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Łódź

# PERMAFROST EVOLUTION AND ITS IMPACT ON DEPOSITION CONDITIONS BETWEEN 20 AND 10 ka BP IN POLAND

Abstract

The evolution of Pleistocene permafrost in Poland between ca 20,000 – 10,000 years BP, i.e. from the maximum cold of the Vistulian to the end of the Vistulian is presented. The mountainous regions are excluded. The role of permafrost and of permafrost evolution in the transformation and formation of the sedimentary environment is described. Analyses of the stages of the development of ice-wedge casts are the basis for the reconstruction of the growth, existence and degradation of former permafrost.

Permafrost that had formed in the Middle Plenivistulian existed continuously throughout the Upper Plenivistulian until the Pomeranian stage in the whole non-glaciated portion of Poland. In the glaciated part, the ice-sheet encroached on the ground with permafrost. Under the thick ice-sheet permafrost degraded.

After the maximum ice-sheet advance (the Leszno phase) rapid regeneration of continuous permafrost took place in the area freed from the ice-sheet, and dead ice blocks were incorporated into ground ice. This process lasted by the Pomeranian phase. There are a few signs of permafrost existence in the area free from ice-sheet after the Pomeranian phase since permafrost was probably discontinuous or even sporadic there.

The existence of the Upper Plenivistulian permafrost had an influence on the processes taking place in various sedimentary environments, in particular in fluvial and slope environments.

At the end of the Upper Plenivistulian the thickness of the active layer increased significantly, and large areas with taliks may have appeared. This can be viewed as the preliminary phase of permafrost degradation. Widespread degradation of permafrost began in the Late Vistulian. This was temporary stopped or even regeneration of permafrost occurred in places.

The degradation of permafrost was first accompanied by a change from braided channel patterns to meandering ones. Later, as a result of thermokarst process closed depressions formed, and lacustrine or boggy accumulation started there. The ice-ground melt and depression formation in the glaciated area were totally different from the processes in the extraglacial area. In the latter, thermokarst processes were confined to the places where permafrost grow synchronously with the accumulation of ice-rich sediments, this is to river valleys mainly. In the area glaciated in the Vistulian, where blocks of glacier ice were buried, the development of closed depressions was much more intense and common.

## INTRODUCTION

The growth, existence and degradation of permafrost has an influence on the development of sedimentary structures and processes in periglacial environment. The changes of sediment characteristics relating to permafrost and resulting from its degradation are fundamental sources of information for studies upon former permafrost. These have been broadly de-

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scribed in the literature, including for example, monographs by DYLIK (1966), JAHN (1975), FRENCH (1976), and WASHBURN (1979).

The influence of permafrost upon the specific sedimentation environment in the periglacial zone, and the recognition of such environments based on features of sediment that accumulated syngenetically with permafrost aggradation are problematic. Difficulties arise because sedimentation processes depend on several factors and it is not easy to separate the impact of permafrost, even if it is significant. To date, only a few sedimentary features or palaeoforms indicative of permafrost have been identified.

This paper discusses the evolution of Pleistocene permafrost in Poland, between ca 20,000–10,000 years BP. The mountainous regions are excluded. This period represents the transition from the maximum cold of the Vistulian to the end of the Vistulian. The role of permafrost and of permafrost evolution in the formation and transformation of the sedimentary environment is described.

## FORMER PERMAFROST INDICATORS

Phenomena that require permafrost for their occurrence are particularly significant for the reconstruction of permafrost history. These include ice wedges, pingos, and sometimes, composite wedges are mentioned as well (DYLIK, 1966; MACKAY, 1973; JAHN, 1975, FRENCH, 1976; WASHBURN, 1979). The structures resulting from their melt are regarded as evidence of former permafrost (DYLIK, 1966; GOŹDZIK, 1973; ROMANOWSKIJ, 1977; VANDERBERGHE 1983; HARRY, GOŹDZIK 1988).

Unlike pingos, ice wedges are very frequent in areas of continuous permafrost. Moreover, the structural features of ice-wedge casts enable their origin to be identified rather easily. Ice-wedge casts with graben-like faulting, formed when ice wedge thaw, are the most often. Special attention should be given to specific structures that develop in unconsolidated, but not plastic materials, such as compressed peat or clay. These deserve particularly to be called ice-wedge pseudomorphs as the shape of the primary ice wedge has been preserved with almost no change (Fig. 1, Pl. 1, 2). This issue will be elaborated in detail in a forthcoming paper (GOŹDZIK and FRENCH, in preparation).

With respect to pingos, the form and structure of depressions surrounded by ramparts have been used to infer the previous melt of an ice core of a mound. It does not however, specify whether a palsa or pingo existed in the past (WASHBURN, 1979). This is especially significant since palsas commonly occur in areas of discontinuous and even sporadic permafrost.

