Pleistocene glacial limits in the territory of Poland

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A b s t r a c t . The limits of four major ice sheets can be traced in the present landscape of Poland. Glacial deposits and ice-dammed lakes indicate a stream-like pattern of advancing ice bodies, dependent both on ice dynamics in the marginal zones and on the pre-existing landscape in their forefields. The southernmost extent of the Pleistocene ice sheets is indicated by the Scandinavian erratics and was formed by the South Polish Glaciations (Elsterian), partly replaced in the west by the Odranian of the Middle Polish Glaciations (Saalian I). The subsequent Wartanian Glaciation of the Middle Polish Glaciations (Saalian II) and the Vistulian Glaciation (North Polish Glaciation, Weichselian) were limited to areas further to the north.

Key words: *Pleistocene, glaciation limits, palaeo-ice streams Poland*

Systematic cartographic works, already carried through for many years in Poland, supplied with abundant geological information that has been only partly used for geological maps, firstly the *Geological Map of Poland in scale 1 : 200,000* and the *Detailed Geological Map of Poland in scale 1 : 50,000.* So far there is no synthetic cartographic presentation that, basing on detailed mapping, would indicate extents of glaciations, i.e. of main stratigraphic-palaeogeographic units of Poland, strictly correlated with the corresponding units in neighbouring countries. Previous conclusions of different authors dealt commonly with fragments of the area only and many a time contradicted one another. Cross-border correlation of limits of the Pleistocene glaciations is a key problem in studies of the Quaternary in central Europe. Varied methodological approach and research tradition in individual areas as well as limited access to complete bibliography result in local stratigraphic schemes that do not take into account the achievements in adjacent areas.

Landscape of the Polish territory during the Pleistocene favoured advances of Scandinavian ice sheets. It has been open to ice sheets that moved southwards along the depressions of the river valleys. Mapping of glacial deposits in Poland indicated a stream-like pattern of the advancing ice bodies, especially during the Last Glacial Maximum (Fig. 1; cf. Różycki & Lamparski, 1967; Petelski, 1985; Marks, 2001a, b, 2002a–c, 2003, 2004a, b; Pettersson, 2002; Wysota, 2002). Shape and limits of palaeo-ice streams depended both on ice sheet dynamics in marginal zones and landscape in glacial forefields. Most advancing lobes indicated a setting of outlet and/or surge type glaciers which were favourable areas for development of glaciotectonic phenomena. Among the others, basing on geological and geomorphologic data from the cross-border area of Poland and Belarus, an interlobal zone of Vistula and Neman lobes during Wartanian Glaciation was distinguished, connected with glaciotectonically deformed elevation of the Quaternary bedrock (Marks & Pavlovskaya, 2001a, b, 2004).

It seems now obvious that individual maximum limits were not synchronous throughout the whole territory, both for younger ice sheets and also presumably for the older ones (cf. Kozarski, 1986; Marks, 1988, 1991a, b, 2000, 2002a–c, 2003; Wysota, 2002).

Limits of four main and well correlated ice sheets can be traced in the present landscape of Poland (Fig. 2; Różycki,

Fig. 1. Ice sheet lobes and palaeo-ice streams in the southern peribaltic region during the Last Glacial Maximum; compiled data from Houmark-Nielsen (1987), Lagerlund (1987), Ringberg (1988), Raukas & Karukäpp (1994), Dreimanis & Zelčs (1995) and Ber (2000); after Marks (2002a), modified. Dating of palaeo-ice stream limits is based on non-calibrated radiocarbon data; palaeo-ice streams: B — Baltic, L — Lithuania, M — Mazury, O — Oder, V — Vistula

