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REVIEW OF THE SEDIMENTARY TYPES AND STRATIGRAPHIC POSITIONS OF THE PLEISTOCENE GLACIAL DIAMICTONS IN THE BEŁCHATÓW MINE (KLESZCZÓW GRABEN, CENTRAL POLAND)

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Abstract

The Quaternary overburden of the giant Bełchatów browncoal mine has provided – and still provides – one of the world's best exposures of Pleistocene glacial sediments. The exceptional geological setting – a graben that has been active from the beginning of the Alpine orogeny – provides conditions for preservation of terrestrial glacial deposits that are unique. Outcrops in Pleistocene glaciation-related sediments are commonly small, but the well preserved glacial sediments in the Bełchatów mine can be studied without significant interruptions in the walls for several kilometers. In addition, the ongoing exploitation provides an opportunity to obtain a 3-D picture of the facies and facies transitions that have no counterpart elsewhere. The stratigraphic relationships between a large number of glacial and interglacial units, some of which have a limited lateral extent, could thus be unraveled. It appears that the glacigenic succession comprises at least eight (but probably more) stratigraphic levels with glacial diamictons, thus recording an unmatched history of a glaciated area.

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Key words: ice advance, ice retreat, glaciation, till, glacial diamicton, graben sediments

INTRODUCTION

The sedimentary remnants of Pre-Pleistocene ice ages consist predominantly of glaciomarine deposits although it is likely, on the basis of what we know from the Pleistocene, that terrestrial deposits were originally present in larger quantities. The preservation potential of such terrestrial deposits is extremely low, however, which implies that the Pleistocene glacial sedimentary record as we know it now is exceptional (Van Loon 2000): most of these terrestrial deposits will disappear by erosion in the course of time.

Even though much remains of the terrestrial glacial deposits that were formed during the Pleistocene – and even though their study is extensive if only for economic reasons – insight into the wide variety of glacial facies, their horizontal and vertical extent, and their mutual transitions is far from complete. The main reason is that most present-day glaciated areas where such deposits can be studied are difficult to access (if accessible at all), whereas Pleistocene deposits are often badly exposed, commonly in quarries much smaller than those in use for hard-rock exploitation.

The Bełchatów opencast browncoal mine, situated in the Kleszczów graben in central Poland (Fig. 1A), is therefore, apart from its economic significance, of great scientific value. This regards both the paleobotany of the browncoal deposits (see, among others, Worobiec, Worobiec 2005) and the sedimentology and stratigraphy of the Pleistocene. Much research into the Pleistocene overburden has been carried out in the past 25 years (Brodzikowski, Van Loon 1979, 1985, Van Loon *et al.* 1984, Brodzikowski *et al.* 1987a, b, Van Loon 2002), but it was for some time not allowed to publish research results obtained in the mine, so that works referred in the earlier days of the geological investigations to the Kleszczów graben rather than to the Bełchatów mine (see, for instance, Brodzikowski 1985). Nowadays, the ongoing exploitation of the mine has proceeded so far that the geological data from the mine can be considered as representative for the entire graben; the terms 'Kleszczów graben', 'Bełchatów graben' and 'Bełchatów mine' as an indication for the study area are therefore all used with a meaning that is practically identical. We will adhere here to the term 'Bełchatów mine', since all observations detailed in the present contribution stem from this mine.

Important work has been carried out with regards to the glacigenic and glacial deposits in the mine's overburden. The giant dimensions of the mine (Fig. 1B), in combination with the lack of scientific manpower to keep up with the ongoing exploitation, have prevented, however, the availability of a full 3-D record of the deposits that have been removed. The complex pattern of the glacigenic facies (not only due to the complexity of the glacial sedimentary environments, but also to the ongoing tectonic activity: Gotowała, Hałuszczak 2002), has – unfortunately – resulted in rather chaotic lithostratigraphic terminology and correlations. In addition, disturbances caused by mining activities (Gibowicz *et al.* 1983) contribute to the complexity of the correlation. Brodzikowski (1992) provided, nevertheless, a brilliant overview of the glacial units in the mine on the basis of both his own ex-