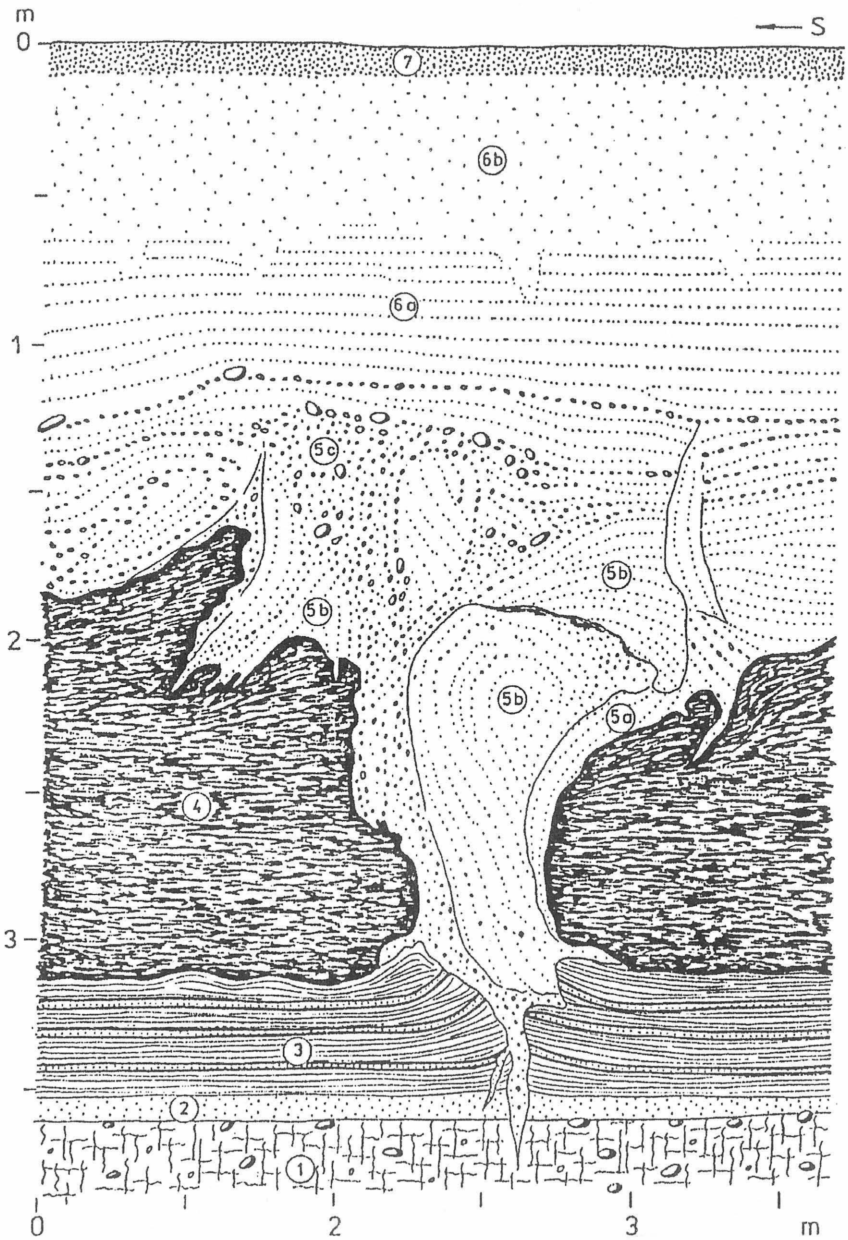
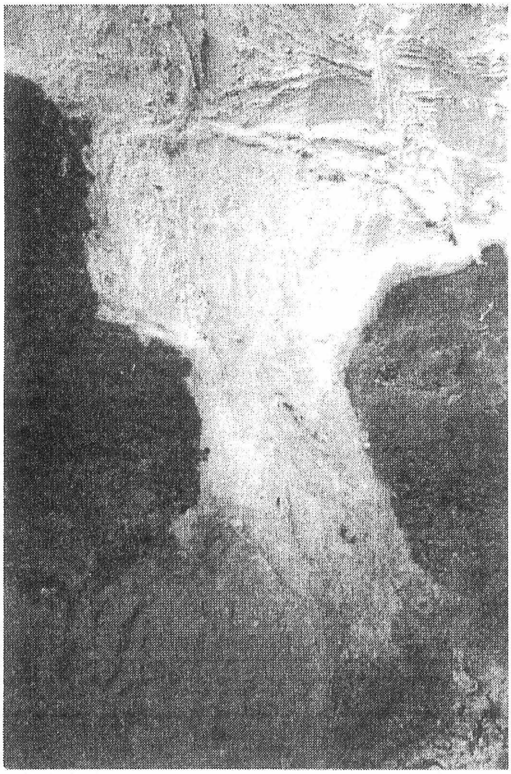
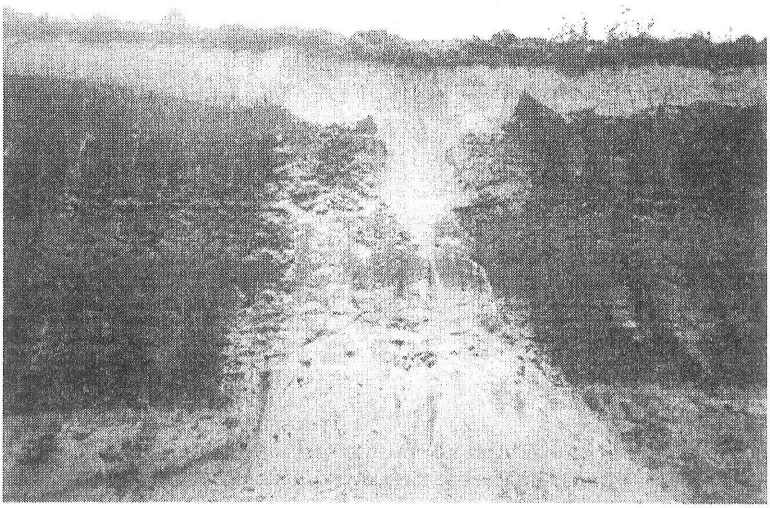



Fig. 1. Bełchatów open-cast mine (Central Poland). Ice-wedge cast with rather well preserved primary shape of ice-wedge. The cast is developed almost totally in unconsolidated, but not plastic material: till, rhythmically stratified clay and peat with bituminous schist

Key: Saalian deposits: 1. till; 2. sand; 3. clay with fine sand; Eemian and Early Vistulian deposits: 4. peat with bituminous schist; Upper Plenivistulian deposits: 5. sand; 5a. medium and fine sand; 5b. medium sand; 5c. coarse sand with gravel; Late Vistulian deposits: 6. medium sand; 6a. stratified sand; 6b. structurless sand; 7. sand with humus



Pl. 1. Bełchatów open-cast mine. A middle part of the ice–wedge cast shown on Fig. 1.