1965; Rühle, 1965), however due to different stratigraphic subdivisions of the Pleistocene in Poland there are several local discrepancies (Żarski, 1990, 1994; Dolecki et al., 1994; Lindner & Marks, 1994, 1995a, b; Marks et al., 1995; Pożaryski et al., 1995). Maximum extents of Pleistocene glaciations are indicated by the southern limit of Scandinavian erratics. The southernmost glacial limit is attributed to the South Polish Glaciations (Elsterian) and is much less controversial in eastern Poland than in the western part of the country (Lindner & Marks, 1995b; Wójcik, 1999). In SW Poland it was overridden by the Odranian ice sheet of the Middle Polish Glaciations (Saalian I). In this area, limits of the South Polish and the Middle Polish Glaciations are very close together and overlap at many localities (Macoun & Králik, 1995; Badura & Przybylski, 1998). Further to the north there are limits of the Wartanian of the Middle Polish Glaciations (Saalian II), and of the Vistulian Glaciation (North Polish Glaciation, Weichselian).

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Methods and scope of research

This paper is based on archival and published cartographic data, collected for the *Detailed Geological Map of Poland in scale 1:50,000* and the *Geological Map of Poland in scale 1:200,000*. These data were supplemented with information from other publications on extents of Pleistocene glaciations in Poland.

Despite varied stratigraphic subdivisions of the Pleistocene of Poland, they only slightly influence the setting of four main ice sheet limits (Fig. 2; Różycki, 1965, 1972; Rühle, 1965). Certainly it does not exclude numerous local discrepancies on individual limits and also their connection with suitable glaciation (among others Wołk-Musiał, 1980; Żarski, 1990, 1994; Dolecki et al., 1994; Lindner & Marks, 1994, 1995a, b, 1999; Marks et al., 1995; Pożaryski et al., 1995).

Middle Pleistocene Glaciations

Ice sheet of the Sanian 2 (Sanian 1 according to Lindner, 2001; Wójcik et al., 2004) occupied most of the Polish territory and its southernmost limit represents commonly the widest extent of the Pleistocene glaciation (Fig. 2). The ice sheet reached the Carpathians and the Sudetes, entered the Moravian Gate in the Upper Odra River Valley (cf. Lewandowski, 1987; Lindner & Marks, 1994; Macoun & Králik, 1995). Ice sheet margin was dissected into numerous lobes that advanced in the mountain valleys open to the north. In the area occupied by the ice sheet there were presumably ice-free areas, particularly in the Polish Jura (Różycki & Lamparski, 1967), the highest fragments of the Holy Cross Mts and in the foreland of the Sudetes. In the Tatra and Karkonosze Mountains, valley glaciers developed (cf. Lindner & Marks, 1995b).

During its maximum extent the ice sheet of Middle Polish Glaciations reached northern slopes of the Lublin Upland (cf. Lindner & Marks, 1999). Advancing ice sheet of the Odranian Glaciation dammed waters of the Vistula, Pilica and Wieprz rivers, and large ice-marginal lakes

Fig. 2. Limits of the main Pleistocene glaciations in Poland: S — Sanian 2 (or Sanian 1), O — Odranian, W — Wartanian, Vistulian: L — Leszno Phase, Pz — Poznań Phase, Pm — Pomeranian Phase; after Marks (2004a), modified

developed in their valleys (e.g. near Koniecpol and Sandomierz). Ice sheet reached northern slopes of the Sudetes, Polish Jura, Holy Cross Mts and the Lublin Upland. It entered the Moravian Gate, through which its outwash waters flowed to the Danube (Macoun & Králik, 1995). In eastern Poland the meltwaters flowed eastwards along the sub-Carpathian ice-marginal spillway. In the Tatra and Karkonosze Mountains numerous valley glaciers developed (Lindner & Marks, 1995b).

The Warta Stadial as a separate stratigraphic unit of the Pleistocene was distinguished by Woldstedt (1927) on the basis of geomorphological criteria. He delimited ice sheet extent of this stadial along end moraines in the vicinity of Kalisz, Łódź and Grójec. Then, ice sheet limit of the Warta Stadial in Poland was presented on maps in different scales by Halicki (1950), Różycki (1952), Rühle and Sokołowska (1956) as well as Galon and Roszkówna (1961). Marginal zone of the Warta Stadial in Poland was found to predominate in landscape, and it distinctly widened to the east (Klatkowa, 1993, 1995). The Upper Warta drainage basin is a key region, with particularly distinct ice-marginal zone where geological criteria could be applied, firstly a relation of the Eemian and Holsteinian sediments to glacial tills. Since the 1970s, the Warta Stadial has been more and more frequently named the Wartanian Glaciation, in spite of a lack of convincing evidence for stratigraphic individuality of the preceding Odranian Glaciation.

