S_1 and S_2 units, which are interpreted as a result of mass flows, are relatively uncommon in glaciolacustrine environments. The presence of disrupted and deformed fragments of laminated deposits and rounded clay pebbles indicates some erosion of deposits (Thomas & Connel, 1984; Paluszkiewicz, 1997; Paluszkiewicz, 2008). An erosional phase is evidenced by a discordance between S_1 and R_3.

On the basis of CPTU probings, it is possible to obtain more information about postdepositional processes. The R units (R1 to R4) differ from each other in their degree of preconsolidation, represented by the OCR index and the preconsolidation pressure (σ'_p) (Fig. 3). The preconsolidation pressure increases with depth (which is a common feature), but not continuously. This is shown by the shape of the OCR curve for the succession, which represents the ratio between the preconsolidation pressure and the present-day geostatic pressure. Some levels with sudden changes of the overconsoli-

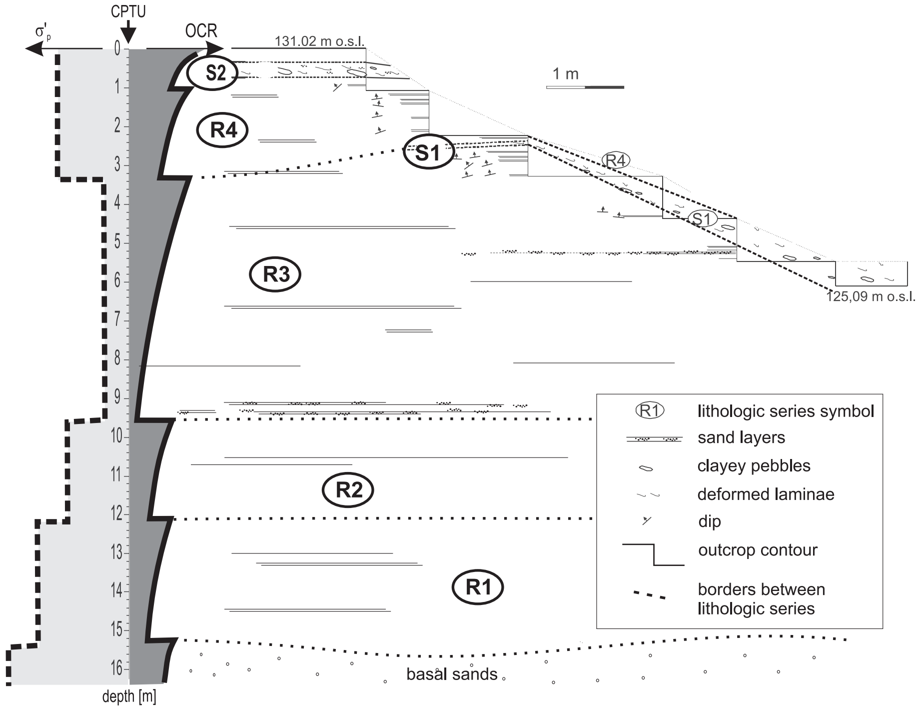

Fig. 4. Cross-section of the Wierzchowo deposits.

dation ratio occur in this curve. These changes imply that the deposition was not a continuous process. At least four depositional stages, divided by some hiatuses due to non-deposition or even erosion can be distinguished within the succession (Fig. 3). This division is strongly supported by the presence of two mass-flow units (S) (Fig. 3). The above-mentioned changes in OCR values suggest that some non-depositional stage (possibly even with erosion) occurred after the deposition of the R units (in the case of erosion of overburden deposits, the overconsolidation can be considered as an effect of unloading).

R_1 and R_2 differ from R_3 also if the basic CPTU parameters are compared. The sleeve friction (f_s) increases more distinctly than the cone resistance (q_t) in R_1 and R_2, which suggests that the overconsolidation was caused by unloading rather than desiccation or secondary creep. A similar correlation has been found by Wierzbicki (2010) during an experiment with the glaciolacustrine sediments. This suggests that significant erosion occurred between the

