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LITHOFACIES AND PALAEOENVIRONMENTAL CHARACTERISTICS OF THE SUWAŁKI OUTWASH (PLEISTOCENE, NORTHEAST POLAND)

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Abstract: Glacifluvial sediments of the Suwałki outwash (Vistulian, NE Poland) are subdivided into seven lithofacies and five lithofacies associations and interpreted in terms of depositional bedforms, stream channel topographies and palaeoflow hydraulics. The associations comprise the deposits of main channel with longitudinal bars (*A*), sand-bed braided channel with transverse bars (*B*), shallow braided channel (*C*), catastrophic flood channel (*D*) and of abandoned channel (*E*). The bulk of these sediments consists of sand which was deposited within transverse bars developed in the secondary channels of outwash braided system. Gravelly deposits were laid down in the main channels which during high-energy discharges were dominated by longitudinal bars. Lithofacies characteristics combined with palaeohydraulic data indicate deposition of all these sediments in the proximal reach of the outwash system.

Key words: outwash, stream channel, palaeohydraulics, Pleistocene.

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INTRODUCTION

The present paper provides the sedimentological analysis of Pleistocene outwash deposits from the Suwałki area (Suwałki Lake District, NE Poland). The deposits are excavated in a number of pits across an extensive low of the Czarna Hańcza River valley (Fig. 1A). The valley originated during the Saalian. During later stages the area lay beyond the junction of two huge ice lobes (Mazurian and Lithuanian lobes; Ber, 1982) and it was the site of widespread glacifluvial sedimentation. During the Vistulian an outwash plain developed here and was fed by melt-out waters funnelled within three, large glacifluvial tracts which coalesced north of Suwałki. The present remnant of the tract is a train of channel-like valleys – the Hańcza, Wiżajny and Szelment valleys (Ber, 1982; Fig. 1B). The Suwałki outwash plain orginated during the decay of an ice-sheet related to the Pomeranian, the main phase of the Vistulian (Ber, 1971, 1974, 1982).

