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Diamicton in Besiekierz (central Poland) – how to avoid misinterpretation of superposition in Quaternary geology

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Diamicton in Biesiekierz (central Poland), whose age and origin has long provoked debate, is located above unquestionable Eemian biogenic deposits documented by palynological and *Cladocera* analyses. Petrographically, this diamicton shows some similarities to Warthanian till. Lithologically, it shows considerable weathering of the deposit, a possible selection of the component minerals and addition of dispersed biogenic matter. The results obtained so far as well as the palaeomorphological situation indicate that the diamicton is reworked till material, as are sand intercalations within it. Given the organic content of this diamicton, we infer that a long-term agricultural exploitation of its immediate surroundings was the main factor behind colluvial reworking and displacement occurring above the Eemian biogenic deposits in the fossil depression.

Key words: stratigraphy, Weichselian, diamicton, indicator erratics, tillage erosion.

INTRODUCTION

The Besiekierz site near Łódź (central Poland) is well-known in the literature on Quaternary geology due to the presence of till deposits above the Eemian organic infill of the fossil depression (e.g., Klatkowa, 1972, 1993a; Janczyk-Kopikowa, 1991; Klatkowa et al., 1994; Mirosław-Grabowska and Niska, 2005). However, the site is located 50 km south of the generally accepted maximum extent of the Vistulian (Weichselian) glaciations – LGM (Fig. 1). Analyses of the organic deposits, including palynological studies by Sobolewska (in Klatkowa, 1972) and Janczyk-Kopikowa (1991), and *Cladocera* analysis by Mirosław-Grabowska and Niska (2005) have corroborated its Eemian age. Uncertainty, though, has surrounded the origin and age of the diamicton, which covers the Eemian deposits as a layer 1 to 2.5 m thick, and which is also found outside of the fossil depression (Klatkowa, 1993a; Klatkowa et al., 1994). Lithological analysis has showed that the deposit has different granulometric features than typical lodgement till and it is almost devoid of calcium carbonate (Klatkowa, 1993a).

Research into the diamicton at Besiekierz was undertaken to determine its origin, the conditions of its deposition above Eemian biogenic deposits and the age of the (re)depositional processes. It was assumed that the petrographic composition of the pebble fraction in the diamicton would be helpful in determining its position in the Quaternary stratigraphic profile of central Poland. And, analysis of the lithological characteristics should indicate what factors influenced the sediment after its initial deposition. These investigations should resolve whether this diamicton is preserved in its original position, i.e. as a true till above Eemian deposits and belonging to Weichselian glaciation, whether it is a redeposited Warthanian glacial till, which was reworked after the Eemian Interglacial. The results of this research should contribute to the solution of a problem that is relevant also for some other localities in Poland, where Eemian or Early Vistulian strata are overlain by tills or till-like deposits at sites located outside the generally accepted extent of the LGM (see Morawski, 2001).

SITE LOCATION AND RESEARCH METHODS

The Besiekierz site (51°57'18.43'' N, 19°27'56.45'' E) is located in the transition zone between the Łódź Plateau and the Warszawa–Berlin ice-marginal streamway within the Wola Mąkolska Plain. The fossil depression, filled with Eemian biogenic deposits, is situated about 60 m east of the edge of the Moszczenica Valley (Fig. 1). Several boreholes have been drilled in the depression, cores being collected for palaeoecological analysis. The exposure made in 2005 was located in the southern part of the fossil basin (Fig. 2), around 25 m south of the open pit, the investigation site of Klatkowa (1993a).