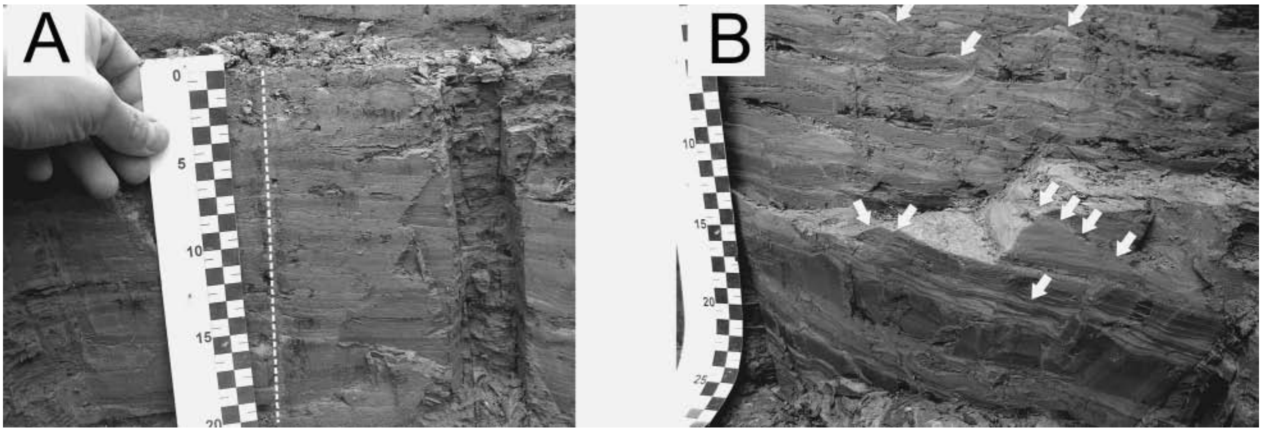

Fig. 5. Sedimentary structures.
A – Varved deposits in unit R_4; **B** – Current ripples within unit R_3.

lower part of the varved clays (R_1 and R_2) and the upper part of the glaciolacustrine deposits.

The CPTU results also show that the sandy deposits at the base of the glaciolacustrine deposits exhibit signs of strong overconsolidation, similar to the sandy sediment under the Złocieniec reservoir (Wierzbicki et al., 2007).

6. Conclusions

It appears that the deposits of the Wierzchowo lake differ from the varves in the Złocieniec lake. The fundamental difference is the thickness of the rhythmically stratified deposits. The varved succession in the Złocieniec lake is about 12 m thick, while the Wierzchowo rhythmites are only a few metres thick. A detailed analysis of the varved successions and mutual comparison indicates that the Wierzchowo deposits also are somewhat coarser.

The two proglacial lakes formed separate basins (Paluszkiewicz, 2004) and had different topographies: the depth of the Wierzchowo lake basin was much more irregular and its sedimentary record is consequently represented by a wide range of facies. Additionally, large-scale erosion surfaces are more abundant there, which suggests that the hydrodynamic energy was higher and more variable than in the Złocieniec basin.

The results of the lithological analysis and the CPTU probings indicates that the Wierzchowo sedimentary succession represents at least four developmental phases:

- phase I: an initial (low-energy) phase of the lake, with deposition of rhythmically stratified sediments (R_1 and $R_{2)}$, separated from one another by an erosional surface;
- phase II: a phase of non-deposition, with some desiccation and extended consolidation of sediments, probably corresponding with a significant drop of the water level;
- phase III: the main phase of deposition, resulting in rhythmically stratified sediments (R_3);
- phase IV: the last phase of the proglacial lake, which can be subdivided into three subphases:
  - IVa: a high-energy subphase, with deposition of unit S_1, and deep erosion related to drainage towards the Lake Wąsosze channel,
  - IVb: low-energy deposition of rhythmically stratified deposits (R_4),
  - IVc: the final subphase, with deposition of unit S_2 under high-energy conditions.

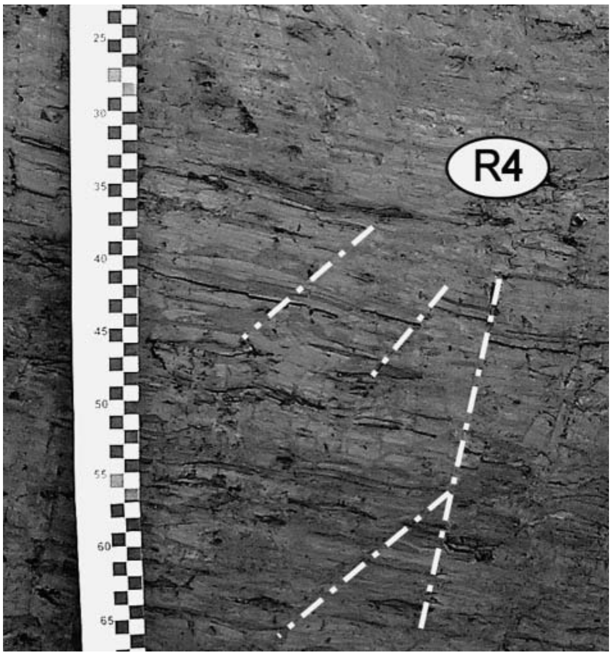

Fig. 6. Faults within unit R_4.

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