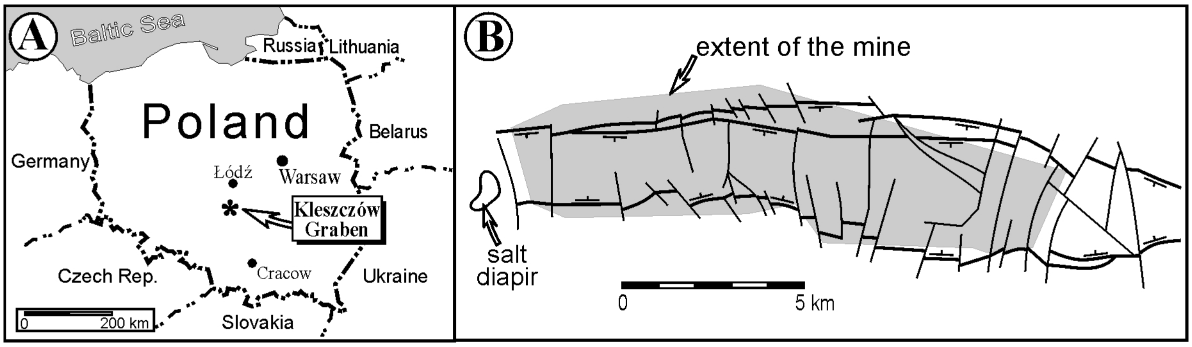

Fig. 1. **A:** Location of the Kleszczów graben in central Poland. **B:** A complex pattern of faults, reflecting the tectonic movements of the hard-rock substratum, limits and crosses the Kleszczów graben in which the huge Bełchatów mine is situated.

tensive observations and his profound knowledge of the literature that had been published about Bełchatów mine until then.

THE GLACIAL DEPOSITS

The glacial deposits described below are glacial deposits *sensu stricto*, i.e. deposited by the ice, not glacigenic (= ice-related) deposits in the sense of Brodzikowski and Van Loon (1991). Considering their unsorted character, they all should be called 'glacial diamicton' or 'till'. As both Brodzikowski (1992) and later authors most commonly used the term 'till', we will do so in this overview as well, although the term 'till' is now considered more or less outdated by most glacial geologists. The Bełchatów tills range in age from Elsterian [= South Polish Glaciation; see Rühle 1955, Mojski 1985, Gruszka *et al.* 2006] to latest Saalian [= Wartian] (see also Fig. 2).