Pl. 2. An ice-wedge cast near the cast shown on Fig. 1 and Pl. 1 with well preserved primary shape of former ice wedge. The ice wedge cast is developed in peat and bituminous schist. The wedge is ca. 3 m long

Ice wedges with primary sandy infill and associated involutions do not necessarily require permafrost for their formation, although permafrost certainly facilitates their development. These phenomena serve only as supporting evidence of former permafrost. Regarding involutions, it has been suggested that flat-bottomed forms (GULLENTOPS, PAULISSEN, 1978) and equally spaced, more regular forms of larger amplitude (1–2 m), were developed in an active layer over permafrost (VANDERBERGHE, VAN DEN BROEK, 1982, VANDERBERGHE, 1983). Since so many deformation structures are not related to the perglacial environment (BUTRYM, *et al.*, 1964, and others), caution must be used when regarding the above mentioned involutions as incontrovertible evidence of permafrost existence.

Recently, micro-scale analyses of sediment structures, so called "cryogenic fabrics" (VAN VLIET LANOË, 1976, 1989), or "cryogenic microfabrics" (HUIJZER, 1993), "crogenetic structures" (MURTON, FRENCH, 1994), have been looked on as prospective indicators of former permafrost. The small number of analyses of this kind for Vistulian sediments in Poland make them unsuitable for the reconstruction of permafrost.

For these reasons, ice-wedge casts are usually used as a fundamental indicator of former permafrost occurrence.

## PERMAFROST IN POLAND DURING THE UPPER PLENIVISTULIAN

The period from 20 to 10 ka BP in Poland can be divided into two principal periods with the boundary around 14,5 ka BP. The older belongs to the Plenivistulian (i.e. the upper part), whereas the lower part belongs to the Late Vistulian[1]. The paucity of organic sediment is a characteristic feature of the first period and results in a small number of $^{14}C$ datations for that time (GOŻDZIK, PAZDUR, 1987). TL dating is not helpful because its standard deviation accounts for 15%; this margin of error exceeds the length of the period under consideration and makes the setting of a more precise chronology of the Upper Plenivistulian difficult. It also means that the absolute age of the Upper Plenivistulian boundaries is determined on the basis of organic material from the neighbouring lithostratigraphic units, namely from the top of Middle Plenivistulian sediments and from the bottom of Late Vistulian sediments.

Sediments older than 20,000 years (i.e. before the maximum cold of the Vistulian) usually yield dates around 22,000 years BP (STANKOWSKA,

[1] It should be noted here that opinions on the begining of the Late Vistulian are not unanimous. For example, an older date (Pomeranian phase) is accepted by VAN VLIET-LANOË (1989) and KOZARSKI (1992), and a younger date of ca 13 ka BP by VANDERBERGHE and PISSART (1993).

STANKOWSKI, 1979; PAZDUR, *et al.*, 1981; BARANIECKA, 1987; MANIKOWSKA, 1994; TURKOWSKA, 1990). These belong to the end of the Middle Plenivistulian. Loess and sandy valley deposits were the most often types of sediment which accumulated during the Upper Plenivistulian. Ice-wedge casts are commonly encountered in both of them.

In river valleys in central Poland a distinct change of sediment has been observed at the boundary of the Middle and Upper Plenivistulian. It has been attributed to the alternation of the sedimentation conditions. During the Middle Plenivistulian mainly sandy-silty deposits accumulated, and sandy material prevailed in the Upper Plenivistulian (GOŹDZIK, 1980, TURKOWSKA, 1990). The accumulation of sandy deposits began to cease around 14,500 years BP. Ice wedge casts are often found in the deposits of both periods (GOŹDZIK 1973, 1980; KUYDOWICZ-TURKOWSKA, 1975; FRENCH, GOŹDZIK, 1988; TURKOWSKA, 1988), but during the Upper Plenivistulian, in addition to ice-wedges, wedges with primary sandy infilling and composite wedges developed. The large frequency of syngenetic ice-wedge casts in Middle and Upper Plenivistulian deposits, together with numerous layers of epigenetic structures related to pauses in accumulation of the deposits prove that permafrost existed during the period of sediment accumulation, and that its top moved upwards together with the accumulation.

Some admixtures of organic material found recently in the Upper Plenivistulian deposits by TURKOWSKA (1992) gave dates of 16,200 ± 200 and 17,100 ± 200 years BP. There are, however, no datings for sediments from the final phase of the Upper Plenivistulian, particularly for the sediments in which ice-wedge casts have subsequently developed. Therefore, it remains problematic when melt of the permafrost began, and when melt of ice wedges, if found, started.

Observations of ice wedge casts indicate that deformation of sediments adjoining the wedges, which are often associated with meltout of the main generation of Upper Vistulian epigenetic wedges, usually include synchronous or older sediments. Gravelly-pebble layers lying at the top of the contraction cracks separate the deposits of the Upper Plenivistulian and Late Vistulian. These layers frequently form a boundary between material deformed and non-deformed when the ice wedges melted. Only a few cases of Late Vistulian deformations due to ice-wedge melting are known (for example, ice wedge GOŹDZIK, 1973, Fig. 4, p. 21). It can be assumed therefore that ice wedges started melting before the Late Vistulian. Unfortunately, the lack of organic material within the top of the Upper Plenivistulian sediments prevents $^{14}C$ dating to be carried out. It should be stressed that melting of ice wedges, especially of their upper parts, did not denote a widespread degradation of permafrost, because this process begun later. This will be discussed elsewhere. Nevertheless, the thickness of the active layer increased, and large areas with taliks may have appeared.

