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Influence of bedrock on the Quaternary deposits in the central Krajna Lakeland

Władysław NIEWIAROWSKI, Michał PASIERBSKI

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An elevated bedrock (Więcbork Elevation), caused by uplifting related mostly to salt tectonics, significantly affected types of the Quaternary sediments in the central Krajna Lakeland. It caused development of destructive processes which resulted that the older Pleistocene deposits, from sediments of the Odranian Glaciation (Drenthe, Older Saalian), have not been preserved. The bedrock topography also affected thickness variability of the Quaternary deposits, from 80 to 95 m in topographic depressions and from 30 to 60 m at elevations. Sediments of three stadials of the Wartanian Glaciation (Warthe, Younger Saalian), which constitute more than 50% of the entire thickness, are the most significant. They caused considerable planation which reduced effects of bedrock topography on deposition of sediments of the Vistulian Glaciation (Weichselian). Ice sheets of the Early and Middle Vistulian Glaciation, advancing to the Lower Vistula Region as well as the Warmia and the Mazury, have not reached the study area. Hence, occurring here the sediments of the Vistulian Glaciation were deposited during the Main Stadial (about 20–16 ka BP). The bedrock elevated at the watershed resulted in a very poor development of fluvial ice-dam lake, and lake-marshy deposits. The latter are the most important among the Holocene sediments. Six tills of five glacial episodes, forming about 70% of the entire deposit thickness, are the main Pleistocene sediments. Petrographic composition of tills of the Wartanian and the Vistulian Glaciations is closely related to the one of tills from central Wielkopolska (Great Poland), reflecting similar directions of advancing ice sheets. A till of the Mława Stadial of the Wartanian Glaciation, which occurs in the Krajna Lakeland, probably does not occur in central Wielkopolska. The Krajna Lakeland, as far as thickness and structure of the Quaternary deposits is concerned, belongs to the Kujawy–Pomeranian Region which is significantly different from the Lower Vistula Region, Warmia and Mazury.

Władysław Niewiarowski, Michał Pasierbski, Institute of Geography, Nicolaus Copernicus University, Fredry 6/8, 87-100 Toruń, Poland
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INTRODUCTION

A central part of the Krajna Lakeland, described in the paper, includes an area of two sheets, i.e. Więcbork and Sępólno Krajeńskie, of the *Detailed Geologic Map of Poland* in scale 1:50 000 (Fig. 1). This area has been poorly identified in terms of geology and the Quaternary stratigraphy until the recent time. Although the oldest references about occurrence of terminal moraines (G. Maas, 1900) and an esker at Borówki (A. Jentzsch, 1906) are dated at the beginning of this century, however, any detailed study of selected, relatively small areas or selected landforms only came from a period since the fifties. A geomorphologic study of the Więcbork area (R. Galon, 1952) should be mainly listed here and, based on this study, the term Krajna Phase as one of major phases (currently subphases) of the Poznań Stadial (currently a phase).

Some kames and eskers from the vicinity of Więcbork were studied by T. Murawski (1961*a, b*), and all landforms of the Krajna Lakeland were reviewed and presented by the same author (T. Murawski, 1969) on a morphogenic map in scale 1:100 000. Geology and the Quaternary stratigraphy were presented on the *General Geologic Map of Poland* in scale 1:300 000, sheet Bydgoszcz (R. Galon, 1949), and in more detail on the *Geologic Map of Poland* 1:200 000 and in explanations for the sheets Chojnice (N. Butrymowicz, 1978) and Nakło sheet (M. Uniejewska *et al.*, 1979).

Since interglacial or interstadial deposits in the study area have not been documented by biostratigraphic methods, and detailed lithostratigraphic or petrographic studies of tills have

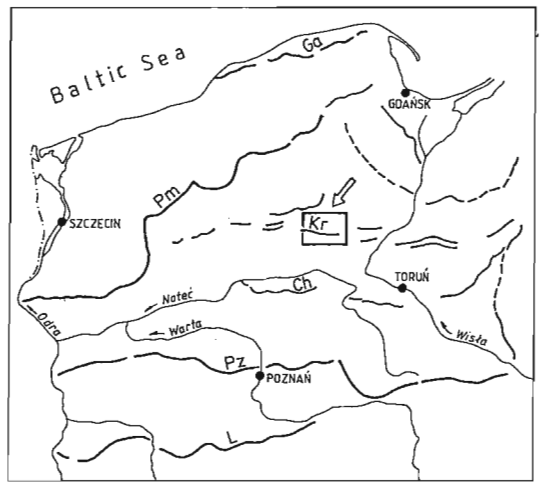

Fig. 1. Location of the study area (indicated by arrow)

Extent of ice sheet during the Vistulian Glaciation: L — Leszno Phase, Pz — Poznań Phase, Ch — Chodzież Subphase, Kr — Krajna Subphase, Pm — Pomeranian Phase, Ga — Gardno Subphase

not been conducted, understanding of the stratigraphy of the Quaternary deposits in this area was very simplified and poorly documented. For example, only a single thick till (dichotomous locally) of the Middle Polish Glaciation and two tills of the Vistulian (North Polish) Glaciation were accepted in a generalized concept.

New study results, in addition to studies of surficial layers, are based on six profiles from exploratory drillings, where the following parameters were determined: grain size distribution of the deposits, contents of $CaCO_3$ and heavy minerals, rounding of quartz grains (fraction 0.8–1.0 mm) and petrography of tills based on their gravels of 5–10 mm diameter. Scandinavian (northern) and local rocks were distinguished. In accordance to the *Instrukcja w sprawie opracowania* ... (1991, 1996) the following rocks were determined in gravels of the Scandinavian provenance: crystalline (K) and sedimentary (O) rocks, Palaeozoic limestones and dolomites (W), rocks resistant (B) and non-resistant (A) with respect to weathering. Based on the petrographic study of tills in Poland (J. Trembaczowski, 1967; J. Rzechowski, 1980; J. A. Czerwonka, D. Krzyszkowski, 1994; W. Gogołek, 1994; S. Lisicki, 1997), it may be concluded that the coefficients O/K, K/W and A/B varied most among different tills and thus they are used to till correlation, at least in a regional scale. Other features of deposits studied allow to determine the origin, but because of their significant variability they can not be used as the basis for a broader correlation. Organic deposits were studied palynologically by B. Noryśkiewicz (1996, 1997). In addition to exploratory drillings, 180 archival drilling profiles were analyzed, from which 41 penetrated the entire Quaternary complex.

Palaeogeomorphologic analyses and reference to new stratigraphic approaches in the adjacent areas were helpful to determine stratigraphy of deposits (B. Noryśkiewicz, 1979; S. Kozarski *et al.*, 1980; S. Kozarski, 1981, 1991, 1995; S. Dąbrowski *et al.*, 1987; K. Mamakowa, 1989; J. A. Czerwonka, D. Krzyszkowski, 1994; W. Gogołek, 1994).

Results of these studies provided new data about characteristics of the Quaternary deposits and their stratigraphy, and allowed to revise the older approaches. A part of these results is presented in this paper, where an issue of the relationship between morphology of the Quaternary bedrock and characteristics of the Quaternary deposits are emphasized.