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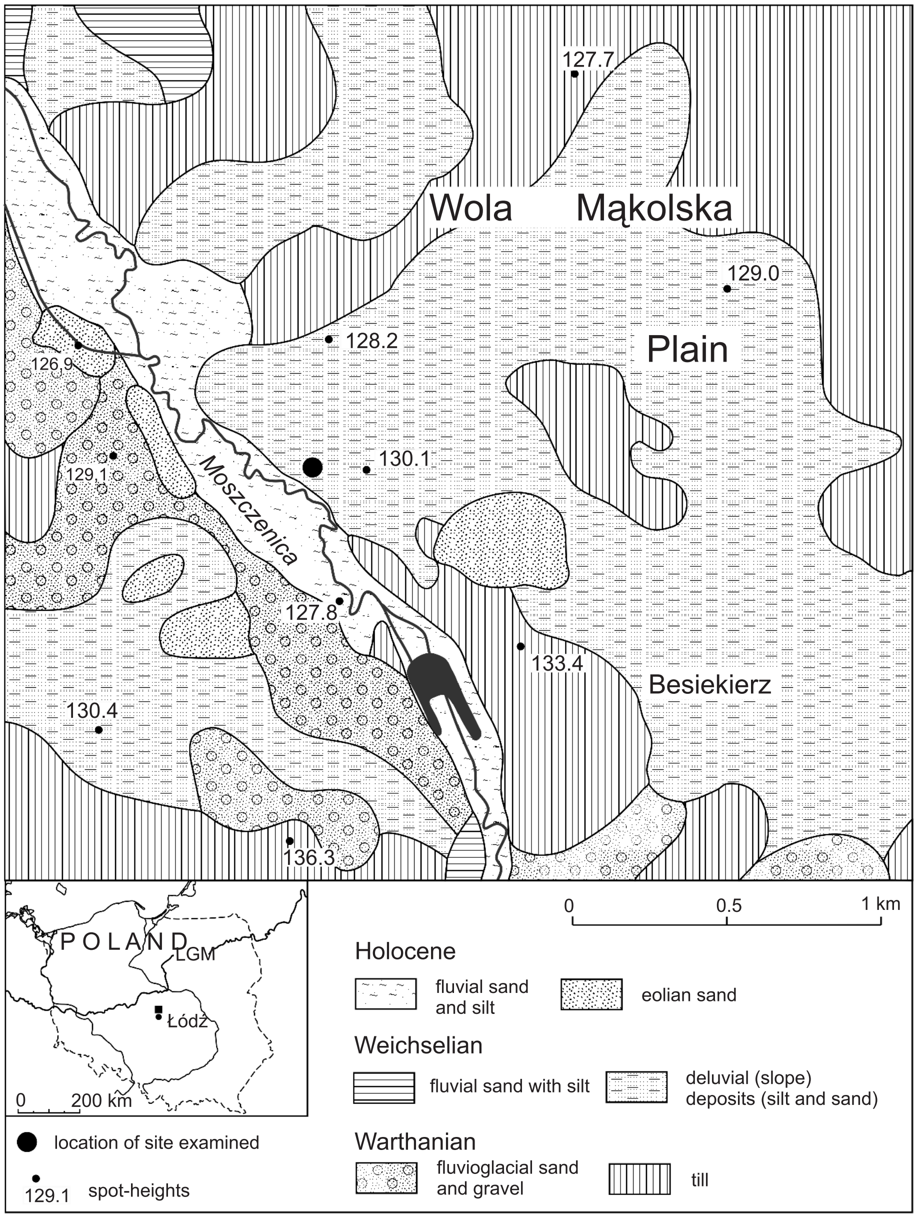

Fig. 1. Geological sketch of the Besiekierz area (after Klatkowa et al., 1994, modified); LGM limit on the location map after Karabanov et al. (2004), Ehlers et al. (2011), Marks (2011), Lindner et al. (2013) (simplified)

In 2005, a 2.2-m-deep excavation was made. Small pebbles (>20 mm across) were extracted from a diamicton bed 1.3 m thick. These clasts were studied by means of petrographic analysis using indicator erratics via Lüttig's method (1958) modified by Smed (1993), Vinx et al. (1997) and Czubla (2001). In addition, lithological analyses were carried out, which supplement the results of petrographic analyses made to constrain the origin of the diamicton (Czubla and Forysiak, 2006). The deposits sampled from the excavation wall (Fig. 3) were analysed in terms of grain size, quartz grain morphology and calcium carbonate and organic matter contents. Eleven samples were taken, of which seven samples were of diamicton. Grain size analyses were accompanied by determination of calcium carbonate (using the Volume Analysis – Scheibler Method) and organic carbon (Tiurin Method) contents. Other analyses included the use of Caileaux Method further modified by Manikowska (1993) to analyse quartz grain abrasion.