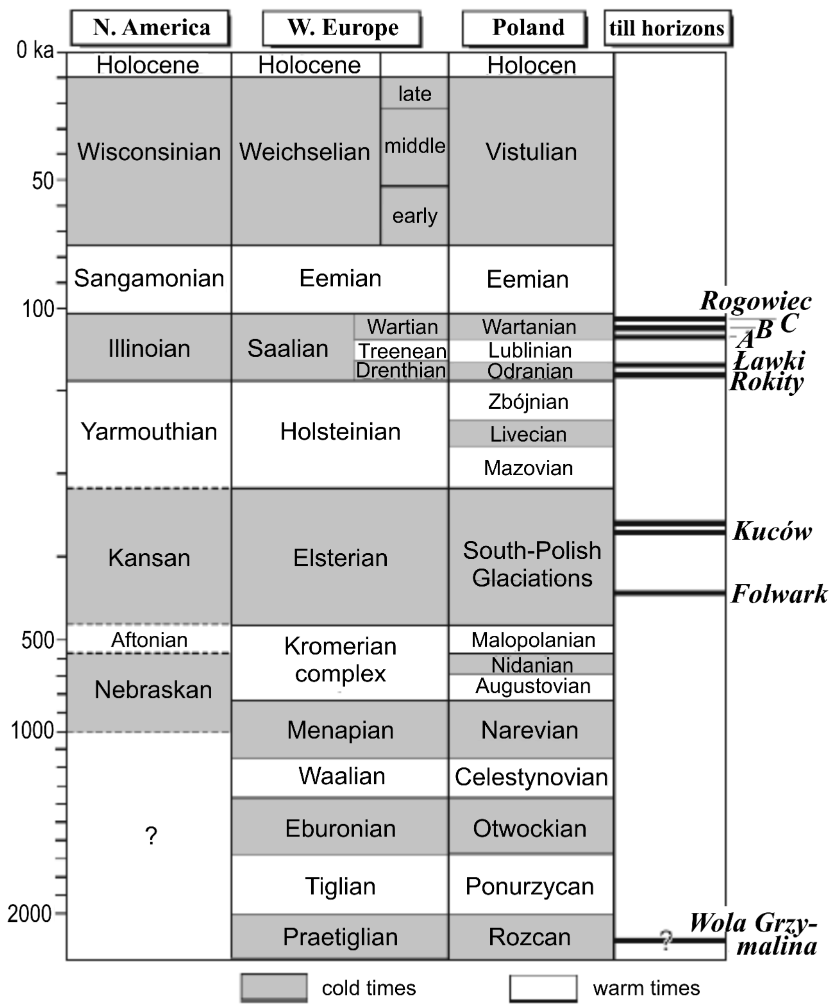

Fig. 2. Stratigraphic position of till levels in the Quaternary overburden of the Bełchatów browncoal mine, and chronostragraphic correlations.

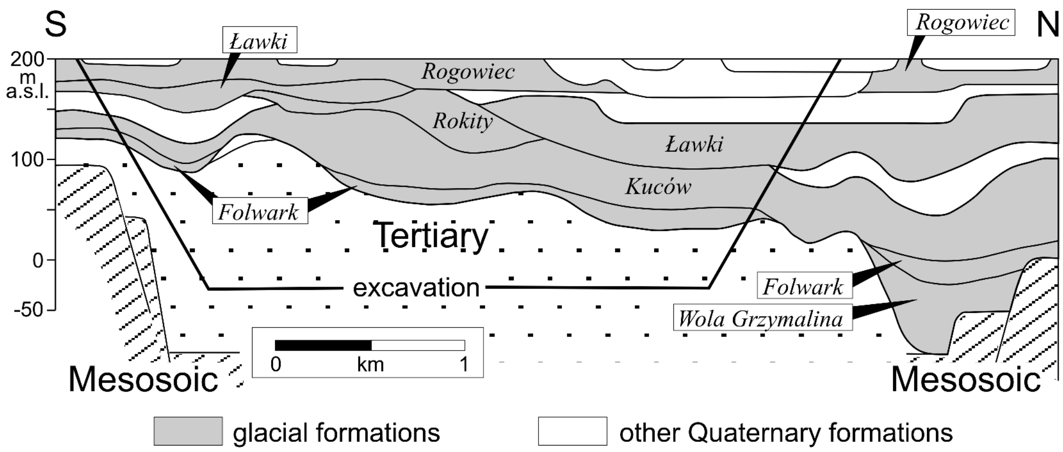

Fig. 3. Schematic (composite) cross-section through the Bełchatów mine, showing the position of the 'cold' formations.

The most complete and detailed descriptions of the various units are those by Brodzikowski (1992) and Krzyszkowski (1995, 1996). These authors have slightly different approaches towards both litho- and chronostratigraphy but they agree that six 'cold' (glacial) formations occur in Bełchatów with, jointly, 8 till horizons (the uppermost 8 till horizons in Fig. 2). The just-mentioned researchers set the cold units in slightly different positions, however, and they attribute slightly different ages to them. It seems now that the five 'cold' formations (from young to old the Rogowiec, Ławki, Rokity, Kuców and Folwark Formations that jointly contain the 8 till horizons mentioned above) might be extended with at least one more. Borings have reached a unit that was named the 'Wola Grzymalina Formation' (Figs. 2, 3), and some deposits of this unit are interpreted as glaciofluvial, which indicates that it must have been formed during a (another?) cold period. So far no associated tills have been encountered, but it is expected that they exist, as tills are known to exist in the Bełchatów mine from all cold times from which glaciofluvial deposit have been found. The age of this 'new' unit is not known, but it might be early Pleistocene. A Praetiglian (Rozcian) age has tentatively been assigned to it (Zieliński, Univ. Poznań, pers. comm. 2005). It is not unlikely that even more 'cold' units (possibly with tills) will be found during ongoing exploitation of the mine (particularly since exploitation of a new part of the graben started recently), but such possible new finds are considered out of scope here.