MORPHOLOGY AND ORIGIN OF THE QUATERNARY BEDROCK

The study area overlies the Kujawy–Pomeranian Anticlinorium, occurring in the basement rocks (at 87–200 m b.s.l.) and with NW–SE axis, which formed at the turn of the Cretaceous and the Tertiary, partly in its central part and partly along its eastern limb. The anticlinorium experienced peneplanation which produce a peneplain. Hence, it is composed in the central part of rocks of the Lower and Upper Jurassic, and of the Cretaceous in the limbs.

Marine transgressions and regressions occurred on this peneplain as a result of vertical tectonic movements, and significantly thick fluvial, lacustrine and marshy sediments were deposited in the Neogene, partly brackish in the Miocene. The entire thickness of the Tertiary deposits, i.e. sands, silts, and clays and brown coal layers, ranges from 150 to 240 m in the southern part and about 130 m in the north (W. Niewiarowski, M. Pasierbski, 1996, 1997). Deposits of the Upper Pliocene have not been determined.

The Więcbork Elevation (Fig. 2) with transverse faults is a dominant component in a morphology of the Quaternary bedrock. According to R. Dadlez and S. Marek (1969, 1974), this elevation belongs to local structural components associated with salt cushions and ridges present in a deeper bedrock. Such elevations are always associated with salt tectonics. It is very probable that these structures were subjected to uplift movements in the Upper Pliocene and the older Quaternary. J. E. Mojski (1977) assumes that uplifting of the Kujawy–Pomeranian Anticlinorium have occurred throughout the entire Quaternary. It specifically refers to salt diapirs (*cf.* W. Niewiarowski, 1983). The basement morphology was subjected to intensive denudation and glacial erosion, which resulted in significantly reduced thickness (to only 13–20 m) of deposits, mainly clays of the Upper Poznań Series of the Lower Pliocene (M. Piwocki, M. Ziembińska-Tworzydło, 1997). Basement of the Quaternary rises on the Więcbork Elevation to 88–100 m a.s.l., thus several dozens of metres higher than in stable areas. Detached blocks of these sediments occurring within a till, and significant enrichment of tills in clayey fraction and the Tertiary heavy minerals resistant to weathering, present evidence of surficial glacial erosion of the Pliocene deposits. Overlying of the Pliocene clays by tills of various age indicates that the sub-Quaternary surface at the Więcbork Elevation has not been formed at the same time.

The Więcbork Elevation is dissected by the polygenetic Sępólno Depression, characterized by a near-meridional

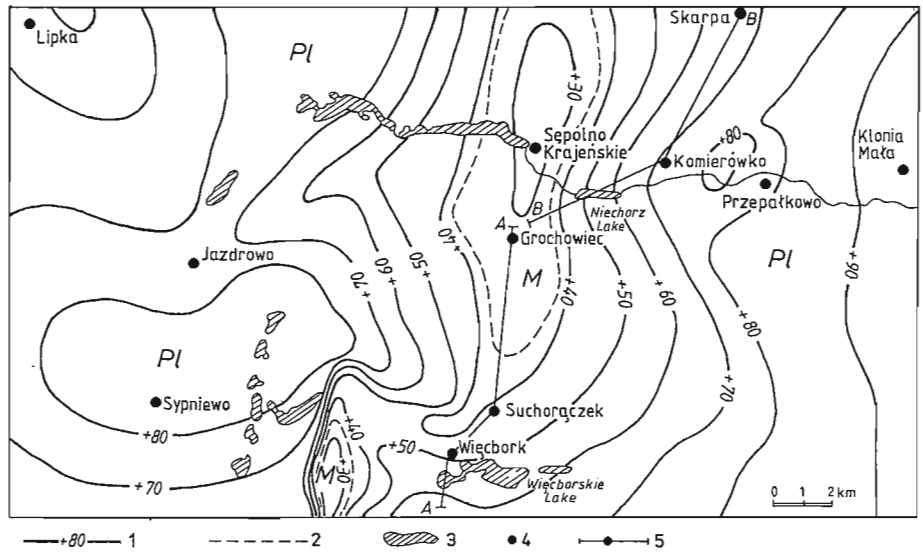

Fig. 2. Outline of the Quaternary basement topography in the central Krajna Lakeland

1 — contour lines, 2 — stratigraphic boundaries, 3 — lakes, 4 — major boreholes, 5 — geologic cross-sections; M — Miocene, Pl — Pliocene

trend. Its width is 2–4 km, depth 30–40 m, and the bottom is located at 25–40 m a.s.l. (Fig. 2). In its deepest part, it is cut in deposits of the Upper Miocene. Glacial erosion during older glaciations and river erosion in the Lublinian Interglacial and the Regimin Interstadial of the Wartanian Glaciation played a major role in its development (W. Niewiarowski, M. Pasierbski, 1997).

In addition to this depression, it has been determined that a buried deep and narrow subglacial trough occurs, with its bottom at 24–29 a.s.l., cut in deposits of the Upper Miocene during the Odranian Glaciation. In the northwestern part of the study area a depression, probably of a glacial erosion origin, occurs in the vicinity of Lipka and Bługowo, and its bottom descends to about 46 m a.s.l.

From the information presented above, one may conclude that surface of basement of the sub-Quaternary deposits in the central Krajna Lakeland was mainly shaped as a result of glacial erosion during successive glaciations, and fluvial and glaciofluvial erosion. Thus, this surface is also polygenic. However, its relatively high elevation is associated with younger vertical movements, related mostly to salt tectonics. Relatively small elevations, resulted from glacial tectonics may occur here locally. Differences in elevation of the sub-Quaternary surface reach about 70 m, thus greater than at the present-day surface. In comparison to the neighbouring area, this one has been a watershed throughout the Quaternary. It resulted in a poor development of a valley network and peculiar characteristics of the Quaternary deposits. The watershed location can be also observed at the present time, because a watershed between the Vistula and the Odra rivers occurs here.

QUATERNARY STRATIGRAPHY

Stratigraphy of the Quaternary deposits in this area encountered several difficulties. An entirely developed biogenic interglacial and interstadial sediments have not been found, and dating of sediments using thermoluminescence method did not provide satisfactory results. Nevertheless, there is evidence which allows to determine more or less documented stratigraphic data. Study conducted (W. Niewiarowski *et al.*, 1996, 1997) allowed to determine the occurrence of two thick, of different age, fluvial series in the Sępólno Depression, including one which probably is a residual part of interglacial sediments (with a thin layer of peat) and one thicker series (from 20.2 to 38.8 m) of fluvial deposits, developed in at least two sedimentary cycles during an interstadial. The conducted study indicated that tills mostly differ in petrographic composition of gravels and calculated petrographic coefficients (O/K, K/W, and A/B), and relative relationship of occurrence of crystalline Scandinavian rocks and Palaeozoic limestones (Wp). Based on them, occurrence of six tills, representing five glacial episodes of different stratigraphic rank, were determined.