RESULTS

LITHOLOGICAL FEATURES OF THE DEPOSITS

The diamicton is covered by a thin layer of sand, found underneath the recent soil horizon (Figs. 3 and 4). The grain size distribution shows considerable variation in the investigated succession. Two layers were recognized within the sand deposit. The upper one is represented by fine, slightly sorted sand (Fig. 4). Quartz-grain abrasion analysis revealed a large num-

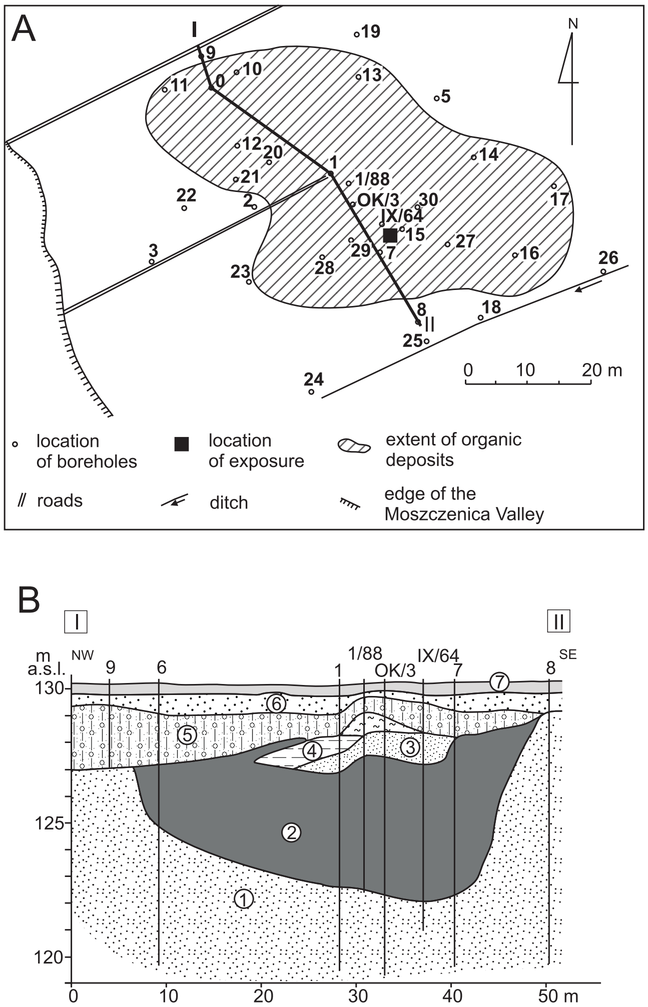

Fig. 2. Besiekierz site

A – sketch of the buried Eemian depression (after Klatkowa, 1993a); **B** – geological section I–II (after Klatkowa, 1993a); 1 – medium-grained sand, 2 – biogenic deposits (peat, gyttja), 3 – fine-grained sand, 4 – silt, 5 – sandy diamicton, 6 – sand with gravel, 7 – topsoil; location of geological section I–II is marked on sketch (A)

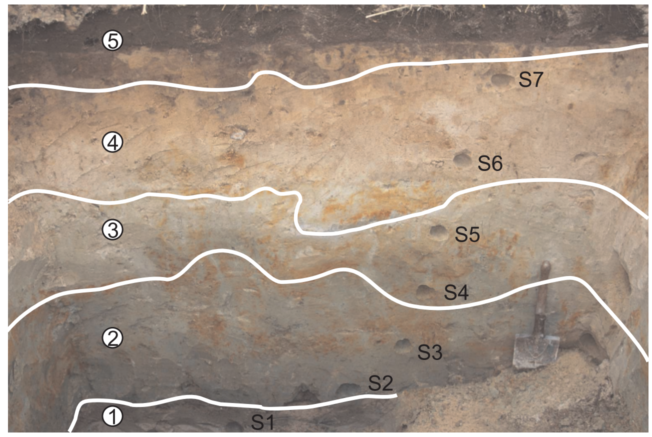

Fig. 3. Diamicton in the Besiekierz artificial pit excavated in 2005

1 – sand (with intercalations of silt in the upper part), 2 – diamicton, 3 – sandy diamicton, 4 – sand, 5 – accumulation soil horizon; S1–S7 – indicate the location of sampling points (in Figs. 3 and 4 only selected samples are shown – those taken along the most accessible pit wall); shovel length 50 cm (photo by Piotr Czubla)

ber of rounded grains with a matt surface, typical of aeolian sands in central Poland that accumulated in the Late Weichselian (Manikowska, 1993). The lower layer is formed by poorly sorted sand with an admixture of silt.