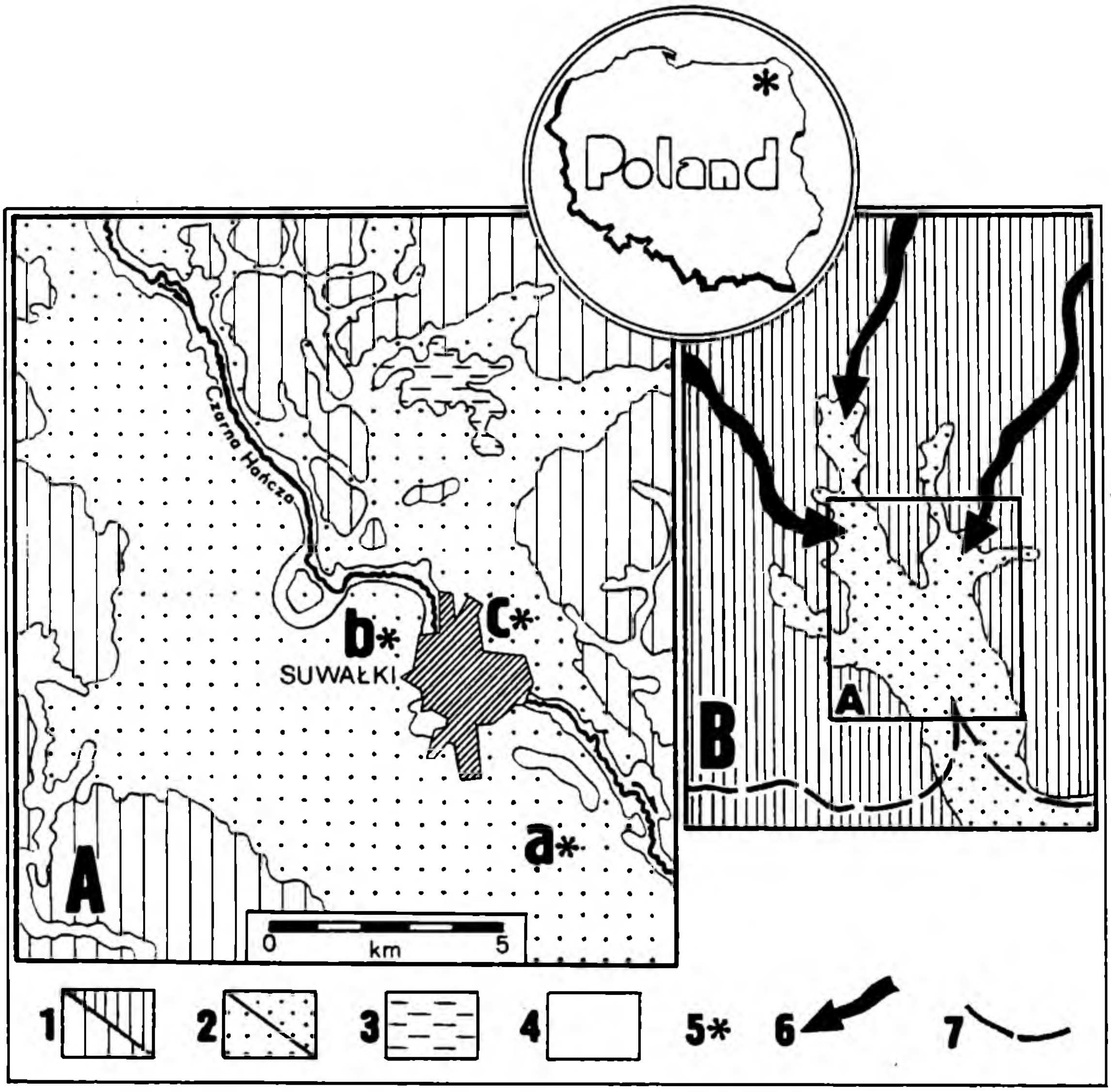

Fig. 1. (*A*) Geological setting and location of sections analysed (geology modified after Ber, 1971). (*B*) Southern margin of ice sheet and major glacifluvial tracts during the Pomeranian stage of the Vistulian (after Ber, 1982). *1* — glacial deposits; *2* — glacifluvial deposits; *3* — glacilacustrine deposits; *4* — alluvial deposits; *5* — location of sections: *a* — Sobolewo *b* — Krzywólka, *c* — Suwałki-NE; *6* — major glacifluvial tracts; *7* — southern limit of ice sheet

STUDY AREA AND METHODS

Fieldwork was done at three localities: Suwałki-Sobolewo, Suwałki-Krzywólka and Suwałki-NE (Fig. 2), which provide well-exposed sections through the middle and uppermost parts of the Suwałki outwash. Deposits were classified into seven lithofacies, following procedures and coding scheme of Miall (1977, 1978) and Rust (1978), and interpreted in terms of bedforms and corresponding flow stage conditions. The lithofacies were next assembled into genetically related associations and these interpreted in terms of subenvironments of an outwash system. Palaeohydraulic analysis was also attempted for selected lithofacies in order to characterize channelled discharges and to provide quantitative data for sedimentological interpretation.