Ice sheet of the Wartanian Glaciation advanced further to the south in western Poland (Fig. 3). It occupied Wielkopolska, Mazowsze and Podlasie (Baraniecka, 1971; Krupiński & Marks, 1993). In the Polish-German border zone the ice sheet of the Wartanian Glaciation reached the Muskauer, Lusatian and Fläming Hills. In the Lower Silesia its limit is indicated by the Silesian Rampart and accompanying sandur, and in the Wieluń Upland by end moraines of Prosna, Warta and Widawka glacial lobes. In the Łódź Upland the advancing ice sheet disintegrated into two lobes, Widawka and Rawka, a result of the rising forefield that acted as a distinct obstacle. The ice sheet reached Tomaszów Mazowiecki, Inowłódz, Stanisławów, the Lower Pilica and Wieprz valleys. In eastern Poland the maximum ice sheet limit is considerably controversial (Nitychoruk, 1994; cf. Krupiński & Marks, 1993). Most Polish authors speak for ice sheet limit of the Wartanian Glaciation from Garwolin through Stoczek Łukowski, Łosice to Siemiatycze (Baraniecka, 1971), from Łosice through Terespol to Janów Podlaski (Falkowski et al., 1984–1985; Lindner, 1988) or still more to the south, along the Krzna River valley (Nowak, 1973; Baraniecka et al., 1984). Ice sheet limit in this territory is composed of the lobes Wilga, Liwiec, Muchawka, Toczna and Klukówka.

Lobal margin of the maximum ice sheet limit of the Wartanian Glaciation in Poland suggests varied dynamics of the ice body (significantly influenced by gradual continentalisation eastwards) and its metachroneity at short distances. In comparison with a distinct marginal zone in the key area of southern Wielkopolska, end moraines in Podlasie are considerably less distinct, although local glaciotectonic deformations are of similar size as in western Poland. In the Tatra and Karkonosze Mountains valley glaciers developed (cf. Lindner & Marks, 1995b).

In western Poland, the Wartanian meltwaters flowed along the ice-marginal spillway in the Sudeten Foreland towards the Elbe drainage basin. In central Poland they used the Lower Pilica–Wieprz spillway, passing through

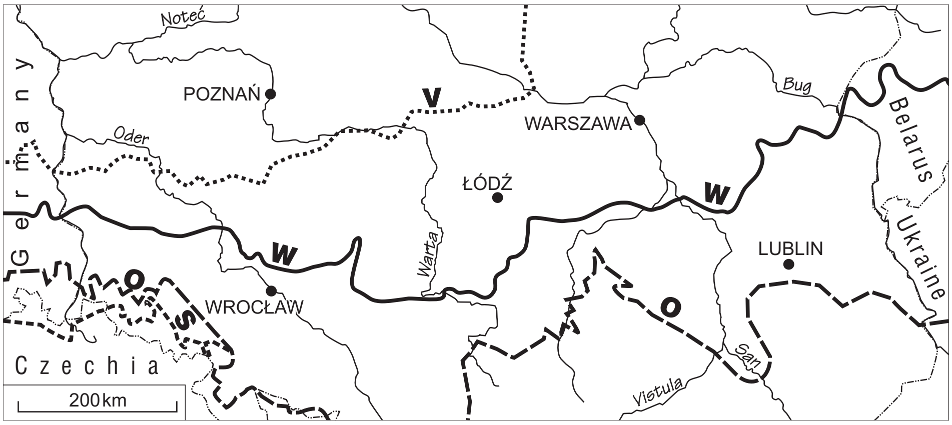

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Fig. 3. Ice sheet limit of the Warta Glaciation in Poland and adjacent areas of Germany and Belarus on the basis of papers of Żarski (1993), Haisig & Wilanowski (1998), Rdzany (2000, 2004), Badura & Przybylski (1998), Marks & Pavlovskaya (2001a, b). Ice sheet limits of: E — Elsterian, O — Odranian, W — Wartanian, V — Vistulian; after Marks (2004b), modified

the Krzna drainage basin towards the Pripyat valley in Belarusian Polesye (cf. Mojski, 1993).