The diamicton was in some places sandy and it contained some intercalations of sand and gravels. Samples taken from the diamicton show a bi- or tri-modal distribution (Fig. 4). It consists a relatively small percentage (<20%) of clay/silt and a prevalence of sand (47–62%). By contrast, in a typical Warthanian glacial till in central Poland, clay and silt constitute >50% (Klatkowa, 1972, 1993b).

Analysis of quartz grain abrasion in the diamicton has shown the presence of round, matt grains (RM) ranging from 24 to 39%, shiny grains (EL) ranging from 21 to 30% (Fig. 4) and a considerable amount of cracked (C) and non-abraded (NU) grains. Such proportions of the first two types are characteristic of glacigenic sediments but the high proportion of type C and NU grains is indicative of considerable damage to the sediment.

A considerable proportion of the RM grains in the sands found within the diamicton, as well as in the uppermost layer of the deposits analysed, indicate that the sediments had been reworked under eolian conditions (periglacial?). They may have been located in the fossil depression before the diamicton was deposited, while the deposits covering the diamicton may have been transported by wind action from the Moszczenica terrace, that was deforested in the Holocene.

The deposits analysed are almost completely decalcified. Only a few samples showed a content of about 0.5% of calcium carbonate (Fig. 4). The typical calcium carbonate content in the Warthanian glacial till in the area of Besiekierz, by contrast, ranges up to 10% (Klatkowa et al., 1994). In order to define the origin and age of the diamicton, it is necessary to analyse the organic carbon content, carried out for the first time at Besiekierz. Organic matter content ranged from 0.2 to 0.8%, indicating that the entire diamicton formed during pedogenesis. Tillage diamicton may well contain even less organic matter. In the Bronów site, a similar tillage diamicton, which overlies Holocene organic deposits (dating ^{14}C to 2730 ± 50 years BP), contained only 0.1–0.2% of organic matter (Twardy et al., 2004). No such additions of dispersed organic materials have been identified in primary lodgement or melt-out tills in the Łódź area.

PETROGRAPHIC ANALYSIS

A total of 607 pebbles extracted from ca 4 m^3 of diamicton were used for the analysis of indicator rocks. The content of coarse gravel fraction found in the deposits analysed was relatively low. There was a conspicuous absence of carbonate rocks, which are commonly found in morainic tills of central Poland and which usually make up up to 35% of the Nordic rocks total (Czubla, 2001). In addition, the material analysed did not contain relatively friable and susceptible to weathering local rocks (mudstones, fine-grained calcareous sandstones, Mesozoic chalky limestones and chalk). This indicates considerable weathering of the material. The absence of relatively large erratics 1 dm across and more was also atypical. Their presence in morainic tills is not usually high anywhere in Poland, but they nevertheless are typically present.

