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The development of periglacial sedimentation in the Wolica Valley (SE Poland) during the Weichselian Upper Pleniglacial

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Abstract: The development of the Weichselian Upper Pleniglacial periglacial sedimentation in the Wolica Valley was evaluated by means of geomorphological, geological and sedimentological investigation. Sediments of the medium (II) raised terrace, the surface area of which is a dominant element of the valley, were examined. The terrace has a complex structure comprising deposits of different age, lithology and origin. The basal part of the terrace is formed from terrace remnants from the Middle Pleniglacial and the phase before maximum cold of the Upper Pleniglacial. The base consists of sandy channel deposits and silty-sandy floodplain deposits. The upper part of the terrace is a thick series of deposits from the phase after maximum cold. It is built from slope, floodplain and channel deposits, as well as alluvial fans. The complexity of the structure results from the specific character of periglacial processes and their rhythmical course, as well as from the influence of local conditions. The deposits of the basal part of the terrace were shaped in a subpolar climate with maritime features, whereas the sediments of its upper part formed in continental subpolar climate. Local factors, such as: lithology of rocks in the river drainage basin, a dense network of valleys in the basin and alluvial fans, determined the suspension type of transport, the shape of the river channel and retention of a large amount of sediment in the Wolica drainage basin and on its valley-floor.

Key words: periglacial sedimentation, the Lublin Upland, terrace deposits, Weichselian Upper Pleniglacial

Introduction

The Weichselian Upper Pleniglacial was a period of abundant periglacial sedimentation, not only in the river valleys of the uplands of Southern and Middle Poland and in the Carpathian Foreland (Buraczyński, 1980/1981; Gębica, 1995; Gębica & Starkel, 1987; Harasimiuk, 1991; Jahn, 1956b; Jersak, 1976, 1991; Jersak & Sendobry, 1991; Jersak *et al.*, 1992; Manikowska, 1996; Starkel, 1988, 1994, 1995, 1997; Superson, 1979, 1995, 1996a; Turkowska, 1988, 1990), but also in many other river valleys in the periglacial zone of Eurasia and North America (*cf.* Vandenberghe, 1985, 1993; Liedtke, 1993; Törnqvist, 1998, Blum *et al.*, 2000; Straffin *et al.*, 2000). However, the sedimentation process varied depending on allogenic factors (climatic conditions, sea-level oscillations and broad-scale neotectonic movements), as much as on autogenic variables (both regional and local). Most researchers emphasise the significance of the impact climatic conditions exert on the thickness and lithology of fluvial deposits, yet only a few studies take into account the conditions inside a drainage basin, such as: natural obstacles in valleys, the lithology of slope and hilltop deposits, the size of the river catchment basin and the slope angle, or tectonic movements on a fault line (*see* Blum & Törnqvist, 2000).

A similar emphasis on climatic conditions is noticeable in publications on periglacial fluvial deposits in the valleys of the Lublin Upland and the Roztocze region (the eastern part of the uplands of southern Poland). The development of periglacial sedimentation in those valleys aroused the interest of researchers as early as in 1950s. Investigations into the problem were initiated by the eminent expert on the contemporary periglacial zone and fossil periglacial structures, after A. Jahn (1952, 1956a, 1956b, 1975). Later studies were largely based on the material compiled during the construction of individual sheets of the Large-Scale Geological Map of Poland 1 : 50 000 (Mojski, 1961, 1968; Harasimiuk & Henkiel, 1980, 1982; Harasimiuk & Szwajgier, 1984; Harasimiuk *et al.*, 1988a, 1988b; Buraczyński & Superson, 1996). Lublin Institute of Earth Sciences began systematic studies of periglacial valley sediments early in the 1970s and has continued the work up to the present. This has resulted in numerous publications, mainly concerned with river valleys in the Wieprz drainage basin (Harasimiuk, 1991; Superson, 1977, 1979, 1987/1988, 1995, 1996a, 1996b; Superson & Warowna, 1996), in the Tanew basin (Buraczyński, 1980/1981) and in the Bug basin (Szwajgier, 1998; Superson & Szwajgier, 1999). Only a few of these publications deal with the problem of autogenic factors' influence on valley sedimentation. Harasimiuk (1991) interpreted the floodplain deposits of the medium (I) Weichselian terrace in the Krasnystaw Gap of the Wieprz River as an effect of "upstream aggradation" produced by alluvial fans of side tributaries and by limited movement of the meander belt on the narrow valley-floor. J. Superson (1996a) attempted to synthesise the deposition and erosion history of the valleys of the upland Wieprz basin during the Weichselian. In this study, the influence of climatic, regional and local conditions on sedimentation and erosion processes in valleys of various rank was analysed. The valleys selected were characterised by different catchment sizes, various deposits overlaying the basins and different cutting of catchment surface. However, due to scarce geological and geomorphological data, relatively little attention was paid to the valleys of the Wieprz tributaries with their loessic catchments.

Given the above, the present study was aimed at evaluating the effect of allogenic and autogenic factors on periglacial valley sedimentation in a small catchment basin covered by loess and cut by a dense network of dry valleys. The Wolica catchment was selected for the study since it fulfilled all the stated conditions.

Following a detailed geomorphological description of the Wolica catchment in recent years, the aim of the study has now been achieved; this supplied a great many data relating to the development of the valleys in the Pleistocene (Zagórski, 1998; Gawrysiak *et al.*, 1998; Superson & Zagórski, 2000). Sediment samples collected in representative profiles were processed, and grain-size distribution was analysed and its parameters were calculated using Folk and Ward's method (1957). Sedimentation structures and the determinations of grain-size distribution provided a basis for the demarcation of lithostratigraphic complexes and for interpreting sedimentation environments and their energy (Visher, 1969; Racinowski & Szczypek, 1985; Superson, 1996a). The stratigraphy of analysed sediments was established considering geological and geomorphological positions and TL analyses of ages. It was based on stratigraphic division of last glaciation used in elaborations of the West European scientists (*cf.* Vandenberghe, 1985; Liedtke, 1993). When constructing the diagrams, modern methods of spatial visualisation were applied using ArcInfo and ArcView programs. Studies were supported by funds for statutory investigations of the Department of Geomorphology of University Maria Curie-Skłodowska in Lublin and by Grant No 6PO4E 03318 from KBN.

Characteristics of the Wolica Valley floor and its drainage basin

The Wolica Valley cuts through the southern part of the Grabowiec Heights which form the eastern stretch of a parallel belt of high plains of the Lublin Upland (Fig. 1A). The valley can be divided into four sections (the uppermost, the upper, the middle and the lower courses); these differ in respect of course direction and in the number and development of Weichselian raised terraces and Quaternary deposits (Fig. 2).

The main relief features of the Wolica catchment are conditioned by the directions of dip and strike of beds and faulting, and by the lithological properties of the bedrock (Jahn, 1956b; Maruszczak, 1972; Harasimiuk *et al.*, 1988a). The influence of bedrock tectonics and lithology is particularly noticeable in the middle course of the drainage basin, where wide, dry erosive-denudational valleys occur, characterised by asymmetric sides, which form structural edges. The Sub-Quaternary foundation (marls, marly limestones and chalkstone, gaizes) crops out on the surface only in the northern and western parts of the lower stretch of the catchment (Harasimiuk *et al.*, 1988a). Surfaces of denudational planations are

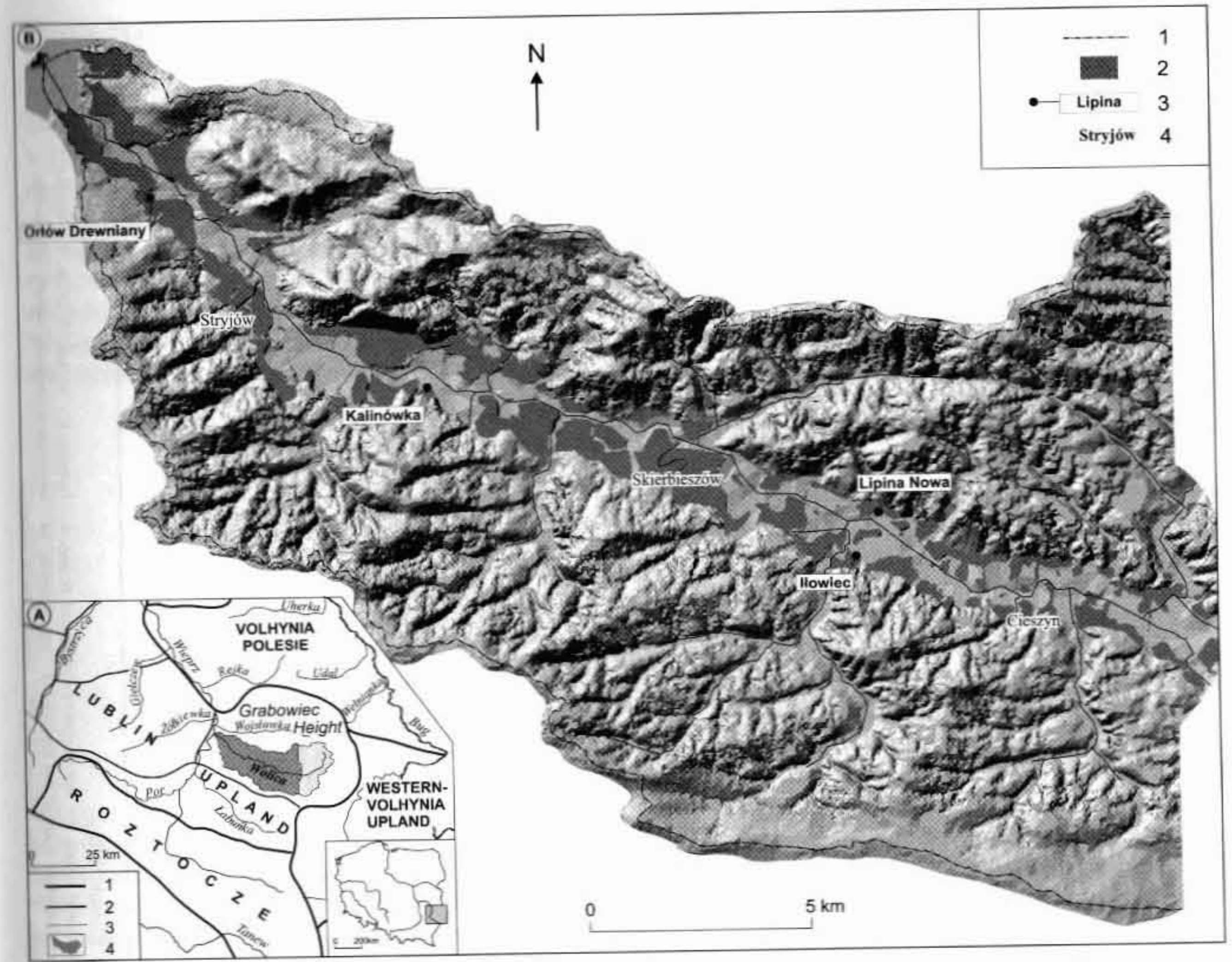

Fig. 1. Localization of study area and digital model of relief of the middle and lower course of the Wolica Valley
A: Geomorphologic regions (after Maruszczak, 1974): 1 – boundary of the regions, 2 – boundary of the subregions, 3 – state boundary, 4 – drainage basin of the Wolica River, **B**: 1– drainage basin boundary, 2 – terrace 14–16 m, 3 – localization of study profiles, 4 – location of towns quoted in article