The deposition processes and the evolution of permafrost were more complex in southern and northern Poland, as compared to the part of central Poland that remained ice-sheet-free throughout the Vistulian.

In Southern Poland, in Upper Silesia, north of the area covered with loess, the sediment sequence in river valleys (sandy-silty series of the Middle Plenivistulian and sandy ones of the Upper Plenivistulian), and ice-wedge casts (JERSAK, SENDOBRY, 1991) are analogous to the ones observed in central Poland. Some differences are found in river valley sediments in the zone where intensive loess deposition took place. In the Wieprz valley the lower part of Vistulian alluvium resembles the Middle Plenivistulian sediments found in central Poland and comprises sandy-silty material (HARASIMUK, SZWAJGER, 1984). As demonstrated by JERSAK (1991), the accumulation of the sandy-silty series lasted here longer, as the top of these, the so-called "Dryas silt", gave radiocarbon dates of 19,320 ± 320 and 18,400 ± 320 years BP. Above, fine sands rest. Here also syngenetic and epigenetic ice wedges formed within the whole series of Plenivistulian age deposits.

As mentioned before, loess accumulated quickly in the Upper Plenivistulian besides sediments in river valleys. The accumulation of loess in the Uplands of central-south Poland took place not only in river valleys and on the slopes, but, more important, on the interfluves. Syngenetic ice wedges developed in all the loess deposits (MARUSZCZAK, 1987; JERSAK, *et al.*, 1992). A Plenivistulian age for ice-wedge casts in the loess had been recognised earlier (DYLIK, DYLIKOWA, 1960; JAHN, 1969; JERSAK 1969, 1975; MOJSKI, 1969; MARUSZCZAK, 1972), but JAHN (1970), MARUSZCZAK (1987) and JERSAK *et al* (1992) pinpointed the maximum occurrence of ice-wedge development during the Upper Plenivistulian. Additionally, MARUSZCZAK argued that ice-wedge melting in the loess begun around 14–15 ka BP (MARUSZCZAK, 1991).

Obviously, ice wedges of Plenivistulian age in the part of Poland which was not glaciated in the Vistulian developed not only in river valley sediments and in loess. The ice wedges formed also in other deposits, for example, in till, glaciofluvial and glaciolacustrine sediments, both on slopes and on interfluves. In the deposits there developed, however, almost exclusively epigenetic forms (DYLIK, 1951, 1967; DYLIKOWA, 1956; LASKOWSKA, 1960; KLATKOWA, 1965; GOŹDZIK, 1973; MANIKOWSKA, 1985; WIECZORKOWSKA, 1975; and others). Only in a few places can their Upper Plenivistulian age be precisely demonstrated.

A very large frequency of ice wedge casts of Plenivistulian age in various sediments and in varying topographic situations in central and southern Poland provide convincing evidence of continuous permafrost in the whole area (Fig. 2A). This conclusion agrees with the results of other studies on permafrost extent in Europe, as the southern boundary of permafrost during the period of the Vistulian maximum cold has been delineated over 300 km south of Poland (Poser, 1948; Velichko, 1982; Van Vliet Lanoë, 1989).

The evolution of permafrost was more complex in the area that was covered with the Vistulian ice-sheet. The study at Maliniec, at the margin of the Vistulian ice-sheet, shows that around 22,000 years BP boggy, organic sediments accumulated under tundra conditions (Stankowska, Stankowski, 1979; Pazdur, *et al.*, 1981). The organic sediments are covered with periglacial fluvial sands that are analogous to ones found further to the south, outside the Vistulian ice-sheet extent (Goździk, 1981; Stankowski, Krzyszkowski, 1991). At Maliniec, the sands are overlain by till that accumulated during the maximum advance of the ice-sheet, this is during the Leszno stage. The alluvial deposits lack ice-wedge casts that could prove the existence of permafrost. Involutions found here are not sufficient evidence. However, tundra conditions are implied by the organic material accumulation. In addition, there is a similarity between the textural, mineralogical and certain structural features of alluvium under till with the synchronous alluvium from the extraglacial zone, where evidence of permafrost has been found. All these considerations allow one to assume that permafrost was also present in the area covered later by the ice-sheet.

It is proposed that permafrost degrades under a sufficiently thick ice-sheet (Büdel, 1959; Bockheim, 1995), but so far any more precise relations between ice-sheet thickness and the degree of permafrost degradation in areas of contemporary glaciation have not been established. This fact hinders the reconstruction of Pleistocene permafrost in areas where ice-sheet encroachment did not ultimately terminate permafrost existence, but only interrupted a cycle of permafrost growth.

From the results of Dylik (1956), Kozarski (1971, 1974, 1993), Nowaczyk (1972), the author (Goździk 1986) and other studies, the conclusion can be drawn that numerous thermal contraction cracks (among these ice-wedge casts) appeared in the area freed from the ice-sheet. These resulting ice-wedge casts are often observed only within the zone between the maximum ice extent and the Pomeranian phase ice-sheet boundary (Kozarski, 1971, 1974, 1993; Goździk 1986). They are sporadic in the area covered by the Pomeranian ice-sheet (Goździk, 1986). Analyses of ice wedges in long ditches situated in various parts of the first zone did not reveal discernible differences in the frequency of wedges (Goździk, 1986). It can be assumed that the conditions of wedge formation did not change significantly from the maximum advance of ice-sheet to the Pomeranian phase.