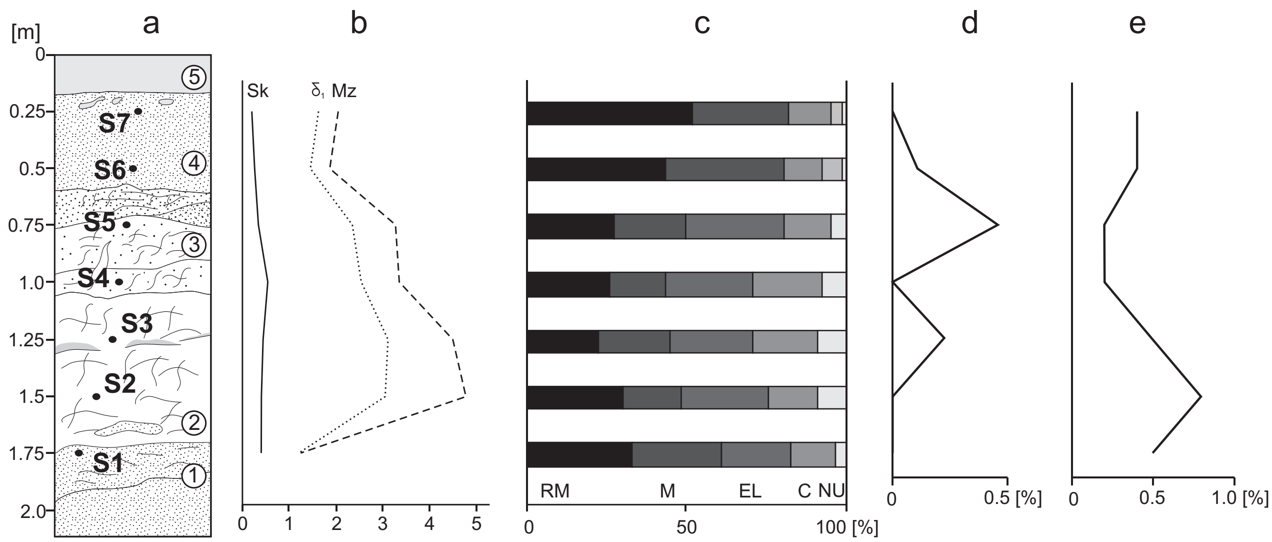

Fig. 4. The results of lithological analyses of the deposits examined (cf. Fig. 3)

a – lithology: 1 – sand (with intercalations of silt in the upper part), 2 – diamicton, 3 – sandy diamicton, 4 – sand, 5 – accumulation soil horizon; b – grain-size coefficients on the phi (φ) scale (after Folk and Ward, 1957): Mz – mean diameter, δ_1 – standard deviation, Sk – skewness; c – quartz-grain abrasion: RM – round, matt grains, M – medial (between RM and EL) grains, EL – shiny, glossy grains, C – cracked grains, NU – non-abraded grains; d – $CaCO_3$ content; e – content of organic matter

The absence of carbonate rocks made it impossible to calculate petrographic coefficients. The reliability of such measures is here limited in any case due to the considerable weathering of the material and the atypical grain size distribution, totally different from the one used in standard lithostratigraphic analyses of glacial tills. The only coefficient which can be reliably calculated is the O/K (O – sedimentary rocks, K – crystalline rocks or sum of igneous and metamorphic rocks) and it stands at 0.26115. It is thus unusually low for till (e.g., Krzyszkowski, 1991, 1995; Czerwonka and Krzyszkowski, 1992, 1994; Lisicki, 2003) and again it stresses the role of chemical weathering which has eliminated carbonate rocks.

Among Baltic-Fennoscandian erratics almost 80% are made up of crystalline rocks including isolated quartz crystals derived from weathered coarse-grained igneous rocks or quartz veins. The remaining 20% consisted mainly of Proterozoic (Jotnian) and Cambrian sandstones. Crystalline rocks are dominated by volcanic rocks from the Dalarna region in Sweden and by fine-grained intrusive rocks from the Åland Islands and surrounding area (Fig. 5). The percentage of coarse-grained Åland Rapakivi granites is disproportionally small. They are usually just as frequent as aplite granite from Åland. However, given the considerable susceptibility of coarse-grained rocks to physical weathering (changes in temperature lead to large stresses on the edges of large crystals) these were soon eliminated from the rock material originally present in the tills. Equally low is the percentage of metamorphic rocks, which due to their texture (clear signs of foliation or lamination, alternating layers of different composition) and mineral composition (e.g., a high proportion of micas) quickly become destroyed in weathering.

It is notable that, during the fieldwork at Besiekierz, no remnants of weathered metamorphic rocks rich in biotite were found; these are characteristic of considerably weathered but well (*in situ*) preserved residual morainic deposits, as for instance, certain till beds in the open-cast mines at "KWB Bełchatów" or "Jóźwin" at Kleczew near Konin (Czubla, 2001). In the case of redeposition, the rock remnants would at least become scattered or even wholly dispersed. At Besiekierz, such remnants must have been completely destroyed. One can conclude that intensive weathering processes must have occurred before the possible redeposition of the diamicton.