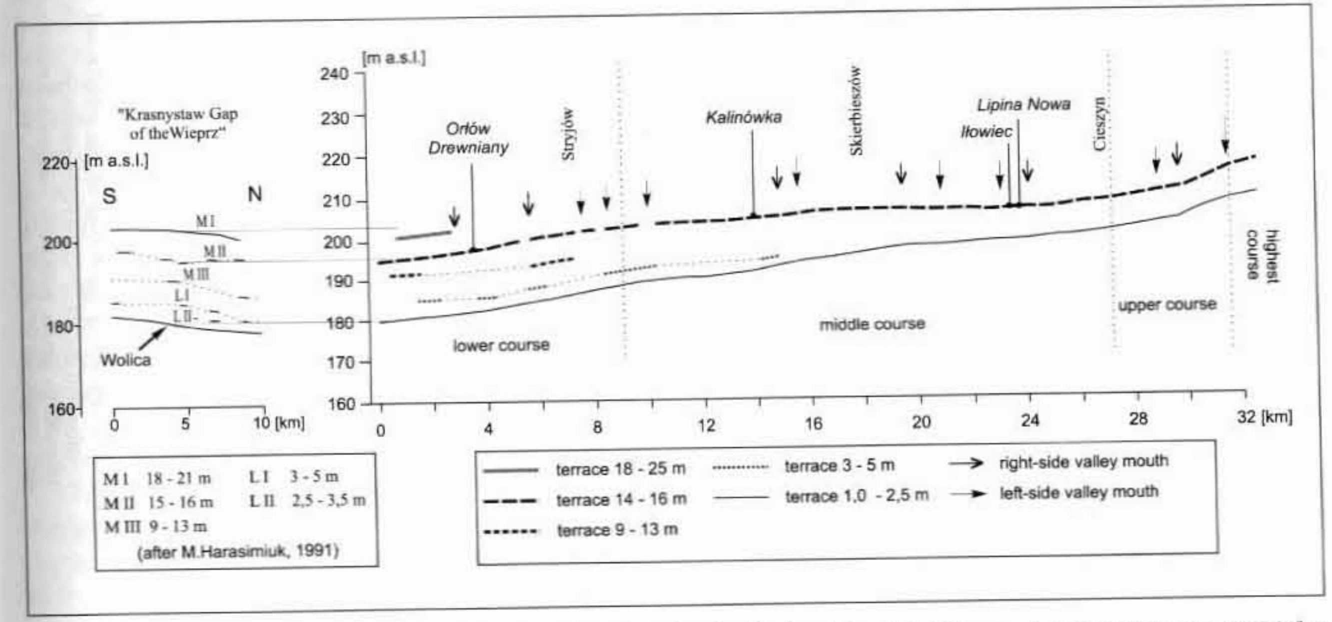

Fig. 2. Longitudinal profile of the Wolica Valley and part of the longitudinal profile of the "Krasnystaw Gap of the Wieprz" (after Harasimiuk, 1991)

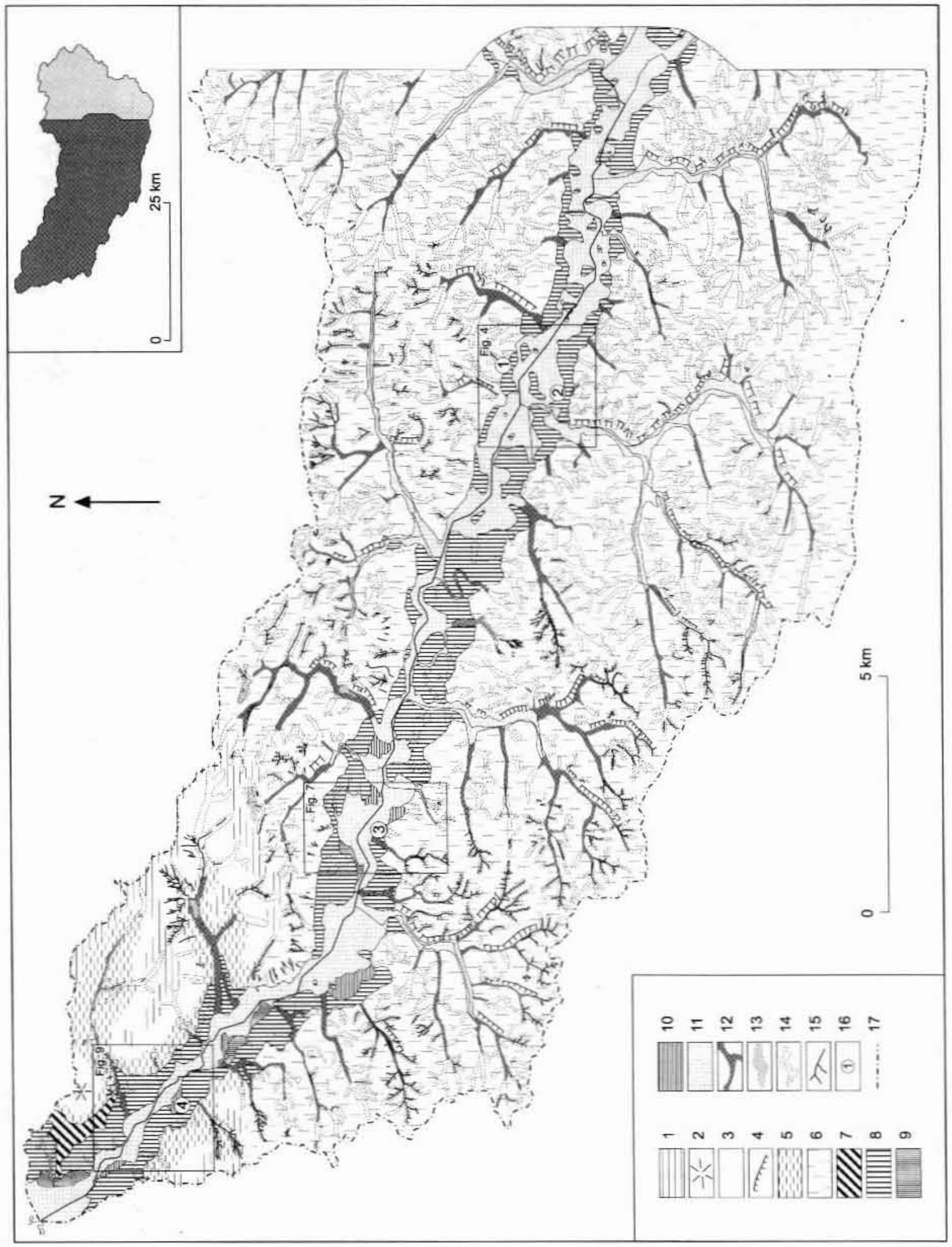

Fig. 3. Geomorphological map of the middle and lower course of the Wolica Valley
1 – planation surface, 2 – denudation mountains, 3 – denudation slopes, 4 – structural edges, 5 – accumulative-denudation slopes, 6 – loesses, 7 – terrace 18–25 m, 8 – terrace 14–16 m, 9 – terrace 9–13 m, 10 – terrace 3–5 m, 11 – terrace 1–2.5 m, 12 – accumulative floor of dry valleys, 13 – eolian sands, 14 – erosional-denudation valleys, 15 – ravines, 16 – localization of studied profiles (1 – Lipina Nowa, 2 – Iłowiec, 3 – Kalinówka, 4 – Orłów Drewniany), 17 – drainage basin boundary

clearly marked in this area (Jahn, 1956b; Harasimiuk *et al.*, 1988a), whereas, in the remaining part of the catchment, a thick loess cover occurs along with its typical relief forms – gullies, small valleys and erosive-denudational valleys, as well as enclosed depressions (Fig. 3).

Two valley courses: the middle and the lower, were selected for detailed examination. The lowest angle values (< 5°–70.8%) of slopes surrounding the middle and the lower courses of the Wolica Valley occur on hilltops, sub-slope flats and terraces, as well as on valley-floors (Table 1).

Table 1. Mean slope angles in the middle and lower valley courses of the Wolica

Angle [°]	Percentage [%]
0.0–2.5	39.0
2.5–5.0	31.8
5.0–7.5	18.2
7.5–10.0	7.3
10.0–15.0	3.2
> 15.0	0.5

Steeper inclinations are most conspicuous in dry erosive-denudational valleys, the slopes of which are structural edges, as well as in young erosive valleys and within erosion scarps which separate successive terrace levels.

The middle course of the valley, about 18 km long, has a rectilinear WNW-ESE direction (Fig. 1B). The catchment area in this reach is noticeably asymmetric – its leftbank, southern part is wider than the right, northern one. Both parts of the catchment are entirely covered by loess (Fig. 3). However, owing to deforestation and intensive agricultural use of the land, few young erosive cuttings can be observed; such forms became transformed into small trough-like valleys which discharge into vast dry erosive-denudational valleys (Fig. 3). The occurrence of the differently preserved medium (II) raised terrace (14–16 m above river level), is characteristic of the middle course of the Wolica Valley floor. In the reach between Cieszyn and Skierbieszów, this terrace is much dissected. It clings to loessic slopes in the form of narrow ledges, remnants and meander islands (Fig. 1B). The inclination of the medium (II) terrace surface in this part of the catchment amounts to 0.3‰ over a 9 km-stretch (Fig. 2). The relative heights above river level are even, though slightly higher in the lower part in the Skierbieszów area (10–12 m above river level).