Syngenetic ice wedges found in many places in glaciofluvial sands indicate that permafrost instantaneously aggraded into freshly accumulated sediment (Kozarski, 1971, 1974, 1993). This could have been possible due to partial survival of permafrost in the ground. Independently of syngenetic structures, epigenetic wedges developed in many places in tills and fluvioglacial deposits. The frequency of the wedges, including ice-wedge casts, and the size of polygons created by them in the area under consideration are approximately two times smaller than those in the zone south of the Vistulian glaciation limit (GOŹDZIK, 1986). In any case, the frequency is large enough to suggest the existence of continuous permafrost when the wedges developed (Fig. 2B; GOŹDZIK, 1994). The rapid invasion of permafrost led to the incorporation of dead ice fragments into ground ice, which stopped their degradation. It is assumed therefore that the following massive icy bodies existed then: 1) syngenetic and epigenetic ice wedges and 2) buried glacier ice. Analogous with areas that were glaciated in the Vistulian, and still remain in a periglacial zone (for example: northern Canada and parts of northern Siberia), it can be suggested that the range of ice types was wider and segregated ice and fluvial (or fluvioglacial) ice occurred too (MACKAY, 1973; KONISHCHEV, TUMEL, 1989; SHPOLYANSKAYA, 1989; POPOW, TUMEL, 1989; FRENCH, HARRY, 1990). The distinction between the traces of former buried glacier ice and massive segregated ice is impossible to make.

The amount of thermal contraction cracks in the area covered by the Pomeranian ice-sheet is very small and the existence of continuous permafrost cannot be inferred from this evidence (GOŹDZIK, 1986). Only discontinuous or even sporadic permafrost may have developed here (Fig. 2C).

Accepting that the Pomeranian phase occurred 15,2 ka BP (KOZARSKI, 1986, 1993), it can be assumed that the climatic amelioration in Poland was significant then, and conditions for more continuous permafrost formation in the area freed from the ice-sheet were unfavourable. As the latest datations show, the ice-sheet left Poland completely, or almost completely, around 14,5 ka BP (ROTNICKI, BORÓWKA, 1995; MOJSKI in this volume). However, in the south, where ground ice had developed earlier, permafrost was preserved, although, as mentioned earlier, the thickness of the active layer increased and the preliminary phase of permafrost degradation began (Fig. 2C).

## THE IMPACT OF PERMAFROST OCCURENCE ON SEDIMENTARY ENVIROMENTS IN THE UPPER PLENIVISTULIAN

The occurrence of continuous permafrost during the Upper Plenivistulian throughout almost all of Poland, except for the area covered by the ice-sheet, influenced sedimentary environments. This impact was varied.

The existence of permafrost had particular importance to river flow regimes. The low permeability of permafrost significantly limited water retention and led to high variability of seasonal runoff, with snowmelt

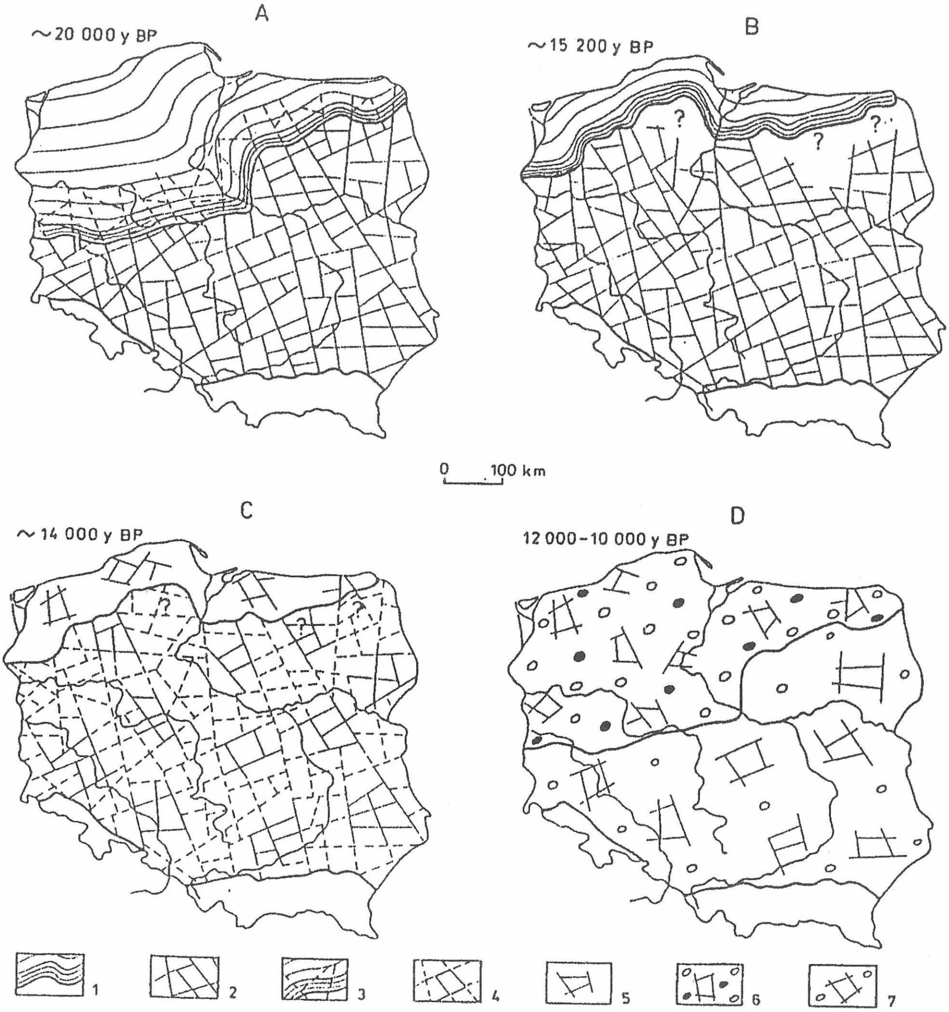



Fig. 2. Stages of change of permafrost extent and character in Poland (without mountainous regions) between 20,000–10,000 years BP