Despite certain methodological reservations related to the analysis of weathered tills (Czubla, 2001), indicator rocks were identified and on this basis, the Theoretical Boulder Center (TBC; Lüttig, 1958) was calculated. The proportion of indicator rocks proved to be unusually high, close to 15% of all Baltic-Fennoscandian rocks, which in turn made up almost the entire sample. This is, however, a situation typical of weathered glacial deposits, where weatherable sedimentary rocks with extensive source areas (outcrops) in the Baltic region (useless for this type of analysis) become eliminated. At the same time, there is a relative increase in easily recognizable extrusive rocks from the Dalarna region, which are highly resistant to weathering. There is also an increase in the presence of microgranites from the Åland Islands (Fig. 5).

The TBC of diamicton from Besiekierz has its geographical coordinates φ = 59.62° N and λ = 16.71° E. This spot is situated near the TBC calculated for younger Saalian (Warthanian) tills from the Bełchatów open-cast mine, the Łódź area and the eastern Wielkopolska Region (Czubla, 2001; Czubla and Forysiak, 2004; Fig. 6). It may be concluded that the diamicton located above the Eemian deposits in Besiekierz dates from the younger Saalian (Warthanian) and it found its present place as a result of post-depositional and most probably post-weathering replacement. The slight shift of the TBC to the west may be attributed to preservation of weathering-resistant Dalarna porphyries from central Sweden, while, at the same time, the more susceptible east-Fennoscandian rocks were eliminated.

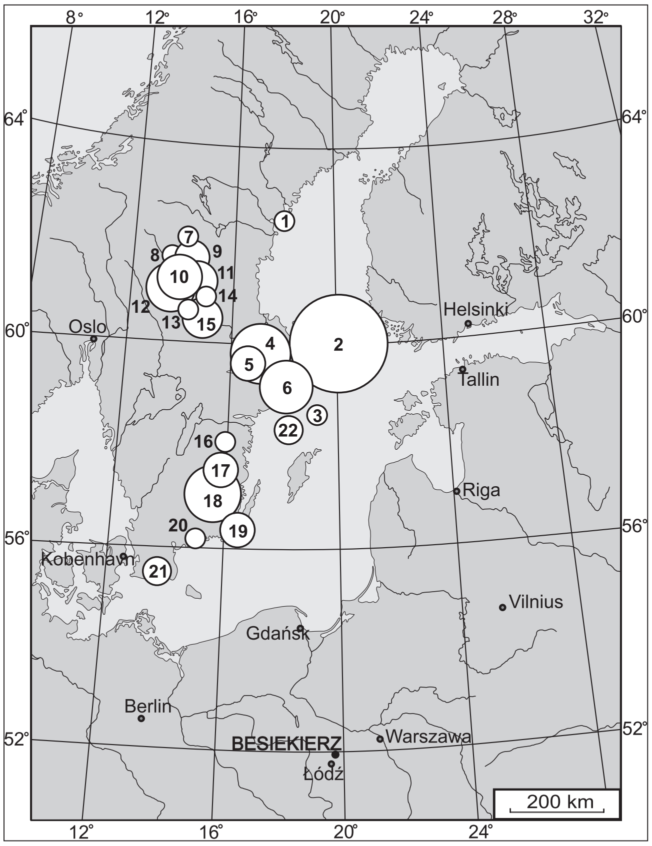

Fig. 5. Source areas of indicator erratics recognized in diamicton at the Besiekierz site (the circle's area corresponds to the percentage of erratics in an analysed stone sample); graphic presentation method (circle map) after Smed (1993)