In the lower part of the middle course, the medium (II) raised terrace is far better preserved and less dismembered (Fig. 1B and Fig. 3). It forms vast undulating planes, mainly on the left side of the valley, interspersed with small erosive-denudational valleys and dry hollows. The terrace is separated from lower terraces by clear-cut steep erosive scarps. In relation to the upper part of the middle course of the Wolica Valley, the terrace slope reduction increases to 0.6 ‰. Relative height above river level also increases to the level of 14–15 m (Fig. 2). Adjacent to the medium terrace edge, small remnants of the two lower raised terraces (9–13 m and 3–5 m) occur only in the lower part of the valley (Fig. 3).

In the Stryjów area, the Wolica Valley narrows markedly; this is probably tectonically conditioned by a fault zone which crosses the valley diagonally (Fig. 1B). Just before the valley contraction, the medium (II) raised terrace has largely been removed and a distinct step appears in the longitudinal profiles of both the medium (II) and the low terrace (1.0–2.5 m above river level).

The nine kilometre-long lower course of the Wolica Valley between Stryjów and the river-mouth is also rectilinear, but the valley changes its course to a more meridional one (NW-SE) and both parts of the catchment have a similar width (Fig. 1B). The difference consists in the development of surface deposits in both parts of the catchment. Its right part is covered with eluvia and eolian sands, while, in the left one, loesses and eluvia are present (Fig. 3). The Weichselian valley-floor of the Wolica River was narrower than in its middle course, yet it is built from as many as five erosive and accumulation surfaces, the heights of which resembles those of the raised terraces in the Krasnystaw Gap of the Wieprz River (Fig. 2). The surfaces include: a contemporary floodplain, a Holocene raised terrace (low terrace) and three Weichselian terraces (medium terraces III, II and I). The medium terrace (II), the principal subject of this paper, forms a level surface in this part of the catchment, where it slopes westward, more so than in the middle course (0.9‰). Moreover, it is separated from younger terraces by a distinct erosive scarp (Fig. 1B). The relative heights all over this valley stretch are quite level, amounting to 14–16 m.

Geological structure of the medium (II) raised terrace

The geological structure of the medium (II) raised terrace in the middle and lower course of the Wolica Valley was identified by means of analysing outcrop sediments in four exposures and deposits obtained from manual boreholes (Fig. 1B). The exposures are situated within:

1) the outlet of a trough-like valley onto the surface of the medium (II) raised terrace (the village of Lipina Nowa),

2) the contact area between the eastern end of a large alluvial fan of a side valley and the floodplain deposits (Iłowiec),

3) the surface of the medium (II) raised terrace (Kalinówka and Orłów Drewniany).

In the lithological description of sediments, the lithofacial code was adapted which is commonly used in sedimentological papers (*vide* Gradziński *et al.*, 1986, pp. 402–403; Zielinski, 1992, 1993).

Exposure in Lipina Nowa

The walls of the 5.1 m deep Lipina Nowa exposure cut through the terrace deposits both across and along the axis of the trough-like valley (Fig. 4). The deeper sediments were elaborated based on drilling. The analysis of grain-size distribution and the type of deposit lamination led to the recognition of four lithocomplexes in the vertical profile (Fig. 5). Lithocomplex "a" lies on a rubble of siliceous limestone. It is built from sandy-clayey silts, which, towards the base, become sandy silts and very fine-grained silty sands. In some places, the silts are interbedded with very fine-grained sands. As the sediment sample was collected using manual boreholes, there are no data on sediment structure. An analysis of grain-size distribution revealed that the mean grain diameter (*Mz*) of sandy-clayey silts was 5.1–5.2ϕ, of sandy silts – 5.05ϕ, and of very fine-grained silty sands – 4.8–5.0ϕ. All sediments in complex "a" are characterised by poor sorting (σ_I = 1.23–1.54).

Lithocomplex "b" is situated on the erosive ceiling of complex "a" and is built from alternating laminae of very fine-grained silty, fine- and medium-grained sands (Fig. 5). Whereas most rhythmite sediments display parallel horizontal lamination (*SFh*, *Sh*), only certain thin layers of medium-grained sands have tabular lamination (*Sp*). The values of the mean grain diameter range from 3.83 to 4.72ϕ in laminae of very fine-grained silty sands, from 2.67 to 3.28ϕ in fine-grained sands, and from 1.95 to 2.65ϕ in medium-grained sands. Medium-grained sands are moderately and poorly sorted (σ_I = 0.70–1.39), while fine-grained and very fine-grained sands show poor sorting (σ_I = 1.16–1.59). The structural and textural features clearly differentiate complex "b" from complex "a".

Lithocomplex "b" is covered with a thin layer of lithocomplex "c". It also developed in the form of a rhythmite, but unlike in complex "b", the laminae are noticeably inclined towards the axis of the trough-like valley. Additionally, the laminae are partly torn and deformed (flaser lamination). In sediments of the complex, thin pseudomorphs of ice-veins were also found. Grain-size distribution of the sediments is similar to that of sediments in complex "b" (Fig. 5).

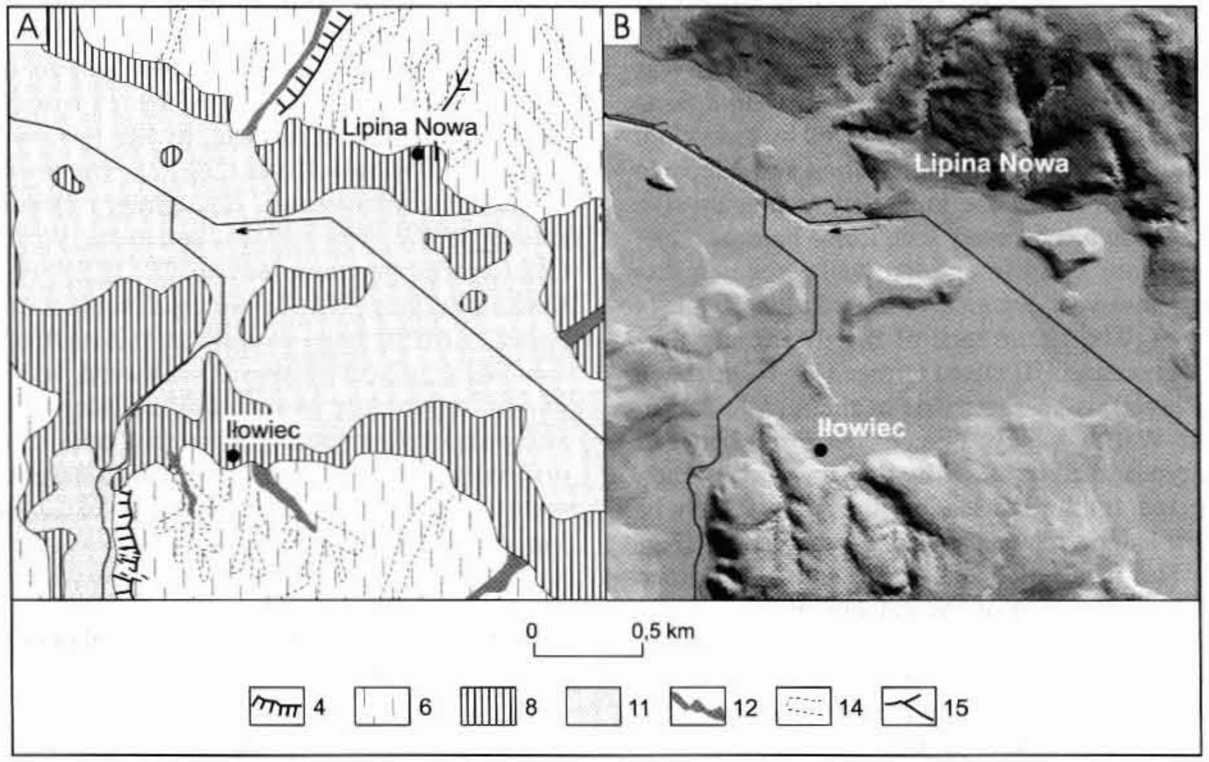

Fig. 4. A: Geomorphological map of the area near profiles in the Lipina Nowa and Iłowiec. Legend, see Fig. 3, **B**: Digital model of the relief