Palaeogeomorphologic analyses and comparison to stratigraphy of the Quaternary deposits in the adjacent areas indicated that the Quaternary deposits older than the Odranian Glaciation have not been preserved in the studied part of the Krajna Lakeland. Older deposits, that is from the South Polish Glaciation, are residually preserved only in depressions within the Quaternary bedrock, typically below a sea level (N. Butrymowicz, 1978; M. Uniejewska *et al.*, 1979). Top of river deposits from the Mazovian Interglacial in the Noteć–Warta

Rivers area is located at 25–30 m a.s.l. (M. Uniejewska *et al.*, 1979), thus at least 30 m lower than the oldest river sediments in the Sępólno Depression.

River sediments in the area of ice-marginal valley of the Noteć–Warta Rivers, dated palynologically at the Eemian Interglacial, and Brörup and Odderade Interstadials, can be considered as reference for the Krajna Lakeland. The top of these deposits is located at Śmielin at about 57 m a.s.l. (M. Uniejewska *et al.*, 1979) and descends to 41–42 m a.s.l. at Łęgnów (K. Wrotek, 1978). Of a significant importance is the fact that two tills of the Wartanian Glaciation and organic deposits, probably from the Grabówka (Lublinian) Interglacial), and underlying glacial deposits with a till of the Odranian Glaciation occur below the palynologically documented sediments from the Eemian Interglacial (52–57 m a.s.l.) at Piła–Baza (S. Dąbrowski *et al.*, 1987).

ODRANIAN GLACIATION (DRENTHE, OLDER SAALIAN)

Preserved sediments of a glacial series from the Odranian Glaciation are characterized by ice-dam lake and glaciofluvial deposits of a small thickness and a single discontinuous till, 2–9 m thick (Figs. 3 and 4). It has been preserved both in the depression of the Więcbork Elevation (70–75 m a.s.l.) with wash-out traces, indicated by a lag concentrate, and in depressions without any traces of water erosion. This till was studied in detail in the Komierówko profile only (W. Niewiarowski *et al.*, 1997), where it is 4.9 m thick, and in the top is covered by a sandy-gravely layer (0.4 m). This is a dark till, disturbed by glacial tectonics, containing 2.0–4.3% of gravel, 31–48% of sand, 33–47% of silt, 6–28% of clay, and also 11–16.5% of $CaCO_3$. Its high content of heavy minerals (1.3%) and their composition indicate that it was enriched in the Pliocene material. A characteristic feature of the gravel petrographic composition is occurrence of extremely abundant, if compared with other tills in this area, gravels of the Palaeozoic sandstones (26%) and predominance of the Palaeozoic limestones (27.4%) over gravels of crystalline rocks (22.2%), and large participation of local rocks (14%). This composition results in specific petrographic coefficients: O/K — 2.07, K/W — 0.91, and A/B — 0.96. They also became the main reason why this till was tentatively classified as of the Odranian Glaciation. One should mention here that it is not possible to compare them with coefficients of the Odranian Glaciation tills from another area of the Krajna Lakeland, because such study has not been conducted yet. The closest area where petrographic studies of tills were conducted using the same method, is the central Wielkopolska (Great Poland) in the vicinity of Leszno and Szamotuły (J. A. Czerwonka, D. Krzyszkowski, 1994; W. Gogołek, 1994). This area indicates similarities to characteristics of the Quaternary deposits in the Krajna Lakeland, however, a type of the Dopiewice tills, classified as of the Odranian Glaciation, indicates predominance of crystalline rocks over the northern limestones, and the coefficients are as the following: O/K — 0.6–1.0, K/W — 1.3–1.5, and A/B — 0.6–0.8 (J. A. Czerwonka, D. Krzyszkowski, 1994), thus quite different than these of the Komierówko tills. Petrographic coefficients of this till also depart from coefficients in tills of the Wartanian Glaciation in the central Wielkopolska. Hence, detailed determination of age of this till requires further studies.

LUBLINIAN INTERGLACIAL

Deposits of this interglacial were probably determined in the Sępólno Depression in the Suchorączek profile (Fig. 3). These are deposits of river bed and oxbow facies, 9.9 m thick. They overlie the Poznań Clays at 41–50 m a.s.l. and are covered by 0.3 m thick layer of lag concentrate, composed of pebbles and gravels derived from a till of the Wartanian Glaciation. Fine- and medium-grained sands (1.9 m) with interlayers of clay (0.3 m) and sandy peat (0.2 m) are covered by sandy deposits in a lower part (3.2 m thick). Palynologic analysis (B. Noryśkiewicz, 1996) indicates that clays were deposited in a tundra-like environment and the overlying peat formed in a boreal climate, where rare pine-birch forest occurred in the vicinity of a river. Pollen does not occur in the overlying fluvial sandy deposits. Palynologic analysis which includes only fragments of fluvial sediments does not allow for determination of their stratigraphic position. However, a small thickness of river sediments, and lag concentrate above them, suggest washing-out of younger part of a fluvial series and a till. A fragment of a buried valley, in which the deposits described above are preserved, intersects a till of the Odranian Glaciation and partly, the Poznań Clays, and the overlying pavement could originate only from destruction of one or even two tills of the Wartanian Glaciation. Hence, these sediments could originate from an initial warming phase during the Lublinian Interglacial, but it seems also possible that they come from an older interstadial during the Wartanian Glaciation. This problem requires further studies.

WARTANIAN GLACIATION (WARTHE, YOUNGER SAALIAN)

Sediments of this glaciation commonly occur in drilling profiles and constitute the dominant part of the Quaternary deposits, in which beds of tills have significant thickness (Figs. 3 and 4). Similarly as in the Piła region (S. Dąbrowski *et al.*, 1987) two tills of this glaciation were determined in the sheet Więcbork, and three tills were documented in the borehole Grochowiec (W. Niewiarowski *et al.*, 1997; W. Niewiarowski, M. Pasierbski, 1997) in the sheet Sępólno Krajeńskie. Tills are typically separated by ice-dam lake and/or glaciofluvial deposits, and exceptionally by interstadial river deposits. Tills of various stadials, however, often overlap each other and form a single thicker bed, in order of about 30–48 m.

Three tills hitherto documented were determined only at Grochowiec, where 14.6 m of a glaciofluvial sediment series is covered by two tills separated by 0.9 m of fine- and medium-grained well sorted sand, containing 6.36% of $CaCO_3$ and characterized by good rounding of quartz (Wo — 1176), according to indexes introduced by B. Krygowski (1964). These tills are covered by glaciofluvial sediments, 1.5 m thick, and by the other till, 1.75 m thick (Fig. 3).

The lower till (W_1), 18 m thick, contains 1–4% of gravels, 26–44% of sands, 30–57% of silts, and 13–16% of clays. Sand

participation increases topwards, similarly to $CaCO_3$ content (from 5 to 14%). Any significant changes in composition of heavy minerals, except for amphiboles and rutiles, are not observed. This till is poor in grains of 5–10 mm fraction. Crystalline rocks dominate among gravels (38.2%) before the Palaeozoic limestones (33%) and local rocks (7%). Mean petrographic coefficients for the till are: O/K — 1.12, K/W — 1.29 and A/B — 0.59. Almost the same coefficients are characteristic for a till at Lipka, 47.9 m thick. It is characterized by a small variability of grain size distribution in $CaCO_3$ content (8–12%) and in composition of heavy minerals. It suggests that it formed during one of the glacial episodes.