1 – Rödö Rapakivi, 2 – Åland Granite, Haga Granite, Åland Rapakivi, Åland Aplite Granite, Åland Granite Porphyry, 3 – Brown Baltic Quartz Porphyry, 4 – Uppsala, Vänge and Arnö granites, 5 – Sala Granite, 6 – Stockholm Granite, 7 – Glöte Porphyry, 8 – Särna Tinguaite and Porphyry, 9 – Grönklitt and Grey Dalarna porphyries, Åsby Diabase, 10 – Åsen, Bredvad and Kåtilla porphyries, Garberg Granite, 11 – Blyberg Porphyry, Klittberg Ignimbrite and Porphyry, Rännås, Blyberg, Orrlok and other Dalarna ignimbrites and porphyries, 12 – Öje Diabase and Melaphyre, Dala Sandstone, Digebergs Sandstone and Conglomerate, 13 – Venjan Porphyry, 14 – Järna Granite, 15 – Siljan Granite, Siljan Rapakivi, Mänsta Porphyry, 16 – Kinda Granite, 17 – Mariannelund Granite, Emarp, Nymåla, Fagerhult and Lönneberga porphyries, 18 – Red Småland Granites, Vislanda Granite, Småland Porphyry, 19 – Kalmarsund and Tessini sandstones, 20 – Karlshamn and Spinkamåla (Halen) granites, 21 – Skolithos and Hardeberga sandstones, Kullaite, 22 – Red Cambrian sandstones

DISCUSSION

Both the results of the earlier research and the new data presented here, comprising lithological and petrographic analyses, as well as the palaeogeographic context, rule out the possibility that the Besiekierz area was covered by the Weichselian ice-sheet. Petera and Forysiak (2003) provided evidence that the last ice-sheet could not cross the Warszawa–Berlin ice-marginal streamway within the Koło Basin that stretches to the north-west of the area investigated.

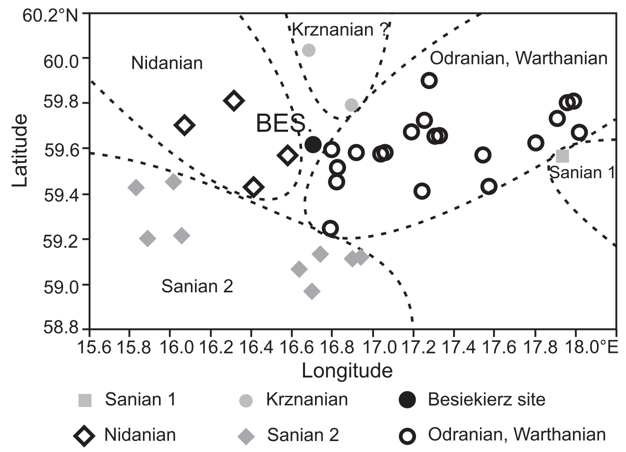

Fig. 6. Theoretical Boulder Center calculated for diamicton at Besiekierz against a background of selected TBC's of Middle Poland (Bełchatów open-pit and Łódź region; Czubla, 2001, modified)

When considering the local situation of the Eemian organic deposits overlain by diamicton, the age and origin of the latter are problematic. An age related to the Warthanian Stage should be treated as the age of source material (sediment), which moved over slopes towards the fossil depression (basin).

Lisicki (2003) reinterpreted the results of petrological analyses of the fine gravel fraction (petrographical coefficients) at the Besiekierz site carried out by Klatkowa (1993a) and compared these with the results obtained for the youngest till bed in the surrounding area (Klwowska Wola type k4, estimated as "...older than the last Pleistocene Glaciation..."). In his opinion the Besiekierz diamicton should be recognized as weathered deluvial (slope) sediment originated from k4 till. A similar inference has been made also by Morawski (2001) based on analogy with the results of analyses carried out on the eastern Mazovia and Podlasie region. Mojski (2005) suggested that the deposit resembling glacial till and covering indisputably Eemian deposits was formed, most probably, as a result of water transport overloaded with deposits, including gravel fraction. Turkowska (2006) reported the results of analyses conducted until then at Besiekierz. She discussed the age and origin of the till deposits without, however, taking a stance on this issue.