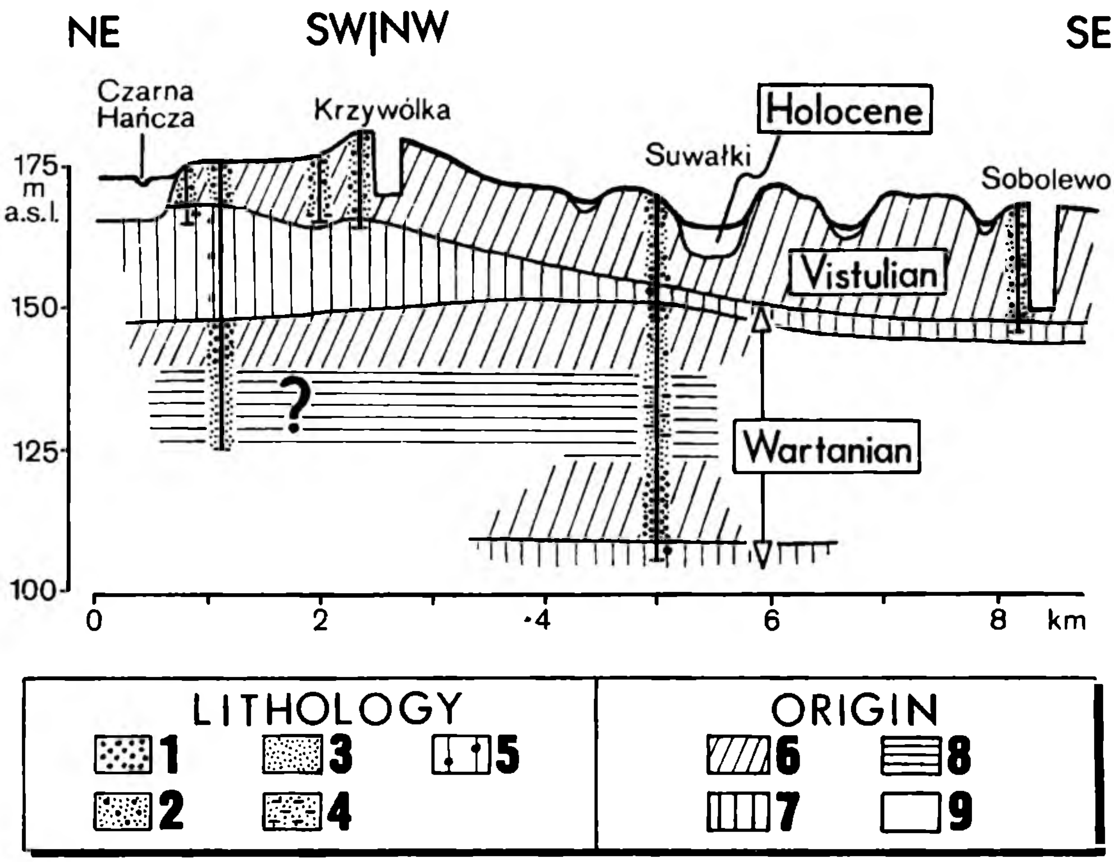

Fig. 2. Geological cross-section through Suwałki area, showing main stratigraphic and genetic units of neo-Pleistocene and Holocene. Lithology: *1* — gravel; *2* —pebbly sand; *3* — sand; *4* — sand and clay; *5* — till. Origin: *6* glacifluvial; *7* — glacial; *8* — glacilacustrine; *9* — alluvial

LITHOFACIES DESCRIPTION AND INTERPRETATION

Lithofacies *Gm*: Massive to faintly stratified gravel

Lithofacies *Gm* was identified in the Suwałki-NE section (Fig. 3). It includes sheet-like beds composed of very poorly sorted, coarse-grained gravel rich in cobble-sized clasts. Most frequently the beds are clast-supported and display a matrix of fine gravel and coarse sand. The beds commonly show a fining-up trend in grain size. Internally, they are massive or, locally, show traces of horizontal stratification. The thickness of the beds averages between 1 and 1.2 m and their lateral extent may exceed 20 m. Imbricated clasts are common. Bedding planes are often delineated by cobble-boulder trains, one-to-two clast thick (Pl. I: 1). Lithofacies *Gm* was also encountered in the Sobolewo section (Fig. 4, Pl. II: 1). Beds average 40—50 cm in thickness and are massive to faintly plane-stratified.