EXCEPTIONAL VARIETY OF TILLS

The tills in the Bełchatów mine show a wide variety of types. They have, however, been relatively poorly studied and described. The main reason is probably that tills can be studied at many locations worldwide, while the Bełchatów mine offers the opportunity to study more rarely occurring features, such as well exposed lateral and vertical facies transitions in the kilometers long and dozens to hundreds of meters high walls of the mine. The little attention paid to the tills so far is unfortunate, because these tills are commonly well preserved, thanks to the ongoing subsidence of the graben, which diminished their susceptibility to erosion (many of the Pleistocene glacial diamicts in the Bełchatów mine have no equivalent outside the graben). Their frequent occurrence, both laterally and vertically, might provide much insight into glacial sedimentation during previous glaciations and into the differences and/or resemblance with the present-day glacial sedimentation.

The relatively little attention that has been paid to the tills in the Bełchatów mine is even more unfortunate because it is commonly impossible to deduce from the descriptions and terminology which precise types of tills are dealt with. This is partly due to the fact that terminology in eastern Europe differed for a long time from that in western countries; the new generation of earth scientists in eastern Europe has now largely adopted the western terminology (see, among others, Krzyszkowski 1994, Gruszka 2001), and the previous names given to till types by, among others, Polish earth scientists in the field (*e.g.* Baraniecka 1978, Krzyszkowski 1994) have consequently become difficult to interpret. Because of the ambiguities introduced in this way, the underneath overview uses the terminology of Brodzikowski and Van Loon (1991), which was frequently used in Poland until fairly recently. If the original authors gave (also) diverging names, these are added in parentheses.

Lodgement tills (Fig. 4) were described by Brodzikowski (1992) from the Rogowiec C Fm. [massive, compacted diamictons]. They show the typical joint systems and the overcompacted nature that is characteristic of this most

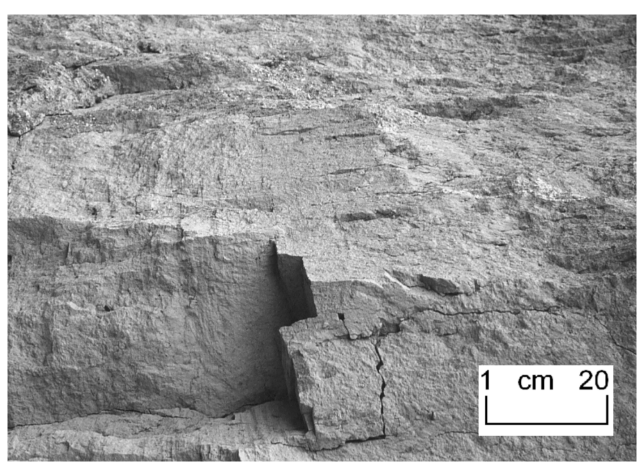

Fig. 4. Lodgement till (upper Wartian till level: Rogowiec C) in the eastern part of the Bełchatów mine.

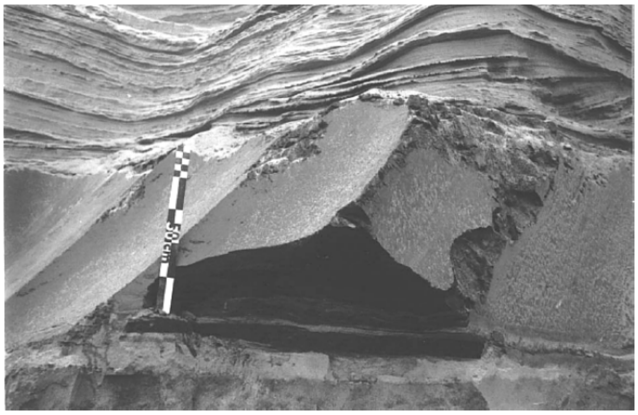

Fig. 5. Basal (melt-out) till from the lower Wartian till level (Rogowiec A) in the eastermost part of the Bełchatów mine.