Transport of the till occurred during farming and it may be linked to tillage erosion. Tillage erosion and the accumulation of tillage diamicton is the consequence of motion on slopes of sediment layers near the surface during ploughing. This leads to the flattering of slopes, the elimination of small hills and the filling of small interior hollows with tillage diamicton of disproportionately large thickness (Zaslavskiy, 1978; Brown et al., 1981; Sinkiewicz, 1989, 1995, 1998; Govers et al., 1994; Twardy, 2003, 2008). Numerous examples of transforming small depressions by tillage erosion leading to their shallowing or even complete infill were provided by Sinkiewicz (1989, 1995, 1998), Niewiarowski et al. (1992), Klimowicz (1993), Twardy (2002a) and others. The present-day rate of tillage erosion is estimated at a few mm per year (Sinkiewicz, 1998; Twardy, 2002b, 2008; Zgłobicki, 2002; Szpikowski, 2005). According to Józefaciuk and Józefaciuk (1984), during 30 years of farming, there occurred a truncation of small land-forms of 3 to 3.5 m and at the same time, the depressions were filled with sediment 1.5–2.0 m thick. Rodzik et al. (2008) estimated that since the Middle Ages, the lowering of small ridges separating dry denudational valleys could locally reach 2 m.

It is worth stressing that tillage erosion did not lead to a change in the structure of source sediment (till). Tillage diamicton, formed by the repeated mixing of sediment during ploughing, has in general a massive structure. As a result, sedimentary structures are not identified or even searched for in tillage diamicton. Such structures could account for the way in which blocks were introduced into fine sediments. Most of the coarse material was extracted from the bed by farming tools pulled at random through the sediments. The sandy interlayers present in the diamicton emerged due to weak run-off across the cultivated surface. The tilloid (till-like) texture was not greatly transformed. A reduction in the content of clays was observed, which probably moved towards the centre of the basin. This can be seen in Klatkowa (1993a; see cross-section in Fig. 2B, symbol 4). The polymodal nature of frequency curves is one of the characteristics of tillage diamicton derived from till (Twardy, 2008). The elimination of carbonate rocks and the disintegrated crystalline rocks may be attributed to weathering and the destruction of blocks during ploughing. In such an interpretation, the weathering may be short-term but nevertheless intensive because it concerned a layer of sediment right next to the surface. An increase in the content of C and NU quartz grains may have been caused by shear stress when ploughing clayely soil (Rousselot and Fischer, 2007). A lack of $CaCO_3$ and an increasing carbon content are one of indicators of tillage diamicton (Twardy, 2008).

In the vicinity of Łódź, diamictons, the emergence of which is attributed to tillage erosion (sites at Bronów, Strońsk, Brodnia) were dated as Subatlantic by means of the ^{14}C method (Twardy et al., 2004; Twardy, 2008). Marked shallowing of the small fossil basin in Besiekierz probably started in medieval times. Due to technological improvements, it became possible to cultivate clayely areas by means of iron ploughs drawn by animals. The occurrence of numerous local archaeological sites from medieval times has been described (Twardy, 2008). It should be emphasized that this farming took place in a small shallow basin with an original surface layer of older Vistulian sands of unknown origin, 0.5–0.6 m thick (Klatkowa, 1972; Klatkowa et al., 1994). Thus, cultivation took place on solid and stable ground which may have been periodically wet. The relief did not hinder the farming because the area was only gently undulating and small, shallow basins separated by till "hillocks" added variety to it (Klatkowa, 1993a; Fig. 2B). The upper sand layer, overlying the diamicton, was probably formed by redeposited sandy material during deforestation that took place in the 19th and 20th centuries (Twardy, 2008).

CONCLUSIONS

The problem of the Besiekierz site cannot be resolved using purely geological and stratigraphic criteria. Following research by the discoverer of this site (Klatkowa, 1972, 1993a) and analyses carried out independently by different researchers, the age of the organic infill of the fossil depression and the diamicton has been determined as Eemian and Warthanian, respectively. It is equally necessary to define the nature of the geomorphological process which led to the movement of the glacial deposits by colluvial processes towards the centre of the basin without affecting its texture or structure. The data indicate that this was connected with long-term agricultural use of the land surrounding the site: particularly with tillage erosion co-occurring with different kinds of weathering processes. The archaeological evidence suggests that this process took place in the course of intensive farming over at least a few hundred years. Most probably, it was preceded by earlier weak run-off processes and by long-term chemical and mechanical weathering processes. The truncation of the gently undulating landscape near Besiekierz may be considered as the result of many centuries of "tillage planation" (Sinkiewicz, 1995) which comprises rapid truncation of small concave landforms, truncation of scarps and short narrow slopes, the flattening of slopes and the filling of small depressions.

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