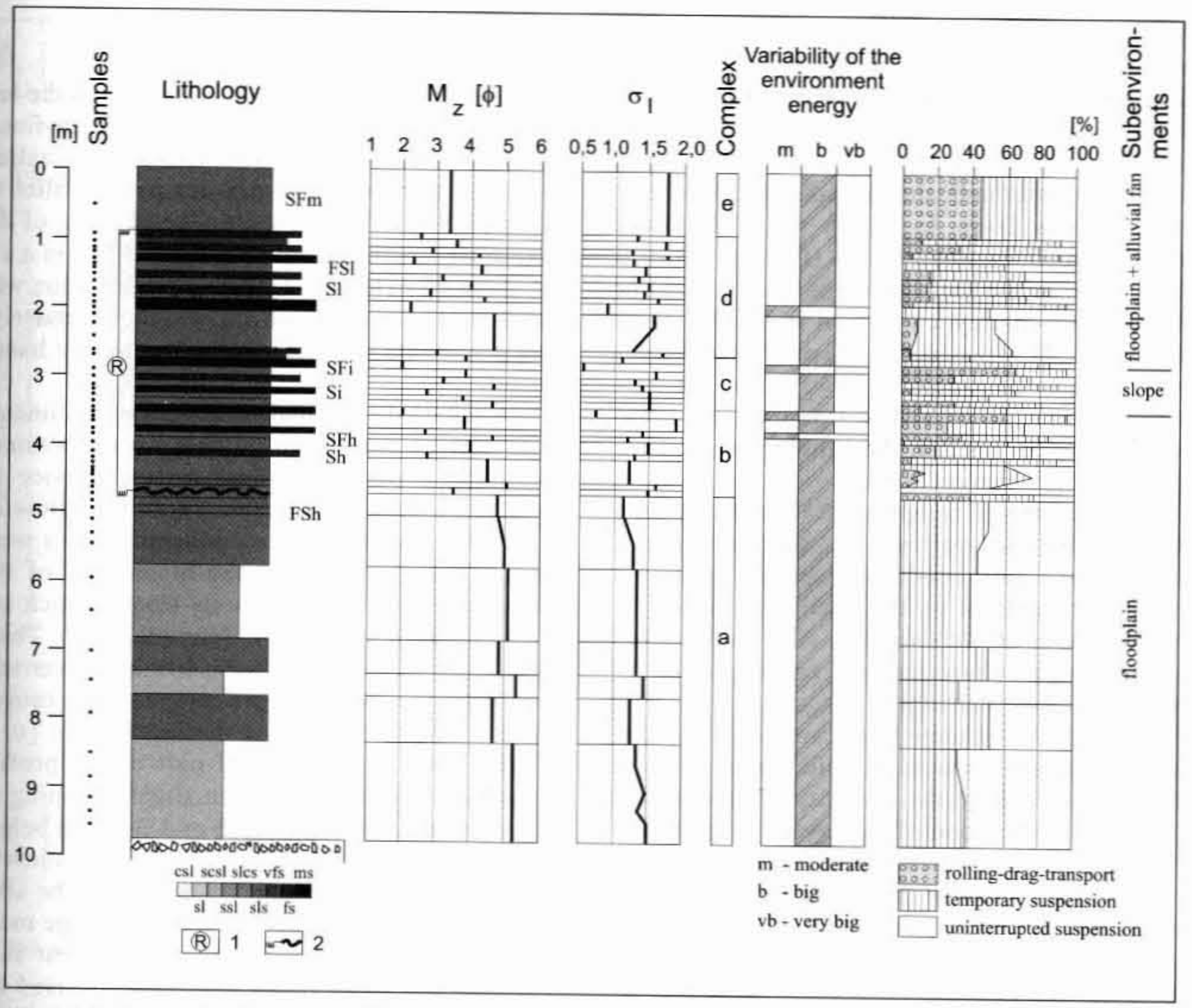

Fig. 5. Lithology and sedimentological features of sedimentary building profile in the Lipina Nowa
Lithology: csl – clayey silt, sl – silt; scsl – sandy clayey silt, ssl – sandy silt, slcs – silty clayey sand, sls – silty sand, vfs – very fine-grained sand; fs – fine-grained sand, ms – medium-grained sand, 1 – rhythmically bedded sediments, 2 – erosional surfaces. Lithofacies code (after Gradziński *et al*., 1986; Zieliński, 1998): Sm – massive structure sand, Sh – horizontal lamination sand, Sl – low-angle cross-stratification sand, Sp – planar cross-stratification sand, St – trough cross-stratification sand, Si – high-angle cross-stratification sand, SFm – massive structure finegrained admixture sand, SFh – horizontal lamination finegrained admixture sand, SFl – low-angle cross-stratification finegrained admixture sand, SFi – high-angle cross-stratification finegrained admixture sand, Fh – horizontal lamination fines, Fl – low-angle cross-stratification fines, Fp – planar cross-stratification fines, FSh – horizontal lamination sandy fines, FSl – low-angle cross-stratification sandy fines

Lithocomplex "d" is located on the sedimentational ceiling of complex "c". The thickness of the form varies according to the location – at the mouth of the trough-like valley it is 1.5 m thick, whereas near the Wolica Valley axis it exceeds 3 m. Complex "d" comprises alternating thin layers of very fine-grained, silty sands and laminae of fine- and medium-grained sands (Fig. 5). In contrast to underlying rhythmites, the layers are thicker and longer. Also, the grain-size distribution of the sediments of this rhythmite varies slightly from the distribution in lower-situated rhythmites. Medium-grained sands (*Mz* = 2,19–2,31ϕ) are well and moderately sorted (σ_I = 0.49–1.46), while fine-grained sands have coarser grain (*Mz* = 2,51–3.18ϕ).

The higher lithocomplex, "e", is a metre-thick layer of massive silty sands, very fine-grained, which have been affected by contemporary soil-forming processes.

The origin of sediments in individual lithocomplexes was determined on the basis of a detailed sedimentological analysis and the situation of the exposure in relation to the forms of the valley-floor and slope. The sediments of complex "a" are characterised by a high content of grains deposited from permanent suspension (50–60%), and lack of grains transported in the bed-load (Fig. 5). Such features, along with a high variability of water energy, imply that the sediments were deposited by shallow sheet floods of short duration. Sediments of complex "b" were deposited in a similar subenvironment. Rhythmical development of the deposits and rhythmical variability of environment energy and of the deposition processes indicate a seasonal recurrence of very shallow flows. In a river valley the flows may come from floodwaters (flowing down a floodplain or the surface of the alluvial fan) or from a low-energy current of a braided river (Zieliński, 1993). A channel genesis for the deposits has to be excluded, however, as the content of grains carried by bed-load transport is too small (Fig. 5). Instead, the lithological features point to high-energy floods.

The features of complex "c" (laminae sloping towards the side-valley axis, discontinuity of laminae and their small thickness, as well as a rhythmical pattern of the sediment) testify to slope genesis of the sediment. Also in this case, sediment grains were carried and deposited by sheet floods of deluvial fans.

The upper rhythmite (lithocomplex "c") probably consists of deposits of a side-valley alluvial fan. It is evident in the diversity of layer thickness and in the slope of the layers in the direction of the main-valley axis. It is not unlikely, however, that some of the layers were formed as a result of a flood in the main valley.

The genesis of deposits in complex "e" was not investigated on account of the changes in its lithological features brought about by contemporary soil processes.

Genetic interpretation of sandy-silty rhythmites is extremely difficult since they are formed as a result of periodic action of sheet floods (McKee *et al.*, 1967; Tunbridge, 1984; Williams, 1971; Zieliński, 1993; Superson, 1996a). According to Fairbridge (1968), the term "sheet floods" should only be used to refer to sediments of large-space rainwashing that can be observed during short but violent storms in semi-dry areas. However, Fairbridge points out that a lack of vegetation may lead to the occurrence of similar phenomena in humid climate. Some investigators (e.g. McKnee *et al.*, 1967; Williams, 1971) claim that flows resembling sheet floods occur in river channels with a periodic rhythm of water supply. Given that, it seems justifiable to count energetically varied floods of short duration among sheet floods. A similar opinion is expressed by Zieliński (1993) who links sandy-silty rhythmites to the subenvironment of secondary braided channels or to the overbank zone of a proglacial braided river.

Exposure in Iłowiec

The exposure in Iłowiec is situated in the left bank, southern part of the Wolica Valley-floor, near the outlet of a large flat-bottom valley (Fig. 4). It cuts the terrace deposits parallel to the axis of the Wolica Valley. The ceiling of the exposure is situated at an altitude of 210 m a.s.l. in about 60 m length. The direct observation was possible to the depth of 5.5 m, but the underlying sediments were recognized using the hand-auger.

A detailed examination of terrace sediments was carried out in two profiles: in the western and central parts of the exposure ("Iłowiec 1" and "Iłowiec 2", respectively). In the "Iłowiec 1" profile, three distinctive lithocomplexes were identified (Fig. 6A). In the lower part of the exposure and 3.5 m below its floor, a thick series of clayey silts occurs (complex "a"). Their grain-size distribution is uniform in the vertical profile – the mean grain diameter (*Mz*) ranges from 5.03ϕ to 5.93ϕ, and sorting is poor (σ_I = 1.45–1.85). In the exposed part of the profile silts have parallel lamination slightly sloping to the east (upriver). At a depth of 4.0–4.5 m below the ceiling of the exposure, silts are clearly gleyed. A sedimentological analysis of the silts shows that sediment particles were, for the most part (70–75%), deposited from permanent suspension and water flows were characterised by a large variability of energy (Fig. 6A). Such features of deposition and the fine granularity of the sediment are typical of a floodplain subenvironment.

The middle part of the profile is formed by lithocomplex "b". This lies on an erosive ceiling of complex "a" and its thickness varies between 2.5 m in the western part of the exposure to > 5 m in its central part. The complex consists of alternating laminae and thin layers of poorly-sorted silty sands (*SFl*), as well as medium- and fine-grained sands (*Sl*), inclined towards the east. The fine-grained sediment is poorly sorted, which indicates a large variability of flow energy (Fig. 6A). The sediment of coarser grain is either moderately or poorly sorted, which indicates a smaller variability of environment energy than in the case of the deposition of finer-grained sediment. Moreover, a sedimentological analysis shows that all rhythmite sediments were deposited by very shallow but high-energy flows. This is indicated by the high percentage (90–95%) of grains deposited from permanent suspension.