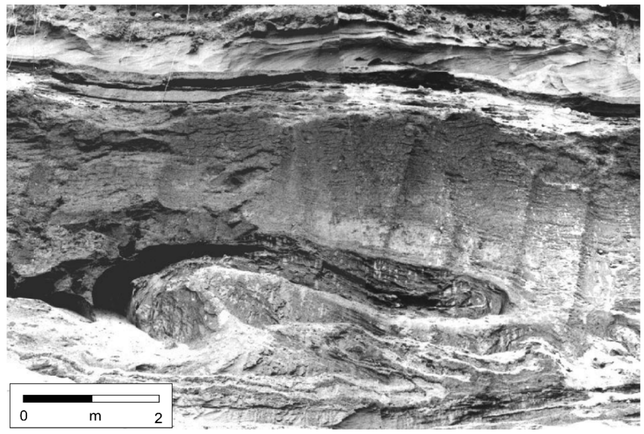

Fig. 6. Characteristic deformation till with deformed slabs of the soft-sediment substratum incorporated (upper Wartian till level, Rogowiec A) in the eastern part of the Bełchatów mine.

fundamental type of till. According to Krzyszkowski (1994), the distinction between lodgement and basal tills (*i.e.* tills that formed subglacially, but under conditions that did not lead to overcompaction by the weight of the overlying ice, and that do, as a rule, not show the sets of joints that characterize lodgement tills) is artificial, as he found tills in the Bełchatów mine that change their character from overconsolidated 'lodgement' tills into normally compacted 'basal' tills in a lateral direction. A similar lateral transition from typical lodgement tills and melt-out tills is known from tills on the Canadian prairies, where the identification of the various till types is based on numerous criteria other than consolidation (John Shaw, Univ. of Alberta, pers. comm. 2005). Krzyszkowski describes these tills and their gradual transition from the Rogowiec Fm. (he does not distinguish three separate Rogowiec Formations but subdivides the Rogowiec Fm. into units A, B and C; see also Krzyszkowski 1996), and attributes similar characteristics to the three tills in this succession. Obervations by the present author indicate that lodgement tills do also occur in the Bełchatów mine in other than the Rogowiec Fm., more specifically in the Ławki and in the Kuców Formations, but these occurrences have been encountered only in places that were tectonically disturbed, so that the precise stratigraphic position of the tills is questionable.

Basal tills (Fig. 5), formed by melting of the base of a temperate ice sheet and consequently not overpressurized by the ice burden, resulting in a diamicton that does not show overconsolidation such as lodgement tills do, occur – according to Brodzikowski (1992) – in the Folwark Fm. [subglacial melt-out deposits], in the Kuców Fm. and the Rokity Fm. [subglacial melt-ice deposits], in the Ławki Fm. [deposits of subglacially melting ice], and in the Rogowiec B Fm. [subglacial melt-out tills]. Krzyszkowski (1994) mentions tills with characteristics of this type also from the Rogowiec Fm. (see above). The occurrence of basal tills in the heighest eight till levels has also been observed by the present author, but a gradual transition of these tills into lodgement tills – as mentioned by Krzyszkowski (1996) – has not been encountered.

Englacial tills are mentioned by Brodzikowski (1992) from the Folwark Fm. and the Kuców Fm. [englacial melt-out deposits], from the Rokity Fm. [englacial melt-ice deposits], from the Ławki Fm. [deposits of englacially melting ice], from the Rogowiec B and the Rogowiec C Fm. [englacial melt-out tills]. The criteria on which he bases his interpretation of this uncommon type of till with a low preservation potential are not made truly clear. Krzyszkowski (1996) does not mention englacial tills at all. The present author found englacial tills in both the Rokity and the Ławki Formations. They both belonged to a subtype that has been indicated by Olszewski (1974) and Drozdowski (1979a, b) as the 'lower' subtype.