Petrographic coefficients presented above for tills from Grochowiec and Lipka are similar to tills of the Karolewo till type in the central Wielkopolska Region, characterized by: O/K — 1.0–1.3, K/W — 0.9–1.1, and A/B — 0.9–1.2. Only the coefficient A/B departs from this similarity, but it should not be neglected because this coefficient is higher in all tills in the central Wielkopolska than in tills from the central Krajna Lakeland. Predominance of crystalline rocks over limestones is also typical for this till. The Karolewo till is classified to the lower stadial (J. A. Czerwonka, D. Krzyszkowski, 1994) or to the older stadial (W_1) (W. Gogołek, 1994) of the Wartanian Glaciation.

The middle till (W_2), 9.6 m thick, in comparison to a lower till in the Grochowiec profile, contains more sandy fraction (37–50%) and less clayey fraction (5–24%), and slightly more $CaCO_3$ (8–16%). Moreover, it differs also in the predominance of the Palaeozoic limestones (39.2%) over crystalline rock gravels (37.2%), and relatively large content of the Palaeozoic sandstones (11.5%) and small content of local rocks. Petrographic coefficients are: O/K — 1.24, K/W — 1.03 and A/B — 0.76. Similar features and petrographic coefficients: 1.28, 0.95, and 0.88, respectively, are characteristic for a till at Komierówko. These tills which belong to the same stratigraphic horizon were classified as the middle stadial of the Wartanian Glaciation. J. A. Czerwonka and D. Krzyszkowski (1994) include the Kopaszewko till in central Wielkopolska (with coefficients: O/K — 1.7–2.1, K/W — 0.5–0.7 and A/B — 1.5–1.8) and the Górzno till in southern Wielkopolska (1.3–1.7, 0.7–1.0 and 1.1–1.6, respectively) to the same stadial. W. Gogołek (1994) classifies the Kopaszewko till to the younger stadial (W_2) of the Wartanian Glaciation.

Comparing these coefficients with the ones determined for tills from Grochowiec and Komierówko, one may conclude that they significantly differ from coefficients of the Kopaszewko till, however, they are similar to coefficients of the Górzno till. The biggest similarity is observed in predominance of the Palaeozoic limestones (slightly smaller in the Krajna Lakeland than in the Wielkopolska Region) over crystalline rocks. The enrichment of tills in dolomites does not occur in tills from the Krajna Lakeland.

River interstadial deposits were only determined in the Sępólno Depression, in the Suchorączek profile and to the west in the Jazdrowo profile (Fig. 2). Lower elevation and more complete development of these sediments in the Suchorączek profile suggests that a major river had occurred here,

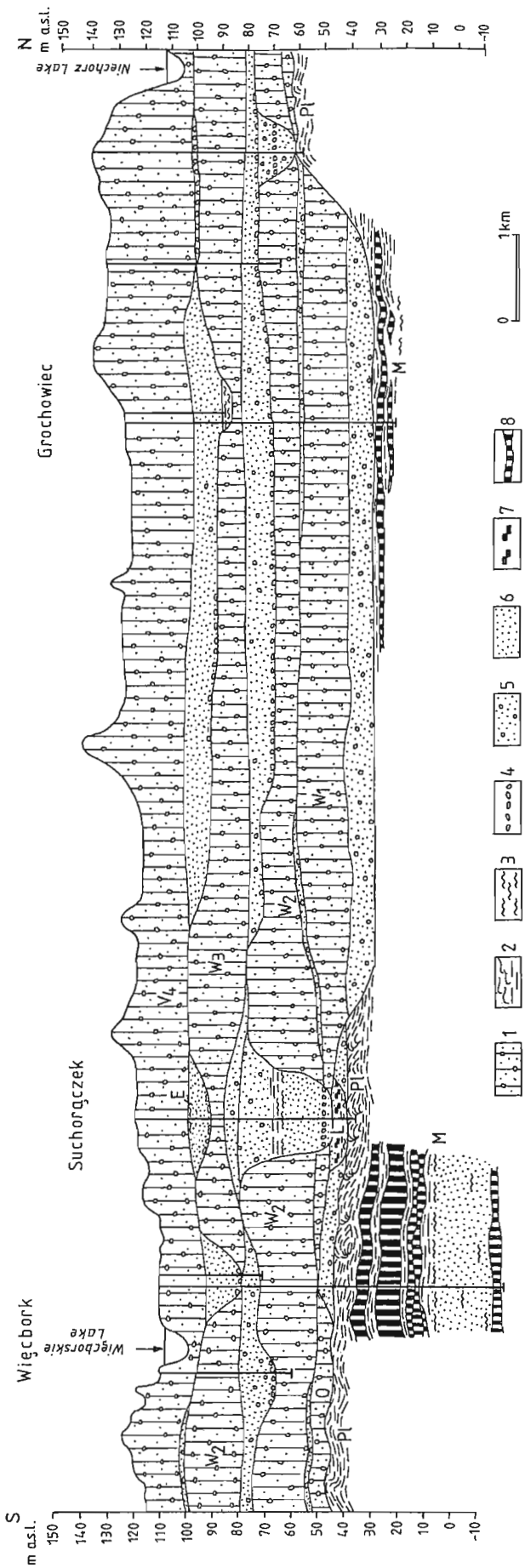

Fig. 3. Sępólno Depression — geologic cross-section A–A

1 — tills, in part disturbed, 2 — clays, 3 — silts, 4 — lag concentrate, 5 — sands with gravel, 6 — sands, 7 — peats, 8 — brown coal; M — Miocene, Pl — Pliocene, O — Odranian Glaciation, L — Lublinian Interglacial, W_{1-3} — Wartanian Glaciation, E — Eemian Interglacial, V_4 — Vistulian Glaciation

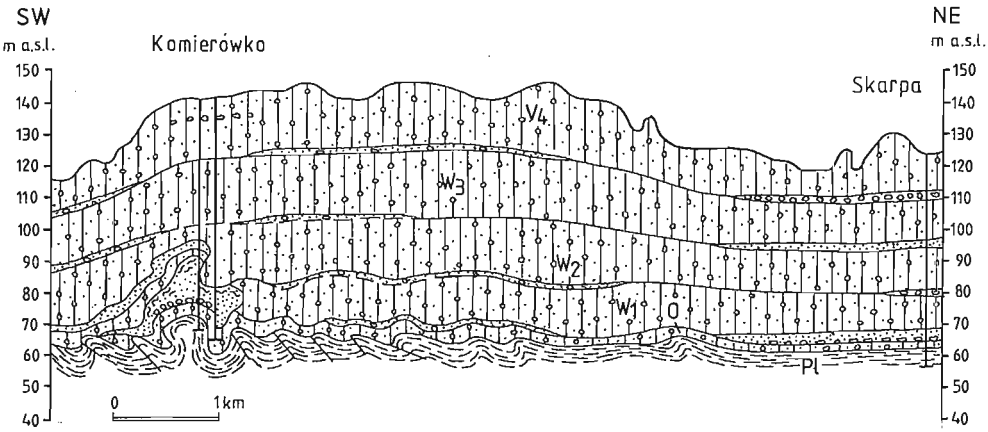

Fig. 4. Więcbork Elevation — geologic cross-section B–B

Explanations as in Fig. 3

however, river deposits in the Jazdrowo profile were accumulated by its tributary. Thickness of river sediments at Suchorączek is significant (38.8 m) and two cycles of river accumulation are observed here — the older with 6.8 m of vari-grained sands (carbonate content of 4%), and further 8 m of fine-grained sands with admixture of medium- and coarse-grained sands and $CaCO_3$ content of 1.1–1.6%. This cycle ends with 1.5 m thick layer of fine-grained sands and 1 m of clay.