Revised stratigraphy and palaeogeography of the Wartanian Glaciation suggests possible more southern extent, e.g. in the Głubczyce Plateau, Holy Cross Mountains and Podlasie Lowland. What was regarded until recently as the Odranian limit, may in fact be the limit of the Wartanian ice sheet (cf. Marks et al., 1995; Lindner & Marks, 1999; Fig. 3). In this case, the Odranian Glaciation ice sheet would have occupied a considerably smaller area and would have been subordinate to the Wartanian Glaciation. In the same time ice sheet maximum limit of the Wartanian Glaciation was presumably metachronous, estimated at 130–160 ka. However, confrontation with oxygen isotope ratio curve from deep-sea sediments suggests the maximum extent at about 180 ka (Paepe et al., 1996).

Recently, Lindner (2005) came back to the Wartanian as the subordinate to Odranian but both limited to oxygen isotope stage 6 and without any separating interglacial-rank interval.

Late Pleistocene Glaciation

The youngest Scandinavian glaciation in Poland was distinguished by Lencewicz (1927) as a "great oscillation" in the Płock Basin, central Poland. Existence of this youngest Polish glaciation was supported by Lewiński et al. (1927) and Woldstedt (1931), and this glacial episode was at first referred to as the Baltic Glaciation (Halicki, 1946) or the North-Polish Glaciation (Halicki, 1950). Later the term Vistulian (Różycki, 1961) or Wisła Glaciation (Marks, 1988) became more common — in accordance with the term Weichselian (after the German name of the Vistula River) that had been introduced by Keilhack (1899).

"Fresh" landscape created a distinguishing factor for this glaciation. Maximum limit of this ice sheet in Poland has not been indicated in detail before Majdanowski (1947) who connected it with the southern extent of glacial channel lakes. Such approach has been commonly accepted and since then, insignificant corrections have been introduced only.

Ice sheet limit of the last glaciation was also determined on the basis of geomorphological criteria, including end moraines and outwash plains (Nechay, 1927; Kondracki, 1952; Galon & Roszkówna, 1961, 1967; Roszko, 1968; Michalska, 1975; cf. Marks, 1984, 1997a, b). Ice sheet extent and lobe-like pattern of its margin depended much on distribution of landforms that the ice sheet could or could not override. Geological criteria were also used: among them mapping of the area occupied by tills of the last glaciation played a significant role (Marks, 1984, 1997a, b; Stankowska & Stankowski, 1988; Gałązka et al., 1999; Morawski, 1998, 1999) and the occurrence of till-covered Eemian organic sediments was established (Stankowska & Stankowski, 1988; Morawski, 1999). Tills in marginal zones of the former ice sheets occur in patches, due to small activity of a thin, marginal part of an ice sheet and intense meltwater erosion. Locally, ice sheet extent during the Last Glacial Maximum was determined on the basis of palynologic analyses of Eemian and interstadial organic sediments (Mojski, 1984), the youngest ones of which were radiocarbon dated to 22 ka (Stankowska & Stankowski, 1988).