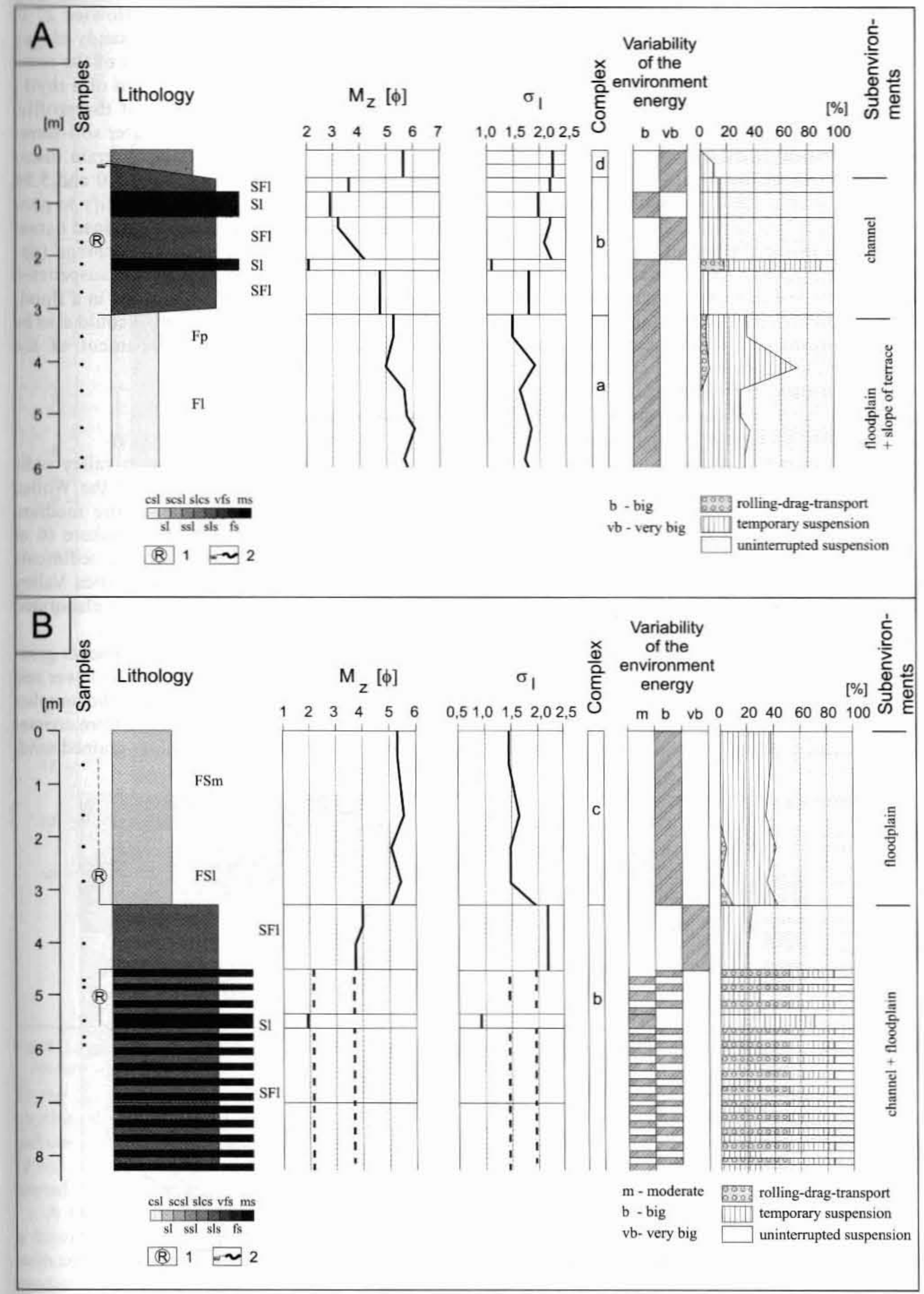

Fig. 6. Lithology and sedimentological features of sedimentary building profile in Iłowiec
A – profile Iłowiec 1 (western part), **B** – profile Iłowiec 2 (central part). Legend, see Fig. 5

It is difficult to define the genesis of a rhythmite unequivocally. Sandy rhythmites may be formed in the subenvironment of streams of secondary importance in a braided river or on the floodplain of the river (Zieliński, 1993). It is also believed that water-flows in the area of those subenvironments were hydraulically very similar to shallow sheet floods of short duration (e.g. McKnee *et al.*, 1967; Williams, 1971). As a consequence, it is possible for sediments to be deposited on the surface of the alluvial fan as well. This hypothesis must be excluded, however, since the sediment development is indicative of the proximal part of the fan while only the subenvironment of the distal part of the fan may be present in that place. In conclusion, the rhythmite of complex "b" was probably formed in the subenvironment of a shallow river channel. The high variability of water energy indicated by the sediment suggests that it represents deposition in the channel of a sandy braided river.

The ceiling of complex "b" is erosively sheared and covered with a thin layer of contemporary deluvia (lithocomplex "d").

In the central part of the exposure („Iłowiec 2" profile), lithocomplex "a" does not occur and was not intersected by manual probing. The lower part of the profile there is represented by a sandy rhythmite (lithocomplex "b"), as also found in the "Iłowiec 1" profile. The structural and textural features of the rhythmite sediments are identical to those in the "Iłowiec 1" profile (Fig. 6A,B). The upper part of "Iłowiec 2" is built from a 3 metre-thick layer of sandy-clayey silts (lithocomplex "c"). Sediments of the complex are also developed in the form of a rhythmite, except that, in the ceiling of the profile, lamination is invisible owing to later soil-forming processes. Values of the mean grain diameter of clayey silts range between 5.0 and 5.5φ and the values of σ_I = 1.50–1.65 testify to poor sorting of the sediment. The fine-grained nature of the rhythmite and the high percentage (approx. 60%) of grains deposited from suspension transport indicate that it was formed in a floodplain subenvironment. However, it could also be representative of the subenvironment of the distal part of the alluvial fan.

Exposure in Kalinówka

In Kalinówka, a profile through valley sediments is present on the left bank of the Wolica Valley, within the steep edge of the medium raised terrace. The walls of the exposure (6 m deep and 30 m long) cut through the sediments perpendicularly to the axis of the Wolica Valley (Fig. 7). The deeper sediments were elaborated based on drilling.

In the studied profile, valley sediments comprise three lithocomplexes (Fig. 8). The lower and middle parts of the profile make up lithocomplex "a", which is > 10 m thick. It is built from coarse-grained silts, blended with very fine-grained sand. In the ceiling of the complex, sediments form a rhythmite consisting of alternating laminae of yellow and grey sandy silts (*FSh*) and grey silts (*Fh*). All sediments in this complex are poorly sorted (σ_I = 1.1–1.6).

A further lithocomplex "b" is represented by a layer of poorly sorted, medium-grained sands with small-scale trough skew-lamination (*St*). The median of the grains amounts to 1.50ϕ, and the sorting index (σ_I) to 1.45.

The ceiling of the profile of terrace sediments forms another rhythmite (lithocomplex "c"), built from thin layers of fine-grained sand mixed with silts and with laminae of sandy silt. The sediments of the rhythmite are poorly sorted (σ_I = 1.10–1.25) and display parallel horizontal lamination (*SFh* and *FSh*).

A sedimentological analysis of sediments in complex "a" leads to the conclusion that the sediment was deposited from two types of

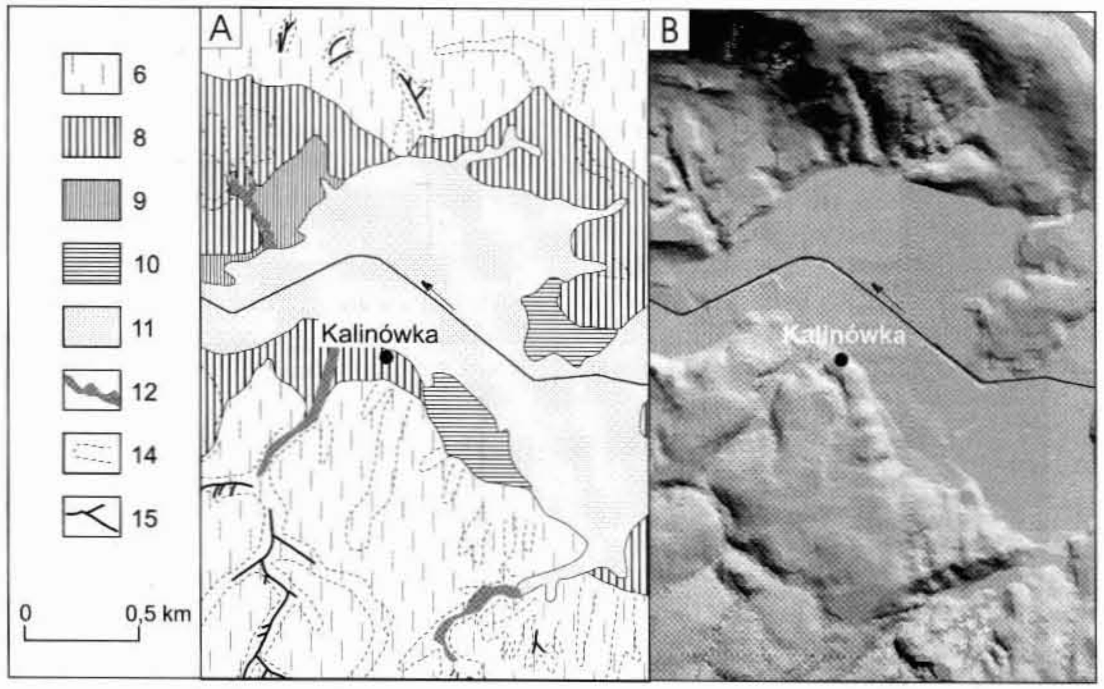

Fig. 7. A: Geomorphological map of the area near the profiles in the Kalinówka. Legend, see Fig. 3. **B**: Digital model of the relief