Among other factors, good and medium sorting of sediments, small amount of $CaCO_3$ and distinct enrichment of garnet (30%) and rutile (17%) indicate their fluvial origin. According to numerous authors, including E. Mycielska-Dowgiałło (1995) and J. A. Czerwonka and D. Krzyszkowski (1994), distinctly increased amount of garnet is a typical feature of river sediments. A thick series of coarse- and medium-grained sands, with admixture of poorly sorted gravels of carbonate content of 3.7–4.1%, was deposited in the younger cycle. Rounding of quartz grains in the entire series is variable (Wo — 769–1091). It is possible that a top part of these sediments comprises glaciofluvial sands with gravel.

River sediments in the Jazdrowo profile are 20.2 m thick and these sediments were deposited in a cycle, which may be probably referred to the younger cycle at Suchorączek. Coarse- and medium-grained sands occur in the lower part, and fine-grained sands and silts in the upper one. Enrichment in garnets (26.1 %), and additionally distinctly better rounding of quartz grains (Wo — 1026) are observed in these sediments, similarly as at Suchorączek. Sediments, both at Jazdrowo and Suchorączek, were formed by braided rivers. Their stratigraphic position is determined by the fact that at Suchorączek they overlie a lag concentrate from tills of older stadials and underlie tills of the upper stadial of the Wartanian Glaciation. They are thus apparently an equivalent of the Regimin Interstadial, distinguished in Mazowsze (Z. Michalska, 1961; S. Z. Różycki, 1961).

Sediments of a glacial series from the upper stadial of the Wartanian Glaciation are ice-dam lake and glaciofluvial sediments, over 10 m thick, a separate till (W_3) which in exploratory drillings was only 0.5–2.6 m thick, but in other boreholes is even more than 10 m thick, and locally upper glaciofluvial sediments and ice-dam lake deposits.

Till W_3 in the profiles Jazdrowo, Lipka and Suchorączek forms a distinct bed, separated from older and younger tills by ice-dam lake, fluvial and glaciofluvial deposits. They are characterized by petrographic coefficients: O/K — 0.98, K/W — 1.51 and A/B — 0.56. It forms, however, only the lower part at Komierówko (20 m thick and with similar petrographic coefficients: 1.0, 1.32, and 0.59, respectively) of a huge 44 m thick till complex, in which an upper part shows petrographic composition typical for tills of the Vistulian Glaciation. Predominance of crystalline rocks over the Palaeozoic limestones is noted in the lower part of the till, what makes it also different from the till W_2, as well as from the till of the Vistulian Glaciation.

J. A. Czerwonka and D. Krzyszkowski (1994) classify Mutowo till to the upper stadial of the Wartanian Glaciation in the northern and central Wielkopolska, as characterized by completely different petrographic indexes: 1.3–1.6, 0.8–1.1, and 0.9–1.0, respectively, and predominance of the Baltic limestones over the crystalline rocks, thus features similar to the Kopaszewko till from middle stadial of the Wartanian Glaciation. W. Gogołek (1994) states, however, that the Mutowo till (T_7) cannot be considered as the stratotype because it is probably glaciotectonically disturbed and its stratigraphic position is ambiguous.

This dissimilarity of tills from the upper stadial of the Wartanian Glaciation in the central Krajna Lakeland, which is an equivalent of the Mława Stadial distinguished in Mazowsze (Z. Michalska, 1961; S. Z. Różycki, 1961), from Mutowo till classified as of the same stadial, suggests that probably the ice sheet advanced to the Krajna Lakeland but did not reach the central Wielkopolska.

EEMIAN INTERGLACIAL

Up to the present, sediments of the Eemian Interglacial were determined in the northwestern part of the study area at Bługowo only. About 21 m thick ice-dam lake sandy and clayey silts and about 25 m of sandy silts gradually passing into fine-grained sands occur there in a deep subglacial trough. This part of sediments was accumulated in an outflow lake. Age of these sediments is indirectly determined by the fact that they overlie a till from the Wartanian Glaciation and are covered by glaciofluvial deposits and two tills of the Vistulian Glaciation.

A lower part of a palaeosol, developed on glaciofluvial sands from the upper part of stadial of the Wartanian Glaciation, is, however, preserved at Suchorączek. Fragments of plant roots are preserved in this soil, though there is a complete lack of pollen. Probably it was a podsol soil which developed on sands during the Eemian Interglacial.

VISTULIAN GLACIATION

Based on the studies of the Quaternary in Poland completed up to the present time, one may conclude that there are no older tills of the Vistulian Glaciation than these from the last ice sheet advance during the so-called Main Stadial (J. E. Mojski, 1969, 1980), which reached the maximum extent about 20 ka BP. There are no equivalents of tills, distinguished in the Lower Vistula Region by A. Makowska (1976, 1980), i.e. BI, BII, BIII, and defined by L. Marks (1988) in the Warmia Region as W2 and W3, which, according to him, were deposited during glacial episodes during the early (about 100–105 ka BP) and middle (about 55–60 ka BP) Vistulian Glaciation. Hence, the oldest till of the Vistulian Glaciation in the Krajna Lakeland (V_4) is correlated with tills BIV and W4 in regions of the Lower Vistula River, Warmia and Mazury, respectively. Till V_4 from the Main Stadial forms here locally a single bed only, to 20–30 m thick, but in most cases, however, two tills (upper and lower) occur, separated by ice-dam lake or glaciofluvial deposits. The upper till to the north of Więcbork is locally dichotomous. Thickness of the lower till is significant and equal from a few to 20 m. In the borehole profiles (W. Niewiarowski *et al.*, 1996, 1997), the following petrographic coefficients were determined for this till: O/K — 1.49, K/W — 0.92 and A/B — 0.79. Distinct predominance of gravels from the Palaeozoic limestones (36–40.5%) over gravels from crystalline rocks (31–35%) is common in all profiles. Additionally, there is a high content of the Palaeozoic sandstones (12–16%).

The upper till commonly occurs at the surface of a moraine plateau, drumlins, end moraines and eskers (M. Pasierbski, 1966). As described above, the till is locally dichotomous, where both beds are separated by a thin layer of glaciofluvial deposits. An ablation sandy till quite commonly overlies this till. The entire thickness of all tills does not exceed 8 m. Differentiation of petrographic composition of ablation till, in comparison to lodgement till, occurred during melting of a stagnant ice as a result of numerous displacements (flows, slides, creep).