Czerwonka and Krzyszkowski (1992) mention the occurrence of ablation tills in Bełchatów, but do not give any information about their stratigraphic position. Brodzikowski (1992) does not mention such tills at all, although he must have been aware of their presence, considering the fact that he and the present author have discussed the genesis of tills from the Ławki and Rogowiec formations, and have come to the conclusion that they represent most probably ablation tills.

Dropstones can be found in almost all glaciolacustrine units in Bełchatów (Brodzikowski, Van Loon 1991, Brodzikowski 1992, 1993, Gruszka 2006, Gruszka, Van Loon, 2006). The occurrence of dumpstones, due to the tumbling over of debris-containing melting icebergs floating in glacial lakes in front (and perhaps on top) of the land-ice mass has been observed by Zieliński (Adam Mickiewicz University, Poznań, pers. comm. 2004). No published data could be found on the occurrence of this specific type of diamicton in the Bełchatów mine, and it is questionable whether such deposits should be considered as tills in a strict sense, although the material is directly derived from a melting ice mass.

Deformation till (Elson 1961) is also abundantly present in Bełchatów. This type of till, which comprises weak rock or unconsolidated sediment that has been detached by the ice sheet at its source and subsequently deformed or disaggregated (Fig. 6), and some exotic material admixed (Hambrey, Glasser 1993), was mentioned by Brodzikowski and Van Loon (1991), but was not dealt with as a separate genetic type, although they provided a representative photograph of such a till from the Bełchatów mine (their Figure 159). These tills, which have also been described as incorporation tills (by, among others, Boulton 1972, and Ruszczyńska-Szenajch 1981), are found in the Bełchatów mine at the basal part of what have been described by most investigators as lodgement tills, though not as the base of lodgement tills that pass laterally into basal tills. It is interesting that most investigators agree that deformation tills seem to be present particularly if the till horizons are thick. This is, as stated before, the case in Bełchatów. For this reason the Bełchatów mine seems to be most suitable for future research concerning deformation tills and their vertical and horizontal transitions into other glacial and/or glacigenic facies.

It is emphasized here that flowtills are not considered here as tills, as they do not accumulate as a direct result of ice melting, but represent mass-flow deposits. Flowtills representing a wide variety of transport mechanisms (such as sliding, slumping, mudflow, debris flow and hyperconcentrated flow) occur abundantly in the Bełchatów mine – in several types of glacigenic deposits (glaciolacustrine, fan, *etc.*) – and have been described by several authors (among others Czerwonka, Krzyszkowski 1992, Van Loon *et al.* 1995).

ORIGIN OF THE WELL PRESERVED SUCCESSION

Although large areas in the lowland of The Netherlands, Germany and Poland were covered with ice during the Pleistocene – and almost the whole area must have been covered by a till after retreat of the ice, even though considerable parts of the tills deposited earlier may already have been eroded by sublacial meltwater streams as is the cases on the Canadian prairies (John Shaw, Univ. of Alberta, pers. comm. 2005) – Pleistocene tills are now found in restricted areas only. The main reason is that terrestrial tills are prone to erosion, partly because they tend to form positive relief forms, partly because in most cases the large amounts of meltwater supplied by the retreating glacier eroded the tills and mixed the material with glaciofluvial material (Brodzikowski, Van Loon 1991). Tills thus have a low preservation potential.

If an area is reached by advancing land-ice masses during successive glacial events, the previously formed glacial deposits form a soft-sediment substratum that is easily eroded, so that successions with tills from successive ice ages are scarce. Northern and central Poland are good examples: most tills and glacigenic deposits date from the last glacial event during which the area was covered by ice. Even loess deposits older than those of the last glaciation are scarce, although it is not clear whether this is due to non-deposition of loess during pre-Vistulian ice ages or to erosion.

During a single glacial, the ice front tends to advance and retreat several times. Hardly any records are available, however, of glacial deposits occurring above each other that were formed during successive stages of ice advance. This, too, must be ascribed to the erosional activity of a re-advancing glacier. Obviously, many sites occur where a number of tills are superimposed, but they almost exclusively represent different types of diamictons that were formed due to different processes (lodgement till, ablation till, flowtill, *etc.*) during one single phase of glaciation.