1. ice-sheet; 2. continuos permafrost; 3. ice sheet covering perhaps partly degraded permafrost; 4. permafrost with thick active layer and possible taliks; 5. discontinuous or sporadic permafrost; 6. discontinuous or sporadic permafrost with thermokarst depressions and in places with buried massive ground ice; 7. discontinuous or sporadic permafrost with thermokarst depressions

floods so intense that "between 25 and 75 per cent of total runoff was concentrated in a few days" (French, 1976, p. 167). This was a very important agent conducive to the formation of braided river channel patterns in Poland, which are commonly supposed to have functioned at that time (Rotnicki, 1991, Kozarski, 1991; Jersak, 1992; Turkowska, 1992; Goździk in print). It should be emphasized that even though permafrost favours braided rivers (French, 1976) it does not exclude meandering and anastomosing river channels in places (VAN HUISSTEDEN, 1990). In central Poland other factors such as sparse vegetation cover, increased supply of slope material (JERSAK, 1991), and intense aeolian supply controlled the development of braided rivers (GOŹDZIK, 1980, and in print; ROTNICKI 1984).

The contact of river water with slopes affected by permafrost triggered thermal erosion, which in turn led to lateral erosion and the development of steeper slopes (WALKER, MORGAN, 1964; WALKER, ARNBORG, 1966; DYLIK, 1971; CHURCH, 1974). In Poland this process was important not only in river valleys, but also in pradolinas (JAHN, 1975). JERSAK (1991) has argued that slope degradation was very rapid and thereby large amounts of material were supplied to rivers. Thermokarst processes led to slumping of blocks of frozen material, of which an example was given by DYLIK (1969).

The presence of permafrost also affected other slope processes. A decrease in infiltration of rain and snowmelt water increased overland flow and intensified slopewash processes. A higher rate of slopewash has been demonstrated by many authors (DYLIK, 1969, 1972; KLATKOWA, 1981; TURKOWSKA, WIECZORKOWSKA, 1986). DYLIK (1971) has stressed that slopewash confined to the polygon furrows developed on very steep slopes in the areas with ice-wedge polygon network. Undoubtedly, permafrost contributed also to the intensity of solifluction, both as regards congelifluction (DYLIK, 1969; TURKOWSKA, WIECZORKOWSKA, 1986) and frost creep (GOŹDZIK, 1967; DYLIK, 1969). The signs of intense slope processes influenced by permafrost were also found in the area freed from the ice sheet before the Pomeranian phase (CHURSKA, 1969).

## THE LATE-VISTULIAN EVOLUTION OF PERMAFROST, THE DEVELOPMNENT OF THERMOKARST AND BOGGY AND LACUSTRINE DEPOSITION

As mentioned before, there is no evidence of well pronounced permafrost development during the period from the end of the Pomeranian stage to the end of the Upper Plenivistulian. Likewise, thermokarst phenomena were not widespread in Poland then. The earliest signs of changes of environments of sedimentation, which can be related to the beginning of permafrost degradation, are found in river valleys. A distinct change from braided channel patterns to meandering ones (KOZARSKI, ROTNICKI, 1977) commenced around 14,5 ka BP (GOŹDZIK, 1980; MANIKOWSKA, 1985; FLOREK, *et al.*, 1987). JERSAK has proposed that the transformation of river channel patterns resulted from an increase in permafrost degradation below river channels (JERSAK, 1991, p.80).

Later, the degradation of permafrost spread into smaller river valley and was not limited to the axis zone of the larger valleys. As a result of ice melt- out within permafrost contained in the Plenivistulian silty-sandy