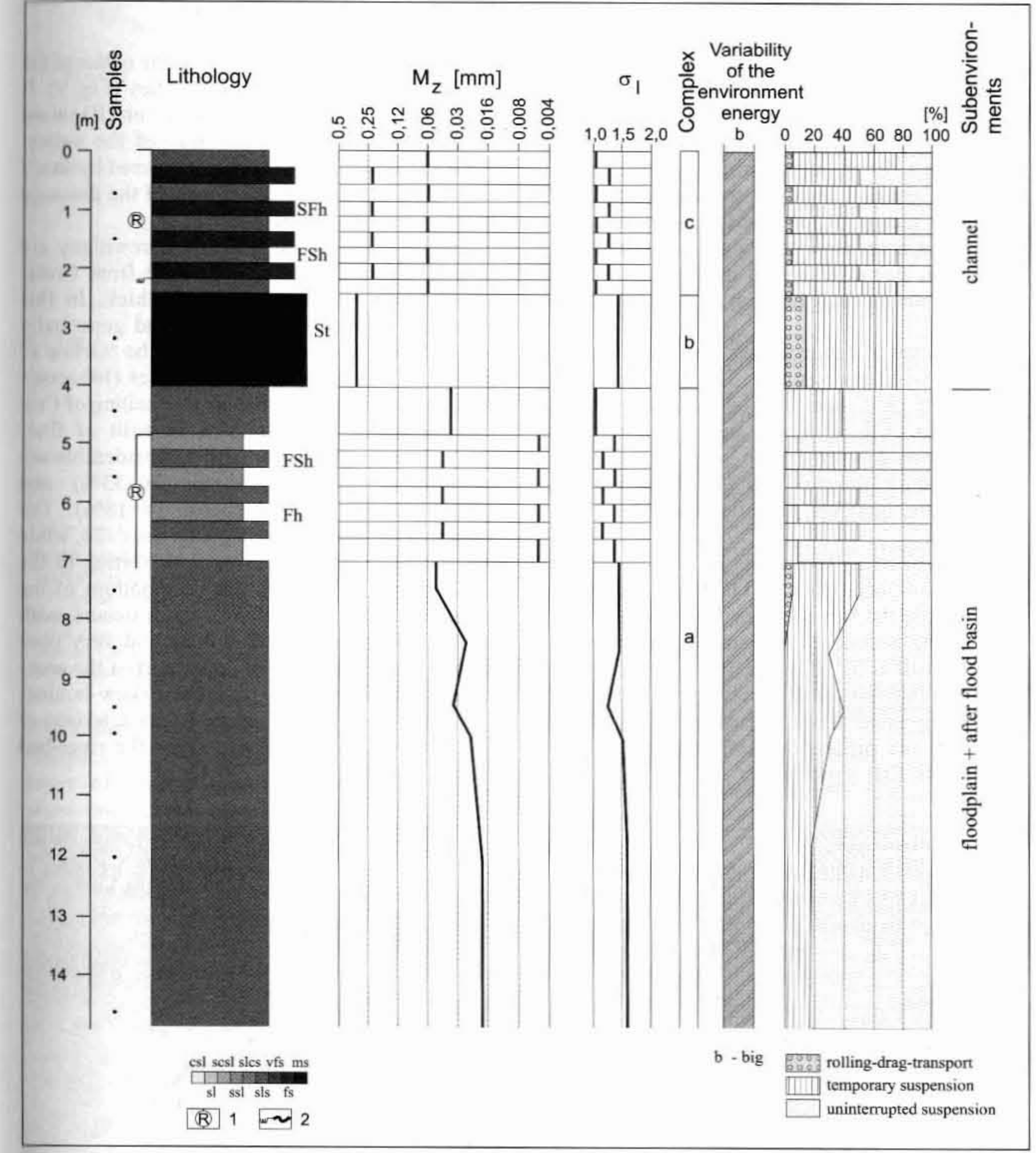

Fig. 8. Lithology and sedimentological features of sedimentary building profile in the Kalinówka (after Superson, 1996, somewhat changed). Legend, see Fig. 5

transport: silts – from suspension, and very fine-grained sands – from intermittent suspension (Fig. 8). That kind of deposition and a large variability in respect of environment energy suggest that the sediments were deposited in two stages from energetically different flows of floodwaters. First, at the higher flow energy, very fine-grained sands were deposited, followed by grains of silt, which were released from suspension slow-moving or stagnant waters. Grain-size distribution in those sediments indicates an increasingly large energy of the flood.

Sediments of lithocomplex "b" were formed in the river-bed environment. The following facts testify to it: chute bars (ripples of medium size), coarse grain of the sediment and a small percentage of grains deposited from permanent suspension transport (approx. 20%). There are not enough data, however, to define the channel development.

The genesis of sediments in the sandy roof rhythmite (lithocomplex "c") is difficult to establish, because the deposits may have been formed both in the secondary stream of a periglacial braid, as well as on a floodplain surface. Considering the relatively small percentage (25–50%) of grains deposited from permanent suspension transport, the present authors are inclined to support the first hypothesis.

Exposure in Orłów Drewniany

This exposure is situated near the outlet of the Wolica Valley into the Wieprz Valley (Fig. 9). It cuts through sediments of the medium (II) raised terrace situated on the left side of the valley. Adjacent slopes and hilltops are covered by sandy eluvia, unlike the remaining part of the drainage basin, where loess predominates.

Terrace sediments in Orłów Drewniany are located on an erosive ceiling built from Cretaceous rocks and are 10 metres thick. In this exposure, several lithologically and genetically varied series crop out (Fig. 10). In the "Orłów 1" profile, a 5 metre-thick sandy series (lithocomplex "b") is situated on the erosive ceiling of Cretaceous rocks. The complex is built of fine-grained sands (42–50%) with a considerable admixture of medium-grained (26–33%) and coarse-grained sands (approx. 16–18%). The values of the mean grain diameter are c. 2ϕ, while the values of σ_1 index show poor sorting of the sediment (Fig. 11A). In the very bottom of the complex, a thin layer of silty sands occurs, with mean grain diameter $Mz = 4.0\phi$ and very poor sorting ($\sigma_1 = 2.05$). In the upper part of the complex, the sediment displays tabular skew-lamination (*Sp*). This type of texture is characteristic of sandy waves which migrate along the river-bed (Allen, 1983; Zieliński, 1993).

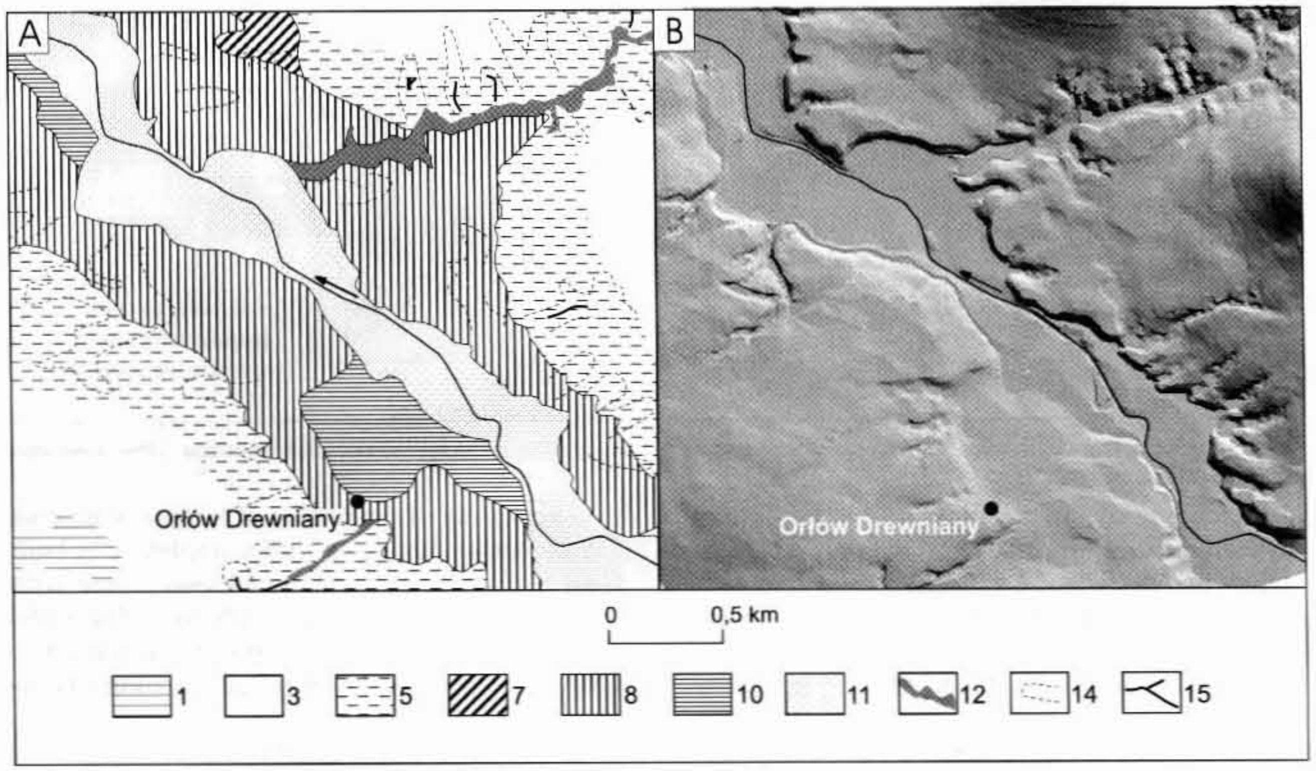

Fig. 9. A: Geomorphological map of the area near the profiles in Orłów Drewniany: Legend, see Fig. 3.
B: Digital model of the relief

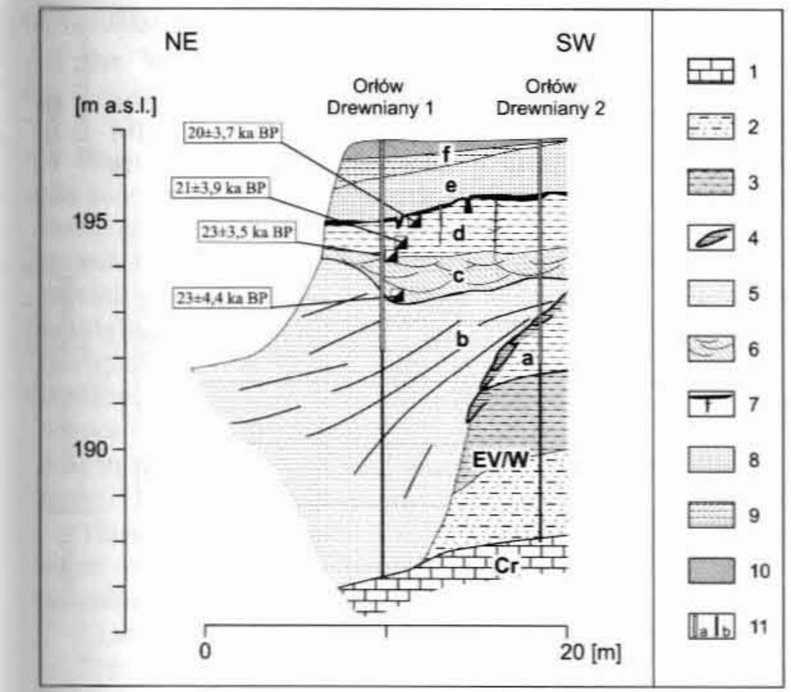

Fig. 10. Synthetic geological profile of terrace sediments in Orłów Drewniany (after Zagórski, 1998, somewhat changed)
1 – graize (Upper Cretaceous), 2 – silty sand, 3 – sandy silt, 4 – solifluction structures, 5 – sand, 6 – diagonal bedding sand, 7 – ortstein layer and frost fissure, 8 – sand with gravel, 9 – sandy-clay interbeddings, 10 – Holocene soil, 11: a – exposure, b – drilling. Lithophacial complexes: Cr – Cretaceous, EV/W – Early Weichselian and older (Wartanian/Odranian) sediments, **a–f** – the complexes explained in the text

On the erosive ceiling of complex "b", lithocomplex "c" is located (Fig. 11A). This is a thin layer of medium-grained sands with trough skew-lamination of medium scale (*St*). The values of the mean grain diameter range between 1.06ϕ and 2.02ϕ, and sorting of the sediment is poor ($\sigma_1 = 1.28–1.38$). The structural and textural features of sands imply that they were deposited mainly from bed-load and from intermittent suspension, and formed large ripples at the bottom of the channel. The depth of the flows was at least 0.5 m (Zieliński, 1993). Absolute dating of bottom and ceiling sediments of the complex using TL method (Fig. 10) indicates that the channel deposits formed 23,000 years ago (the phase before maximum cold of the Upper Pleniglacial).