Petrographic coefficients from the upper lodgement till are: O/K — 1.36, K/W — 1.08 and A/B — 0.67, and are similar to coefficients from the lower till. Similarly, predominance of the Palaeozoic limestones (36–38%) occurs in comparison to crystalline rocks (about 35%). Predominance of gravels of the Palaeozoic limestones in tills from the Vistulian Glaciation in the Lower Vistula Region was determined by K. Kenig (1976) and J. Rzechowski (1980). However, petrographic coefficients in the ablation till at Suchorączek are different: 2.68, 0.55, and 1.02, respectively. This fact indicates that ablation tills, departing in their characteristic petrographic coefficients from most tills, may also occur in borehole profiles.

E. Rühle (1954), N. Butrymowicz (1978) and M. Uniejewska *et al.* (1979) correlated the lower till with the Leszno Stadial (currently the phase), and the upper till with the Poznań Stadial (currently the phase).

S. Kozarski (1981, 1991, 1995) assumed that a till of the Leszno and Poznań Phases and a separate till of the Chodzież Subphase occur in the Wielkopolska Region. Such interpretation was also accepted by him for a southern part of the Krajna Lakeland (in the Noteć–Warta ice-marginal valley). These statements were widely accepted. However, based on a petrographic study of tills, J. A. Czerwonka and D. Krzyszkowski (1994) state that the Maliniec till with petrographic coefficients: O/K — 1.0–1.15, K/W — 0.9–1.2, A/B — 0.8–1.1 and more or less balanced content of gravels from crystalline rocks and the Palaeozoic limestones, and the Bytyń till in the north with the following petrographic coefficients: O/K — 1.2–1.35, K/W — 0.8–1.05 and A/B — 0.8–1.1, and the predominant Baltic limestones (45–50%) over crystalline rocks (35–40%) are the stratotypes within the Poznań Phase for tills of the Vistulian Glaciation. The Bytyń and Maliniec tills often occur in the same level, but there are locations where the Bytyń till overlies the Maliniec till and is separated from it by other deposits. According to W. Gogołek (1994), the Bytyń till occurs only locally in a zone 0.5–3 km wide, behind marginal forms of the Poznań Phase and this does not justify acceptance of the Bytyń till as a separate stratigraphic horizon. Hence, he allows a concept that both tills form the same level are locally petrographically differentiated. One should add here that M. Böse (1990) found a petrographic composition of tills of the Brandenburg Stadial and the Frankfurt Phase in the Berlin region to be identical, and during the Frankfurt Phase (equivalent of the Poznań Phase) only a standstill of the ice sheet margin occurred, without any separate advance. M. Górska (1995) says that general direction of ice sheet advance was the same (N–NE) in the central Wielkopolska, during both the Leszno and Poznań Phases. These statements confirm thus a concept of S. Kozarski (1981, 1986, 1991) that a single till was formed in the Wielkopolska during the Leszno and Poznań Phases, and the youngest till in the northern Wielkopolska and the southern Krajna Lakeland formed during the Chodzież Subphase. According to M. Górska (1995), a direction of ice sheet movement was from ENE during this advance and a till was deposited at Ujście on the Noteć River.

Basing on the comparison of composition and petrographic coefficients from tills in the central Krajna Lakeland, they

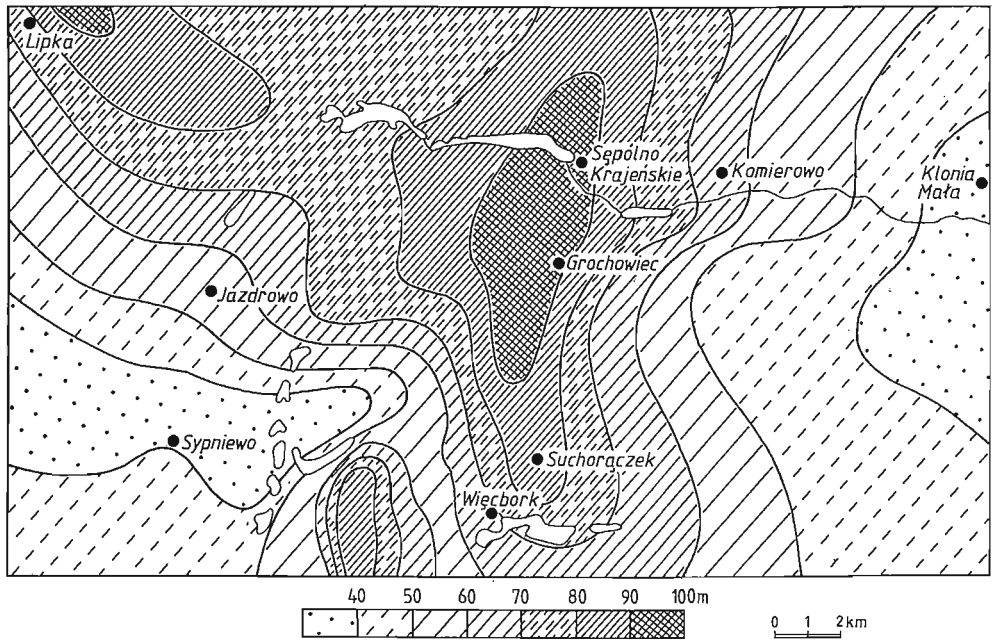

Fig. 5. Thickness of the Quaternary deposits in a central part of the Krajna Lakeland

are more similar to the Bytyń till than to the Maliniec till. The lower till in the Krajna Lakeland seems therefore to represent the Leszno–Poznań Phase, but its deposition occurred mainly in the Poznań Phase. Thereby the upper till is younger and formed during the Chodzież and the Krajna–Wąbrzeźno Subphases.

Petrography of tills in the outcrop Wolsko on the Noteć, which is to the north from the maximum advance of ice sheet during the Chodzież Subphase, was studied by J. Dzierżek and D. Olszewska (1996). They distinguished four sedimentary complexes. The complex I with till layers 3, 4, and 5 referred to the Świecie Stadial from the Middle Vistulian Glaciation. The complex II including tills 6 and 7 formed during the Leszno–Poznań Phase, and the complexes III and IV with tills 8 and 11 formed during the Chodzież Subphase. These tills differ mainly in their grain size distribution. Comparison of petrographic coefficients of tills is difficult, because the authors studied larger clasts, a diameter of which exceeds 10 mm. Nevertheless, only the lowest layer 3, about 2 m thick, has petrographic coefficients different than these of tills of the Vistulian Glaciation. It may be though an ablation till. Petrographic coefficients of the layer 4 (O/K — 1.37, K/W — 0.95 and A/B — 0.55) indicate that except for the coefficient A/B, they are almost identical to these of the Bytyń till, classified to the Poznań Phase (J. A. Czerwonka, D. Krzyszkowski, 1994) or the Leszno–Poznań one (W. Gogołek, 1994). It also demonstrates similarity to the lower till in a central part of the Krajna Lakeland. Similarly upper layers also demonstrate a very big similarity to tills from the Main Stadial, expressed also by the fact, that in clasts there is predominance of the Palaeozoic limestones over crystalline rocks. Thereby the assumption of J. Dzierżek and D. Olszewska (1996) that tills of the lower complex (layers 3 and 4) belong to Świecie Stadial, based on the petrographic studies in the neighbouring areas, cannot be confirmed here.

In addition to tills (lodgement and ablation till), during deglaciation mainly glaciofluvial deposits were formed in outwash trains, commonly of a small thickness (maximum 12 m), in eskers (10 m) and in depositional end moraines. Ice-dam lake deposits are of insignificant importance.