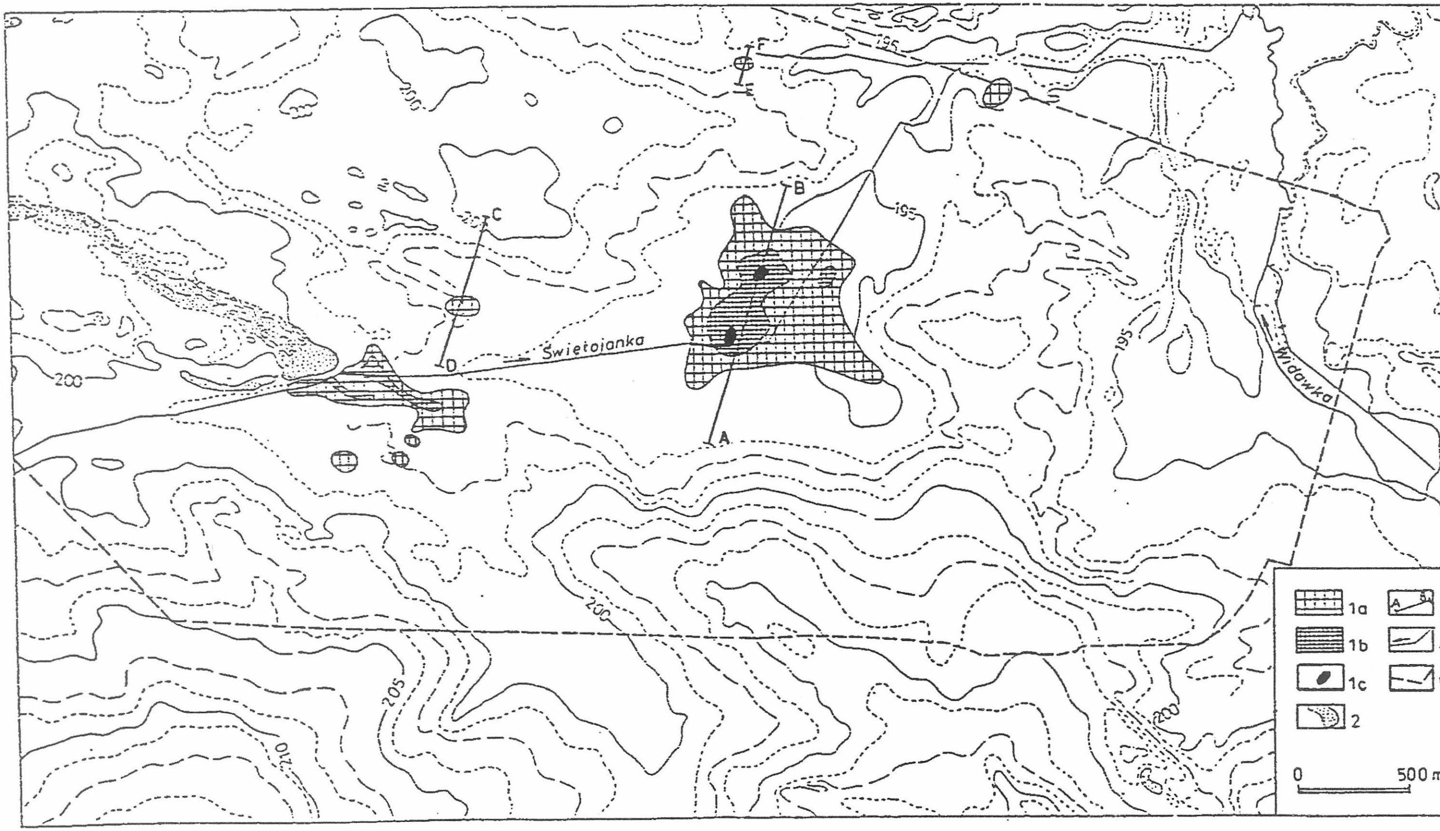



Fig. 3. A map of closed depressions infilled by lacustrine calcareous deposits and peat found in the Bełchatów open-cast mine (Central Poland)
1. thickness of calcareous deposits: 1a. 0–1 m; 1b. 1–2 m; 1c. >3m; 2. dune; 3. cross-sections; 4. creek and ditch; 5. open-cast border; A–B – cross-section shown on Fig. 4; C–D – cross--section shown on Fig. 5; E–F – cross-section shown on Pl. 3

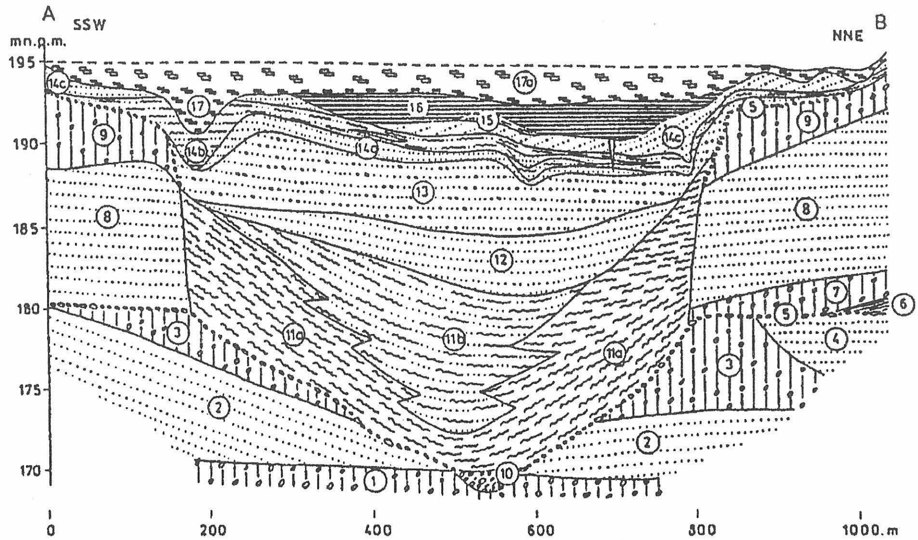



Fig. 4. Cross section A–B through the closed depression shown in Fig. 3, of the thermokarst origin

Key: Saalian deposits: 1. till; 2. medium sand, 3. till; 4. coarse and medium sand; 5. pavement; 6. varved clay; 7. till; 8. medium and fine sand with silt; 9. till; Vistulian deposits: 10. pavement; 11a. silt; 11b, silt with sand; 12. medium sand; 13. sand with admixture of gravel; 14a. medium sand; 14b. silt and sand; 14c. medium sand; 15. peat; 16. calcareous deposits; Holocene deposits: 17. peat