The subsequent complex, "d", consists of thin horizontally-arranged layers of silty-clayey sand, silty sand and medium-grained sand (*SFh*, *Sh*). Rhythmic changes of the parameters of grain-size distribution imply episodic changes of flow energy. It must be emphasised, however, that, in the ceiling of the complex, syngenetic pseudomorphs of ice-veins testify to the deposition of sediments in permafrost. Absolute TL age of sediments of the complex "d" was estimated at 20 ± 3.7 ka BP (Lub-3343) and 21 ± 3.9 ka BP (Lub-3347).

On the uneven erosive ceiling of complex "d", a thin layer of medium-grained sands is present; this displays small scale trough skew-lamination (lithocomplex "e"). The sands are moderately well sorted and their mean grain diameter is below 2ϕ. These features, along with a small percentage of grains deposited from permanent suspension (5–8%) and a moderate variability of environment energy (Fig. 11A), indicate that the sands were deposited by the high-energy flows of a deep river (conditions similar to those of sediment deposition in complex "b").

On account of the transformation of the sediment caused by contemporary soil-forming processes, ceiling lithocomplex "f" was not examined.

The same lithocomplexes are present in the vertical "Orłów 2" profile of terrace sediments, situated some metres to the south-east of the "Orłów 1" profile (Fig. 10), except that lithocomplex "b" is considerably reduced and is laterally and vertically adjacent to a layer of silty sands interbedded with fine-grained sands (lithocomplex "a").

Silty sands of complex "a" are characterised by a rhythmic change of grain-size sorting in the vertical profile – some laminae are poorly, and some – very poorly sorted (Fig. 11B). This indicates a rhythmic variability of flow energy. Moreover, a sedimentological analysis revealed that the sediments were deposited mainly from intermittent suspension. In respect of these features, the authors believe they are sediments of a natural levee. Overbank spilling of floodwaters brought about a large rhythmical variability of energy flows and a characteristic type of sediment deposition (Superson, 1996a).

The development and genesis of other lithocomplexes („b", "c", "d" and "e") are similar to those of profile "Orłów 1" (*cf.* Fig. 11A and Fig. 11B).

To summarise, a synthetic profile of sediments in the medium (II) terrace comprises the following strata:

1) terrace base: channel and floodplain deposits of older terraces,

2) slope deposits with rhythmical grain-size distribution,

3) thick floodplain deposits, or – by the slopes of the valley – deposits of alluvial fans,

4) channel deposits of a sandy braided river.

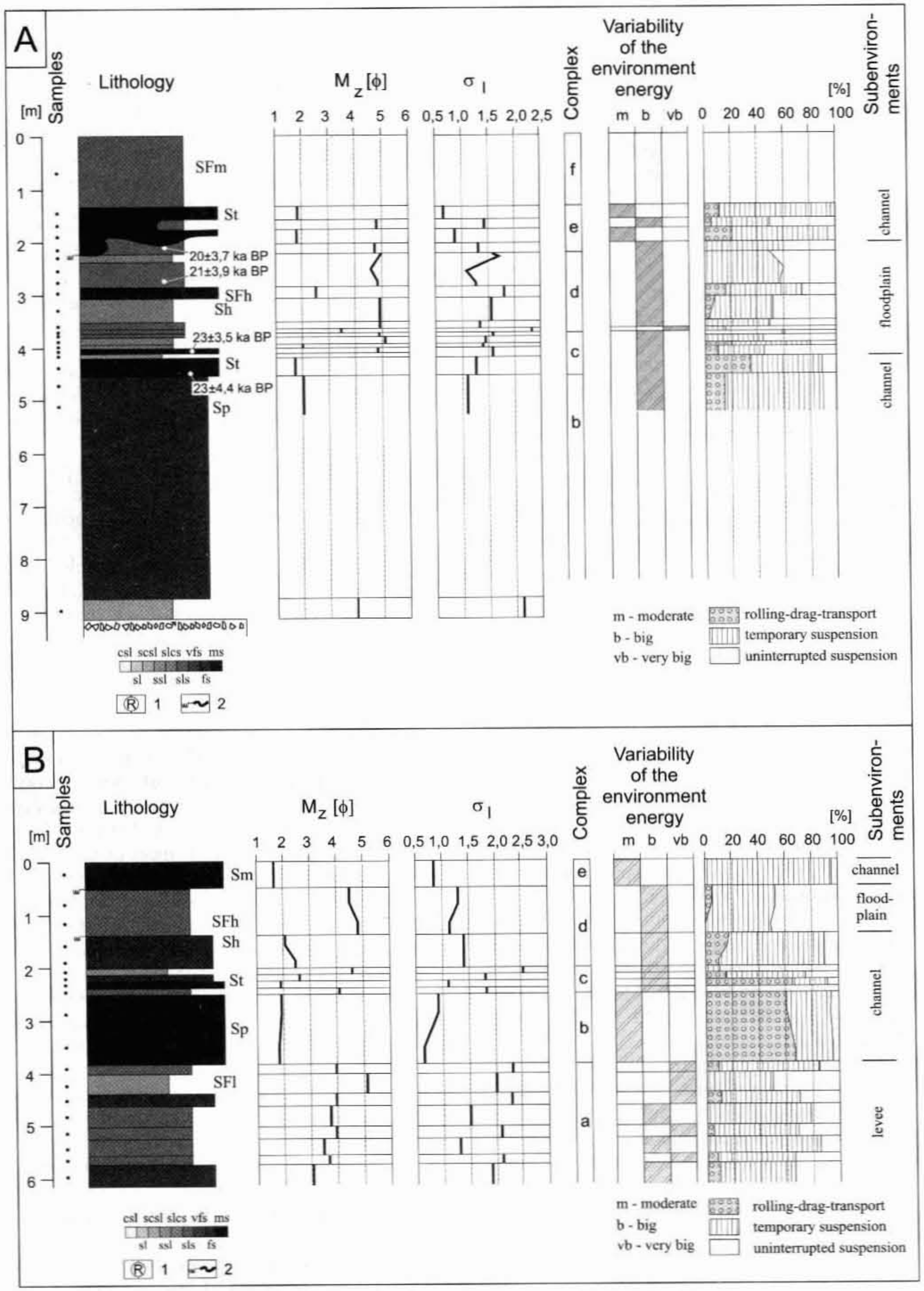

Fig. 11. Lithology and sedimentological features of sediments building the profile in Orłów Drewniany
A – profile Orłów Drewniany 1, B – profile Orłów Drewniany 2. Legend, see Fig. 5

Conditions for the development of the Wolica River valley floor in Upper Pleniglacial

The interdependent processes of the periglacial zone create a morphogenetic system of a high order. In a subpolar climate, fluvial systems are ranked last because other systems: cryogenic, gravitational, deluvial and eolian, form a zone supplying the fluvial system with matter and energy (Superson, 1996a). As a consequence, the development of periglacial sedimentation at the bottom of the Wolica Valley ought to be examined in relation to the above morphogenetic systems.

Thus, the time framework of sediment deposition in the medium (II) raised terrace has to be considered in two stages:

1) sedimentation of the terrace base deposits,
2) build-up of the terrace base with deposits from the waning phase of the cold maximum period.

Terrace base deposits date from the Middle Pleniglacial and from the early part of the Upper Pleniglacial (apart from the base at Iłowiec), and the time framework for the base build-up is constrained by two events: the end of erosion processes occurring in the valley-floor at the beginning of the Upper Pleniglacial (c. 22,000–20,000 BP); the start of floor-erosion processes in the Wolica channel towards of the Late Weichselian (c. 12,000–10,000 BP).

Intense floor and lateral river erosion, which occurred before the cold maximum the Upper Pleniglacial, was widespread and has been identified by Rotnicki and Borówka (1989) in the Prosna Valley, by Harasimiuk (1991) in the Wieprz Valley, by Starkel (1994, 1995) in the valleys of the Carpathian Foreland and by Superson (1996a) in the valleys of the Lublin Upland. This indicates climate as the cause of the erosion. There is no unanimity, however, as to which climatic factors contributed to channel deepening.

Floor and lateral erosion incised the interstadial-anastadial accumulation surface and left behind an erosive discontinuity surface. The accumulation surface subsists only in the lowest part of the valley, at an altitude of 203–205 m a.s.l. Evidence of erosion has also been found in the Krasnystaw Gap of the Wieprz river (Harasimiuk, 1991; Superson, 1996a) and in the valleys of the Zamość Basin (Superson, 1996a). This erosive surface was found in three of the analysed profiles: in "Lipina Nowa" (the ceiling of lithocomplex "a") and in "Orłów 1" and "Orłów 2" (the ceiling of complex "d"). The surface evidently dates back to the period directly preceding the cold maximum, since in its ceiling pseudomorphs of ice-veins were found („Lipina Nowa", "Orłów 1" and "Orłów 2"). The conclusion is confirmed by TL analyses of basal deposits in the "Orłów" exposure (Zagórski, 1998). Consequently, deposits of the medium (I) raised terrace form the base of the medium (II) terrace. In the "Iłowiec" exposure, the basal terrace is built from clayey silts, which are probably older than the Weichselian.

The fabric development and sedimentological analysis of the preserved deposits of the medium (I) terrace indicate that, towards the end of the Weichselian Middle Pleniglacial and during the phase before maximum cold of the Upper Pleniglacial, a large and deep river channel existed in the Wolica Valley; this had well-developed levees. In the floor of the channel, transverse bars and large ripples formed, built from moderately and poorly sorted fine- and medium-grained sands. Sediments of both subenvironments are well displayed in the "Orłów" exposure. Channel and levee deposits also occur in the "Latyczów" profile in a similar stratigraphic position (Harasimiuk, 1991). Concurrently, a floodplain developed in the valley and sediments of its subenvironment were found in the "Lipina Nowa" profile (lithocomplexes "a" and "b"). The development of the sediments points to the growth of flood energy in the course of time. In paleogeographical terms, this is explained by the growth of the permafrost, which gradually amplified surface wash. A similar trend is presented by Rotnicki (1996) in a curve of runoff depth in the Prosna catchment basin over the last 140,000 years. Flood sediments with rhythmic layers originating from the Inter-Pleniglacial period were also found in the small valleys of Central Poland. They occur along the full width of the valley bottoms (Manikowska, 1996) or are situated peripherally in relation to the sandy bed zone (Goździk & Zieliński, 1996) as in the River Wolica Valley.