Clayey-sandy slope covers, 1–2 m thick, formed during the Late Glacial in a periglacial environment. Lakes were formed in subglacial channels and kettles where fine-grained sands, silts, lake marl and gyttja were deposited during warm phases of the Bölling and the Alleröd (B. Noryśkiewicz, 1997).

HOLOCENE

Lake deposits (fine-grained sands and silts, lake marl, gyttja and peat) are the main Holocene sediments. The original lake surface, occupying almost 9% of the entire study area, decreased already by about 80% (M. Pasierbski, 1994). Gyttja played the most important role and its thickness in extreme cases reaches even up to 12 m, while peats are to 7 m thick.

The watershed location in this area caused that river deposits have insignificant participation among the Holocene sediments. Small rivers flow in subglacial channels, and the rubble transported by them was deposited in lakes and mires. River sediments mainly occur in gap river fragments, where rivers cut through thresholds of glacial troughs. From the Neolithic, as deforestation progressed and covering of deforested areas with crops, deposits of accelerated anthropogenic denudation on slopes and bottoms of depression, resulted in covers up to 2 m thick. Agricultural character of this area and

a small density of population caused that relatively insignificant were anthropogenic deposits related to development of cities (embankments mainly at Więcbork and Sępólno Krajeńskie), transport development (road and railway embankments), and exploitation of natural resources and water management. Their thickness reaches up to 3–4 m.

BEDROCK INFLUENCE ON TYPES OF QUATERNARY SEDIMENTS

At present the Quaternary bedrock is located at 25–40 m a.s.l. in depressions and 89–100 m a.s.l. on the Więcbork Elevation (Fig. 2). It has been modified at least from the Odranian Glaciation until the Main Stadial of the Vistulian Glaciation. This morphology was affected by uplift movements, mainly associated with salt tectonics and the Quaternary destructive processes (denudation, and glacial, meltwater and fluvial erosion). Relatively elevated location of the sub-Quaternary surface of the Więcbork Elevation and destructive processes there resulted in lack of the Quaternary deposits older than the Odranian Glaciation (Figs. 3 and 4).

Morphology of the Quaternary basement influenced in a significant thickness of the Quaternary deposits (Fig. 5). The morphology is diversified, because the largest thickness of sediments of 80–95 m, occurs in morphologic depressions. However, it ranges from 35 to 60 m on elevated parts. It also affected age and types of the Quaternary deposits. The Krajna Lakeland is classified by J. E. Mojski (1977) to the Kujawy–Pomeranian Region, characterized among others by relatively small thickness of the Quaternary deposits (although locally significantly differentiated), uplift movements (mainly associated with salt tectonics throughout the entire Quaternary), and also presence of numerous stratigraphic discontinuities. This region significantly differs among others from the Lower Vistula Region, Warmia and Mazury, where thickness of the Quaternary deposits reaches up to 250 m and more complete profiles of the Quaternary deposits are present, e.g. deposits from all 8 glaciations and 7 interglacials distinguished in Poland were preserved in the Mrągowo Lakeland (S. Lisicki, 1997).

The most important are deposits from the Wartanian Glaciation which constitutes approximately more than 50% of all sediments, and deposits of the Vistulian Glaciation form about 35%. Interglacial and interstadial deposits form only about 6%. The pre-Quaternary bedrock morphology predetermined that deposits of the Wartanian Glaciation constitute the dominant mass of the Pleistocene sediments, about 60% of the entire thickness, within topographic depressions. On the contrary, exclusively sediments of the Vistulian Glaciation occur in the most elevated part of the Quaternary bedrock.

Deposits of the Wartanian Glaciation contributed to significant smoothing of the bedrock topography and forming major features of the present landscape. A complete levelling of fossil depressions occurred here during the Vistulian Glaciation and, hence, they do not occur in the present topography. In other regions, for example in the central Wielkopolska (J. A. Czerwonka, D. Krzyszkowski, 1994), Warmia (L. Marks, 1988) and the Mragowo Lakeland (S, Lisicki, 1997), significant levelling occurred during the Mazovian Interglacial.

Relatively elevated location of the Quaternary basement deposits and the watershed during the entire Quaternary resulted in a poor development of river sediments, because they are limited to relatively small buried valleys. Two fluvial series of different age occur in the Sępólno Depression, where the lack of the Eemian fluvial sediments means that it was levelled to a significant degree at that time. River deposits have a minimum significance among the Holocene deposits.

Similarly, ice-dam lake deposits are insignificant, and formed as fine-grained sands, silts and rarely clays, associated with ice sheet advances. They have a relatively small thickness, typically 8–10 m, maximum up to 25 m. Hence, they were deposited in front of advancing ice sheets, in small water reservoirs of a local importance. Under these circumstances, this region differs from regions of the Lower Vistula River, Warmia and Mazury, where among others ice-dam lake deposits underlying the sediments of the Mazovian Interglacial are very widely developed, reaching significant thickness and forming a main complex (L. Marks, 1988, 1994; W. Niewiarowski, W. Wysota, 1995; S. Lisicki, 1997).

More important are glaciofluvial deposits, origin of which is associated both with ice sheet advances and retreats. They are represented by sands, sands with admixture of silts and gravels and rarely gravels. Their thickness is varying and range from a few to 20 m. Similarly to ice-dam lake deposits, they occur within topographic depressions as well as at elevations. Glaciofluvial deposits form about 15% of the Pleistocene sediments.

Relatively scarce network of deep boreholes causes that lacustrine-marshy deposits were only exceptionally determined, but one should assume that these sediments were easily eroded at elevations of the basement.

Tills are the main Pleistocene sediments in the central Krajna Lakeland. They form almost 70% of the entire amount of deposits. Till complexes, however, are often the only Pleistocene sediments in many profiles and then they get a substantial thickness. Profiles from Lutowo (where till is up to 70 m of thick), Komierówko (58–60 m), Przepałkowo and Świdwie (56–57 m) and many others are some examples. Large thickness characterizes non-divided till complexes from one or few stadials of the Wartanian Glaciation, reaching a thickness in order of 40–77 m (profiles Lipka, Wersk and Komierówko) or overlapping superimposed tills from the Wartanian and the Vistulian Glaciations (profiles Komierówko and Lutówko), 44–47 m thick.

As far as stratigraphy is considered, the following tills were distinguished: a thin till of the Odranian Glaciation, 1–3 tills of the Wartanian Glaciation and 2, locally 3 tills of the Vistulian Glaciation. The largest thickness was reached by tills of the Wartanian Glaciation, mainly from the older and middle stadials, and the Leszno–Poznań Phase of the last glaciation (Vistulian). The later reach greater thickness than in Wielkopolska.

Ice sheet of the Krajna–Wąbrzeźno Phase of 16.5–17 ka BP (S. Kozarski, 1986) had the greatest influence on types of

sediments during the Late Vistulian Glaciation. The Quaternary basement topography did not have any influence on glaciation and deglaciation processes during the last glaciation, because this topography was smoothed during the Wartanian Glaciation. Distribution of landforms and deposits during the last glaciation was predominantly controlled by dynamics of glacier movement, which depended on climatic conditions, and by topography of the ice sheet forefield, but not of the Quaternary basement.