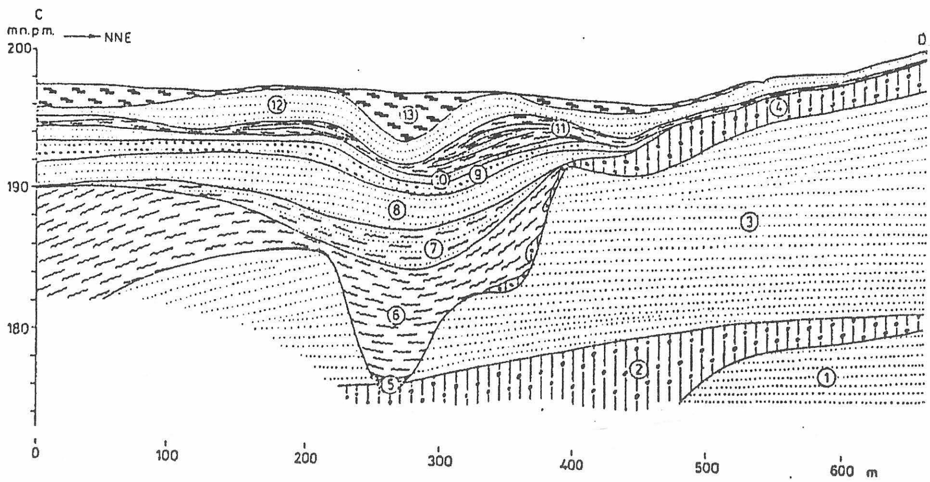
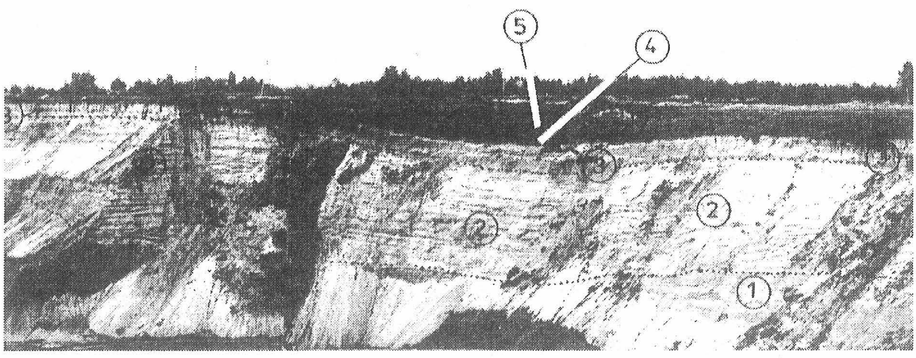



Fig. 5. Cross section C–D through the closed depression shown in Fig. 3 of the thermokarst origin, modified by aeolian processes

Key: Saalian deposits: 1. medium sand; 2. till; 3. medium and fine sand with silt; 4. till; Vistulian deposits: 5. gravel and pebbles; 6. silt; 7. silt and sand; 8. medium sand; 9. sand with gravel; 10. medium sand; 11. silt and sand; 12. medium sand; Late Vistulian and Holocene deposits: 13. peat sediments, closed depressions formed due to uneven subsidence in the places where large amounts of ice were concentrated (GOŹDZIK, KONECKA-BETLEY, 1992). The dates obtained from the bottom of organic sediments found in the depressions show that their development began in the Bølling, around 13–12,5 ka BP (GOŹDZIK, KONECKA-BETLEY, 1992; WOJTANOWICZ, 1994; BALWIERZ, GOŹDZIK in print). Some depressions (Fig. 3) were filled with lacustrine carbonate deposits underlain and overlain by peat (Fig. 4) and others with peat (Fig. 5, Pl. 3). The larger supply of carbonates could have been caused by permafrost degradation and an increase of the zone of till and fluvioglacial sand decalcification (GOŹDZIK, KONECKA-BETLEY, 1992).

Thermokarst activity in the river valleys in central and eastern Poland started approximately simultaneously with dead ice downwasting in the area glaciated during the Vistulian. It was the phase of shallow depressions which preceded initial lake formation (RALSKA-JASIEWICZOWA, STARKEL, 1988). The synchronization on the processes did not occur only in central Poland. Also in places in northern Poland the formation of initial lake depressions began around 13–12,5 ka BP (NOWACZYK, 1994). NOWACZYK pointed out that the beginning of ground ice degradation in the glaciated area was not simultaneous, and dead ice blocks started melting in the Oldest Dryas, in Bølling, Allerød, Younger Dryas, pre-Boreal, and even in Boreal. He did not, however, find any regional order of the start of buried ice melt. More important, he explained that "the reason for the different starting times of the melt-out of dead ice blocks was the differences in the thickness of morainic and/or fluvioglacial deposits overlying them" (NOWACZYK, 1994, p. 110). It could have also depended on the diversity of overlying material and the presence of permafrost in it. This needs further investigation.




Pl. 3. A small closed depression of thermokarst origin Key: Upper Plenivistulian fluvial deposits: 1. silt and sand; 2. sand; the Late Vistulian deposits: 3. aeolian cover sand; 4. calcareous deposits; the Holocene deposits: 5. peat (exploited)

It should be emphasised that widespread degradation of permafrost in the Latervistulian stopped during periods of climate deterioration. Temporary local regeneration of permafrost can be inferred from some wedges which were synchronous with sediments, and containing both primary and secondary infillings (GOŹDZIK, 1973, 1986; KOZARSKI, *et al.*, 1982; KOZARSKI, 1993). Some fissures and sparse ice-wedges developed after ca 12 ka BP. Since organic material over the wedge – within the top of the Late Vistulian sediments has not been found, the end of ice-wedge development cannot be dated precisely. By analogy to the conditions established for north-west Europe, where mainly in the first part of the Younger Dryas, ending at 10,550 years BP, sporadic to discontinuous permafrost was identified (VANDERBERGHE and PISSART 1993), it can be assumed that in Poland ice-wedges may have existed until the first part of the Younger Dryas, ending at 10,550 years BP. During the Late Vistulian the zone of continuous permafrost moved futher north, to Scandinavia (SVENSSON 1988).

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