Fluvial deposits from the cold maximum and from the beginning of the later part of the Upper Pleniglacial have not been identified, either in the exposures analysed or in manual boreholes. Fluvial processes were inhibited most probably owing to the short duration of soil thaw and temperatures which exceeded 0°C. On the surface of the terrace which had formed above the overflow land, ice veins and wedges began to develop, while on the terrace edges and on slopes of small side-valleys, slope processes were activated (lithocomplex "c" in the "Lipina Nowa" profile).

During the latest phase of the Upper Pleniglacial, the valley became filled with floodplain, channel and proluvial deposits. Floodplain deposits of this period were identified in profiles: "Iłowiec 1", "Iłowiec 2" and "Kalinówka". The sediments are represented by sandy-silty rhythmites which reflect a rhythmicity of floodwater energy. The grain-size distribution of the sediments indicates a gradual increase in the flood dynamics.

Near the outlets of the small side-valleys, the floodplain deposits have been replaced by those of alluvial fans ("Lipina Nowa" profile). Proluvial sedimentation presumably developed parallel to flood sedimentation and was associated with channel erosion in the side-valley floors. The large amounts of detrital deposits supplied to the main valley caused rapid aggradation of the valley-floor. Over a period of about 6,000 years, the valley floor was raised by over 15 m. Intense, late Pleniglacial deposits were also observed in other river valleys of the Lublin Upland and Roztocze (Harasimiuk, 1991; Buraczyński & Superson, 1996; Superson, 1996a) and in the river valleys of the Łódź Upland (Turkowska, 1988).

The channel deposits which are present close to the ceilings of the profiles resemble those of a braided river. The river probably developed in two phases. In the older phase, it was a wide, high-energy river, in the floor of which sands with Cretaceous rock gravel were deposited and bars of medium size formed. In the younger phase, the water energy was evidently much smaller, as fine-grained and very fine-grained sands were deposited in the channel, there to form a plane bed or small ripples. The channel deposits of the small valleys of Central Poland situated in a similar stratigraphic position are dated by Manikowska (1996) to the period 20-14.5 ka BP. The aforementioned authors are of the opinion that these sediments were deposited in the cold period of the continental climate by periodical streams.

The wide-river phase was followed by floor and lateral erosion in the Wolica Valley-floor. Field investigations reveal three stages of bottom erosion, interspersed by two depositional phases. Geomorphological data (the shape of the erosion remnants in the terrace) indicate that, during the oldest stage, erosion developed in the channel of a river which had large-radius meanders. A similar phenomenon was observed in river valleys of the Zamość Basin (Superson, 1977, 1979, 1996a).

The development of the River Wolica Valley bottom presented above indicates that individual sediment lithocomplexes of the medium raised terrace in the Wolica basin formed in variable conditions of water flow and deposit supply from the catchment basin to the floor of the valley. Water flow in the catchment is difficult to reconstruct. Attempts have been made to retrodict the Weichselian water balance in the Prosna catchment (Rotnicki, 1996), but, owing to different climatic, hypsometric and hydrogeological conditions, these values cannot be applied to the Wolica Valley.

When reconstructing the deposit supply to the valley-floor, two aspects have to be taken into consideration:

1) how much sediment was denuded from slopes and hilltops (from a unit of surface over a known period of time),

2) how much sediment was retained at the bottom of the valley.

Of course, Upper Pleniglacial denudation can only be estimated from comparisons with contemporary denudation. In the northern part of The Murmańsk Upland (the Kola Peninsula, Russia), on slopes covered by tundra, the wash is not very intensive (Superson, 1994) and soil creep and solifluction, occurring mainly on moist slopes, are of greater importance (Pękala, 1994; Goliszek & Pękala, 1996). Contemporary research in the temperate climate zone also indicates the plant cover has a decisive role in protecting the soil from wash processes (Gil, 1976,1986). On slopes of Carpathian flysch devoid of vegetation, 74.2 tons/ha of sediment was supplied during 1969, while, on the same slopes, covered by grasses, only 0.031 tons/ha (Gil, 1976). The possibility of water infiltration into non-frozen sediment is also important, as this determines the amount of slope wash (Słupik, 1973). On the permafrost slopes of a periglacial zone, slow wash was presumably of greatest importance during land thaw, when the surface flow of waters was not yet intense and part of the sediment was already defrosted. Gil (1976) pointed to similar contemporary phenomena, and emphasised the intensity of wash during winters of continental type, which resulted from the deep freezing of the ground. Also, Lanagbein and Schumm (1958) observed the importance of vegetation in deposit supply from slopes and point out that the influence of plant cover increases with the growth of climate humidity. The importance of other variables was stressed by Walling and Webb (1983) and Milliman and Syvitski (1992). These authors claim that sediment supply from the catchment decreases with the growth of catchment surface area and increases with the growth of relative height. Similar relationships were proposed in Hovius's equation (1998):

$$\mathrm{Ln}E = -0.416\ln A + 4.26 \times 10^{-4}H + 0.15T + \\ + 0.095T_R + 0.0015R + 3.58$$

where E is specific sediment yield (t km^{-2} yr^{-1}), A is drainage basin area (km^{2}), H is mean height of the drainage basin (m), T is mean annual temperature (°C), T_R is mean annual temperature range (°C), and R is specific runoff (mm km^{-2} yr^{-1}).

The above discussion leads to an inconsistency: dense tundra cover reduced the deposit supply from slopes, whereas intense deposition in valley-floors of different order (Superson, 1996a) suggests the converse. Superson (1996a) tried to explain this apparent contradiction, asserting that a large portion of the detrital sediment was brought to the valley by eolian transport and could then have been washed down into the valley-floor from snowflakes or plant leaves, rather than through erosion. This is a logical conclusion, considering that, between 18,000 and 12,000 BP, thick loess (Maruszczak, 1987, 1995) and sandy covers were forming on the Lublin Upland (Superson, 1987/1988, 1996a; Buraczyński, 1994). Maruszczak (1995) estimated the mean rate of loess deposition at 0.8–1.0 mm/year. Loess covers would not have formed at a similar rate of denudation. It is possible that the vegetation of the tundra forest and grassland which covered the Lublin Upland at the time (Starkel, 1993) was dense enough to prevent the denudation of the deposited sediments. Intense accumulation of detrital matter on snow (even to 672.8 g/m^{2}) has been observed on Spitsbergen (Wojtanowicz, 1990).

The ratio of the sediment removed from the catchment to the total mass of the deposit released in the catchment can be estimated using the deposit supply index, as defined by Walling (1983). The index value is calculated from the equation: Sd = Sy/ER, where Sy is the deposit yield at a given point in the basin and ER corresponds to total erosion above a chosen point in the basin. Walling's research (1983) indicates that high index values are characteristic of very small catchment basins, while its small values (of the order of 0.1–0.2) are obtained for basins larger than 1,000 km^{2}. However, owing to the possibility of an error in estimating the size of slope denudation, a detailed evaluation of the Sd index for the lower course of the Wolica Valley is difficult. Presumed values of the index do not exceed 0.2, since the thickness of alluvia in side valleys and in the Wolica Valley indicates intense deposition there conditioned by the alluvial fans, among other things, which are obstacles to floodwater wash.

Approximate values of deposit supply from the catchment to the basin floor can be calculated using Hevius's empirical formula (1998). According to this formula, which involves five variables, about 0.133 tons km^{-2} year^{-1} of sediment were removed from the Wolica catchment in the beginning phase of the cold maximum period, meanwhile about 1.05 tons km^{-2} year^{-1} at the end of this phase. This value was obtained after introducing the following data, respectively: catchment area: 367.7 km^{2}, mean relative height in the catchment: 79 m and 88 m, mean annual air temperature: –5°C and 5°C, annual range of temperatures: 30°C and 20°C, annual precipitation total: 300 mm and 500 mm. Small index values confirm the above conclusion regarding the retention of a large amount of denuded sediments in the Wolica Valley.

The shape of the river channel is another factor which contributes to the intensity of deposition and influences the lithology of the deposits. In the Wolica Valley, a sinuous river with a well developed floodplain and levees probably existed during the Upper Pleniglacial. Not before the end of that period did a braided river form, as indicated by the sediments, and this was soon transformed into a river of large-radius meanders. The suspension load of the Wolica prevented the development of a braided river for a long time and contributed to the prevalence of silty overbank deposits in the valley.

Until recently, it was commonly believed that braided rivers are characteristic of glacial periods and meandering rivers typify warm interstadials and interglacials. The latest investigations show that, on the contrary, depending on local conditions, rivers may be variously developed in the same period of time (Van Huissteden, 1990; Superson 1996a; Szwajgier, 1998).

The influence of tectonic movements on sedimentation and Upper Pleniglacial erosion is difficult to evaluate because, as Paola *et al.* (1992) rightly observe, tectonically determined factors have a significant influence on fluvial processes only in time-scales exceeding 100,000 years.

Conclusions

1. In the Upper Pleniglacial period in the Wolica River valley, periglacial sedimentation developed in two phases separated by a stage of bottom and side erosion. The earlier phase took place during the cooling period in conditions of a sub-polar, oceanic climate, and the later phase occurred during the coldest period and the slow warming of the sharp continental climate.

2. In the sup-polar, continental climate, the mean rate of aggradation of the Wolica River valley was double the rate of aggradation of the valley bottom during the period of the oceanic sub-polar climate. The above fact illustrates the indirect impact of the climate on valley sedimentation.

3. The following have been local influences on sedimentation in the Wolica Valley:

a) the lithology of basin rocks – loess was an excellent ground for the development of a plant cover which protected the rock from denudation. Moreover, loess supplied to the river channel was mainly transported by suspension and the channel was shaped accordingly,

b) the high density of the valley network – this factor was responsible for the retention of a large amount of sediment in the basin,

c) transverse obstacles in valleys, in the form of alluvial fans which ponded floodwaters.

4. Terrace sediments are built from fluvial deposits (floodplain, channel and levee deposits), as well as proluvial, deluvial and colluvial ones. The polygenesis of terrace deposits results from the large influence of the cryogenic system (permafrost) on the other morphogenetic systems.

5. Data from the Wolica basin indicate that small index values of deposit supply to sedimentation basins are characteristic of average size densely cut drainage basins.

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