Although it is true that worldwide many locations have been described where tills occur above each other – with or without other deposits in between – the Bełchatów mine is the only site where a Pleistocene succession has been preserved with eight till units that must be ascribed to at least four different stages (sediments formed under warmer conditions – as shown by their fossil content – are found in between: Fig. 2). This must be due to exceptional local circumstances, as is also proven by the fact that no such succession is found at only a few hundred meters north and south of the mine.

The main reason is the same as why the Bełchatów area is exploited for its huge and thick (several hundreds of meters) browncoal deposits: the latter could originate and be preserved thanks to the fact that a local graben exists that has been active for a long time, and that still is active. The ongoing Pleistocene subsidence (with local differences but in the order of 250 m) resulted in a continuous depression in which deposits could accumulate without much chance of being eroded. One of the results is that well developed glaciofluvial, glaciolacustrine and eolian deposits were not only formed but that they have also been preserved during subsequent glacial phases. Glacial deposits were, however, equally well preserved, because they were soon covered by younger deposits and because a new advance of a land-ice mass resulted in glacial deposition rather than in glacial erosion when the depression of the Kleszczów graben was reached. Only the ongoing subsidence in a graben that is only a few km wide, and that was directed more or less perpendicular to the direction of the ice movement during the successive phases of ice advance, should thus be held responsible for the preservation of the exceptional succession with eight till levels (and possibly more).

PALEOENVIRONMENTAL SIGNIFICANCE AND MODELLING

Tills are rarely of economic importance. Quarries where Pleistocene gravel or sand is mined, therefore often stop exploitation where a well developed till layer is reached, thus preventing analysis of its 3-D characteristics. The situation in the Bełchatów browncoal mine is entirely different, because the ongoing removal of the Quaternary overburden provides an – essentially – complete 3-D picture of the various lithological units, including all vertical and lateral abrupt or gradual facies transitions. Thanks to this exceptional situation the relationship between many of the numerous types of deposits could be unravelled (Brodzikowski, Van Loon 1991).

Consequently, it has been possible to reconstruct the paleogeographical and paleoenvironmental developments in the area covered by the Bełchatów mine during a number of ice advances, to study the similarities and the differences between these developments at different times, and thus to analyse what might be considered as a 'normal' development, and what should be considered as exceptional. Thus fairly detailed models of the sedimentation during ice advance could be established.

CONCLUSIONS

The Bełchatów mine constitutes a scientifically highly valuable exposure, thanks to the rare combination of ongoing subsidence in a graben which has resulted in uncommonly thick and well preserved deposits. Ongoing exploitation with removal of the Quaternary overburden – resulting in kilometers long exposures through commonly many tens (sometimes hundreds) of meters of glacial and glacigenic deposits – make that these deposits and their interrelationships can be studied in detail.

These conditions make it possible to study Quaternary successions with an exceptional number of alternating 'warm' and 'cold' deposits, expressed in, among others, the occurrence of at least eight till levels that can be attributed to six phases of ice advance. Indications for more 'cold' formations are present, but need further elaboration.

The huge dimensions of the opencast mine allow reconstruction of the geological context of the glacial deposits in a way that is probably unmatched in the world. It shows that the various glacigenic units form intricately interrelated complexes, with commonly gradual facies transitions. Diamictons of all types, although commonly distinctly separated spatially, can gradually pass into one another. This indicates that depositional mechanisms gradually changed within short distances, so that a continuum between most genetic till types exists. Moreover, most diamictons tend to undergo several phases of reworking before they become 'fossilized' due to coverage by younger sediments; this also contributes to till types with intermediate characteristics.

Acknowledgement

The present contribution is dedicated to my late colleague and friend, Krzysztof Brodzikowski, who is to be considered as the first (and for a long time only) earth scientist who recognized the immeasurable scientific value of the Bełchatów mine for both sedimentological studies and for analysis of numerous Quaternary geological features.

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