CONCLUSIONS

The basement topography has significantly influenced types of the Quaternary deposits in a central part of the Krajna Lakeland. Major components of this topography are the Więcbork Elevation, mostly controlled by salt tectonics, and depressions formed by of glacial erosion by older ice sheets, and denudation, fluvial and glaciofluvial erosion. The present time basement topography was subjected to changes until the Main Stadial of the last glaciation (Vistulian).

Elevated position of the basement and destructive processes caused that deposits older than the Odranian Glaciation are not preserved. However, large differences in elevation (about 75 m) caused that thickness of the Pleistocene deposits ranges from 80 to 95 m in topographic depressions and from 35 to 60 m at elevations. Deposits of the Odranian Glaciation, interglacial and interstadial deposits are of insignificant importance among all the Pleistocene sediments. Glacial deposits of the Wartanian Glaciation (about 50% of the entire thickness of all deposits), which formed during three stadials (three separate tills) are the most thoroughly developed and the most important. They contributed to a significant levelling and filling of the basement topographic depressions. Sediments of the Vistulian Glaciation come from the Main Stadial, Leszno–Poznań Phase, and the Chodzież and Krajna–Wąbrzeźno Subphases.

Watershed in the study area and relatively high position of the Quaternary basement caused poor development of fluvial sediments (which are also insignificant among the Holocene sediments) and ice-dam lake deposits. Glaciofluvial sediments form about 15%, though six tills, forming 70% of the Pleistocene deposits, play the most significant role. They where deposited during five glacial episodes of various stratigraphic rank. Their thickness varies and ranges from few to 70 m. The most thick are tills associated with the Wartanian Glaciation and the Leszno–Poznań Phase of the last glaciation.

Petrographic study of tills indicated that there is a close similarity of the tills of two older stadials of the Wartanian Glaciation and the tills of the Vistulian Glaciation, and the tills from the central Wielkopolska Region, which suggests that ice lobes advanced from the same direction in both regions. There is probably no equivalent of the Mława Stadial till of the Wartanian Glaciation in Wielkopolska, when ice sheet advanced the Krajna Lakeland, but probably did not move to the central Wielkopolska Region.

Lacustrine deposits are exceptionally poorly preserved among the Pleistocene sediments. However, lacustrine-marshy deposits (gyttja, peats) play the most important role among the Holocene deposits.

The Quaternary basement topography did not play any significant role during the last glaciation. Variability of forms and deposits of this glaciation is predominantly controlled by dynamics of the ice sheet movement, which depended on climatic conditions, and by topography of ice sheet forefield.

With respect to thickness and structure of the Quaternary sediments, the Krajna Lakeland belongs to the Kujawy–Pomeranian Region, characterized among others, by a reduced thickness of the Quaternary deposits, tendency to uplift movements during the Quaternary, mainly within elevated salt structures and lack of preserved deposits of the older Quaternary. Thus, it significantly differs in this respect from regions of the Lower Vistula River, Warmia and Mazury.

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WPŁYW UKSZTAŁTOWANIA PODŁOŻA NA WYKSZTAŁCENIE OSADÓW CZWARTORZĘDOWYCH W ŚRODKOWEJ CZĘŚCI POJEZIERZA KRAJEŃSKIEGO

Strcszczenie

Na wykształcenie osadów czwartorzędowych w środkowej części Pojezierza Krajeńskiego (fig. 1) bardzo istotny wpływ miała rzeźba podłoża. Głównymi jej elementami są: elewacja więcborska, wznosząca się ponad otaczające tereny, uwarunkowana głównie tektoniką solną oraz obniżenia powstałe na skutek egzaracji w czasie starszych zlodowaceń oraz denudacji i erozji przez wody rzeczne i lodowcowe. Aktualna rzeźba podłoża (fig. 2) podlegała zmianom do stadiału głównego ostatniego zlodowacenia (wisły).

Wysokie położenie podłoża i zachodzące w nim procesy niszczące sprawiły, że nie zachowały się tu osady starsze od zlodowacenia odry. Duże deniwelacje (około 75 m) spowodowały, że miąższość osadów plejstoceńskich waha się od 80 do 95 m w obniżeniach i od 35 do 60 m na elewacji (fig. 5). Wśród osadów plejstoceńskich niewielką rolę odgrywają utwory zlodowacenia odry oraz interglacjalne i interstadialne (fig. 3, 4). Najpełniej są wykształcone i mają największy udział osady glacjalne zlodowacenia warty (około 50% całości osadów), powstałe w czasie trzech stadiałów (trzy odrębne poziomy glin zwałowych). Mają one większą miąższość w obniżeniach niż na elewacji. Przyczyniły się do znacznego wyrównania i zasypania obniżeń podłoża. Osady zlodowacenia wisły (stanowiące około 35%) pochodzą z fazy leszczyńsko-poznańskiej oraz z subfaz chodzieskiej i krajeńsko-wąbrzeskiej stadiału głównego.

Usytuowanie obszaru na wododziale oraz stosunkowo wysokie położenie podłoża czwartorzędu spowodowały słabe wykształcenie osadów rzecznych (które też odgrywają nikłą rolę wśród osadów holoceńskich) i zastoiskowych. Osady fluwioglacjalne stanowią około 15%, zaś 6 poziomów glin zwałowych — 70% osadów plejstoceńskich. Zostały one osadzone w czasie pięciu epizodów glacjalnych różnej rangi stratygraficznej. Miąższość ich jest zmienna i waha się od kilku do 70 m. Największą miąższość mają gliny zwałowe zlodowaccnia warty oraz fazy leszczyńsko-poznańskiej ostatniego zlodowacenia.

Badania petrograficzne wykazały, że istnieje bliskie pokrewieństwo glin dwu starszych stadiałów zlodowacenia warty i zlodowacenia wisły z glinami środkowej Wielkopolski, co świadczy, że w obu regionach prądy lodowe nasuwały się z tych samych kierunków. W środkowej Wielkopolsce nie ma prawdopodobnie odpowiednika gliny zwalowej stadiału mławy zlodowacenia warty, w czasie którego lądolód wkroczył na Pojezierze Krajeńskie, ale prawdopodobnie nie dotarł na teren środkowej Wielkopolski.

Wśród osadów plejstoceńskich wyjątkowo słabo zachowały się osady jeziorne. W obrębie osadów holoceńskich największą rolę odgrywają tu osady jeziorno-bagienne (gytia, torfy).

Rzeźba podłoża nie odgrywała już istotnej roli w czasie ostatniego zlodowacenia, a zróżnicowanie form i osadów tego zlodowacenia jest uwarunkowane dynamiką ruchu lądolodu oraz rzeźbą jego przedpola.

Pojezierze Krajeńskie pod względem miąższości i struktury osadów czwartorzędowych należy do regionu kujawsko-pomorskiego, cechującego się m.in. niewielką miąższością osadów czwartorzędowych, tendencją do ruchów wznoszących w czwartorzędzie, głównie w obrębie występujących tu struktur solnych, i nie zachowaniem się osadów starszego czwartorzędu. Różni się więc on istotnie pod tym względem m.in. od regionu dolnej Wisły, Warmii i Mazur.