Suggestions for a further southward extent of the last glaciation, based on the ideas of Halicki (1950) and others, have appeared from time to time. A major revision of the stratigraphic subdivision of the Vistulian, not only for Poland, but for the entire Central Europe, was stimulated by Makowska (1976). She found that marine Eemian Interglacial sediments in the Lower Vistula region occur several dozen metres deeper than previously assumed, and pass southwards into a fluvial sequence (Makowska, 1979). These Eemian sediments are overlain by till, ascribed to three stadials, being referred by her to (from the earliest) as the Toruń Stadial (BI-II), Świecie Stadial (BIII) and Main Stadial (BIV-V). The last of these stadials represents the Last Glacial Maximum. The ice sheet during the earliest stadial was postulated to have reached as far south as Toruń; however the evidence is completely insufficient. The extent of the second, the Świecie Stadial has not been delimited in detail. Its possible occurrence in western Poland has been largely neglected, because no tills of pre-Late Vistulian age have been found there (Kozarski, 1986). The Vistulian stadials were separated by distinct and long-lasting intervals of ice retreat (Makowska, 1986), at least locally represented by interstadial fluvial sediments (Wysota et al., 1996; Marks, 1998; Wysota, 1999). The occurrence of the latter indicates a considerably different river network and base level of erosion in Poland during the Vistulian.

However, revision of ice sheet maximum limit of the last glaciation is still probable (cf. Mojski, 1985; Marks, 1988, 1991b, 1998, 2000; Niewiarowski et al., 1995; Lisicki, 1997, 1998; Gałązka et al., 1998a, b, 1999; Kenig, 1998; Krzywicki, 2002). Basing on recent results of investigation in a marginal zone of the last glaciation, the age of end moraines of the so-called Mława Stadial of the decline of the Wartanian Glaciation should be verified once again (cf. Michalska, 1961, 1967) as well as end moraine of the Chodzież Sub-phase, distinguished by Kozarski (1986; cf. Dzierżek, 1996) in the Middle Noteć River region. Middle and Late Vistulian glacial advances have their equivalents

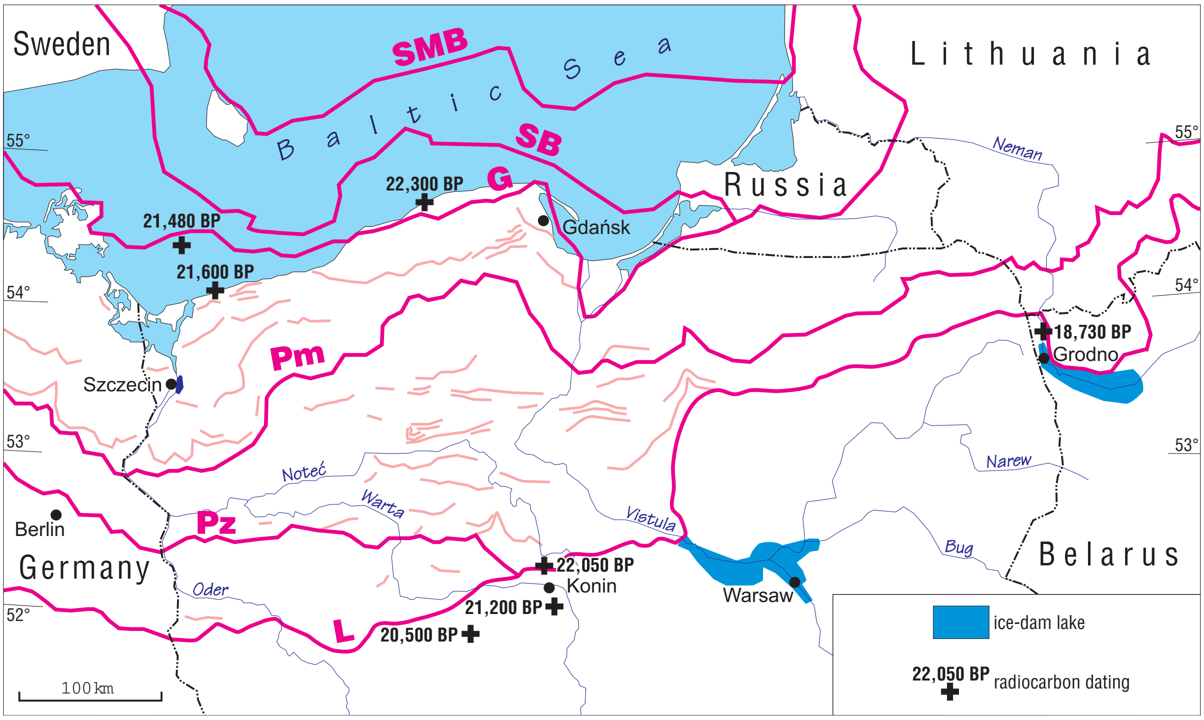

Fig. 4. Limits of the major glacial phases during the Late Vistulian in Poland and neighbouring areas, compiled from different authors; presented are selected non-calibrated radiocarbon dates after Stankowska & Stankowski (1988), Gogołek & Mańkowska 1989), Zimenkov (1989), Rotnicki & Borówka (1990, 1995), Kramarska (1998), Dobracki & Zachowicz (1999) and Uścinowicz (1999); after Marks (2000b), modified. Ice sheet limits: L — Leszno (Brandenburg) Phase, Pz — Poznań (Frankfurt) Phase, Pm — Pomeranian Phase, G — Gardno Phase, SB — Słupsk Bank Phase, SMB — Southern Middle Bank Phase; indicated are also limits of minor local glacial oscillations and proglacial lakes in the Middle Vistula and Middle Neman valleys

in Scandinavia and presumably also in Germany (Lindner and Marks, 1995a; Marks et al., 1995). Absence of these sediments in north-eastern Poland (Ber, 1988, 2000) and in Lithuania (Satkunas, 1997) demands further investigation. In spite of occasional opinions on ice sheet advance during the last glaciation onto the Białystok Plateau (among others Fedorowicz et al., 1995; Banaszuk, 1998), there is no convincing evidence for such episode.

The Last Glacial Maximum is represented by Leszno, Poznań and Pomeranian phases (Fig. 4). Generally, the maximum limit is thought to represent the Leszno (Brandenburg) Phase in western Poland. In central and eastern Poland younger lobes of the Poznań (Frankfurt) Phase have been occasionally found to be the most extensive (Woldstedt, 1931; Mojski, 1968, 1984). An exceptional view was presented by Rühle (1965) who found a tripartite (in age) maximum extent of the ice sheet during the last glaciation in Poland, being represented by increasingly younger glacial advances towards the east, i.e. in turn by Leszno, Poznań and Pomeranian Phases. However, lack of convincing evidence and typological uniformity of end moraines throughout the whole area contradict this last postulate, and the Late Vistulian ice sheet limit in central Poland was ascribed to the Leszno and Poznań Phases (Różycki, 1961, 1965; Wysota, 2002).

Since the discovery of an organic sequence between tills at Olecko in the Mazury Lakeland (Hess von Wichdorff, 1916), the last glaciation has been believed to include two major glacial advances, separated by a warming phase, named the Mazury Interstadial. The key site for this interstadial was re-investigated in the 1950s, but the earlier conclusions of Hess von Wichdorff (1916) could not be confirmed (Halicki, 1960).

The ice sheet occupied southern Wielkopolska, Pomerania, Kujawy and Mazury. It blocked the pre-existing drainage system and caused the development of vast ice-dammed lakes in the Warsaw Basin. A system of ice-marginal streamways, namely Warsaw–Berlin and Warsaw–Toruń–Eberswalde collected all the proglacial and extraglacial waters from the Neman in the east to the Elbe in the west. Valley and cirque glaciers developed in the Tatra and Karkonosze Mountains (cf. Lindner & Marks, 1995a, b).

Conclusions

The maximum limit of Pleistocene glaciation in Poland is indicated by erratics derived from Scandinavia and the Baltic Sea Basin. This limit corresponds mostly to the Sanian 2 (or Sanian 1 according to Lindner, 2005) Glaciation (Elsterian) but locally in the Sudetes also to the Odranian Glaciation (Saalian).

The limit of the Wartanian Glaciation is indicated by prominent ice-pushed end moraines in western Poland, and by smaller and depositional end moraines in eastern Poland. The Wartanian ice sheet limit seems to have been located further to the south than commonly accepted.

The limit of the Vistulian (Weichselian) Glaciation and of its retreat phases is accentuated by ice-marginal streamways running towards the west.

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