The features of lithofacies *Gm* indicate upper plane-bed to transition flow conditions accompanying the emplacement of the gravel, probably within longitudinal bars. Such bars are known to consist of massive units (McDonald & Banerjee, 1971; Vos & Tankard, 1981), sometimes crudely flat stratified (Smith, 1970; Boothroyd & Ashley, 1975), which show normal grading

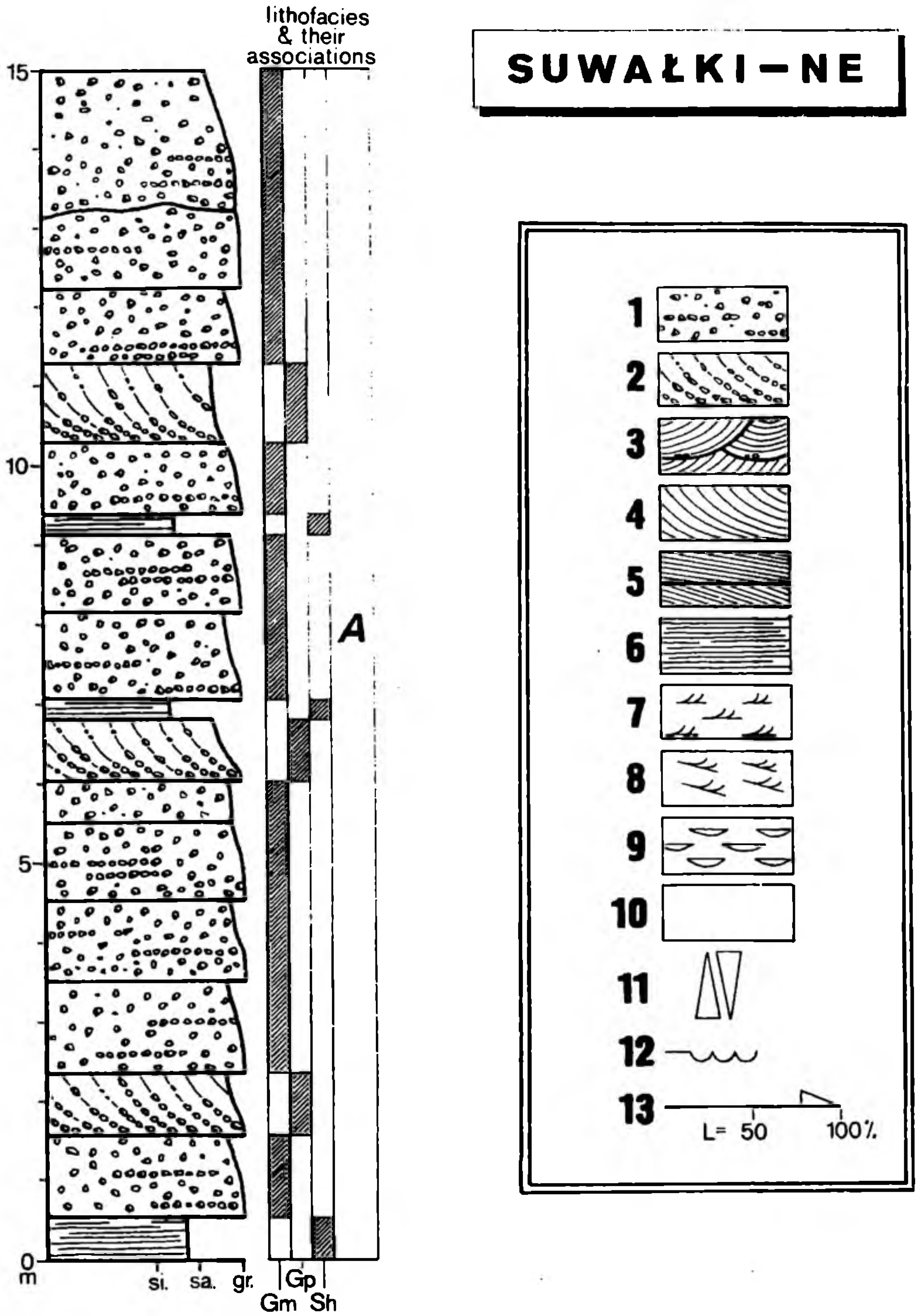

Fig. 3. Synthetic log of Suwałki-NE section. *1* — massive to faintly horizontally stratified gravel; *2* — planar cross-stratified gravel; *3* — trough cross-stratified sand; *4* — horizontally laminated sand; *5* — low-angle laminated sand; *6* — horizontal lamination in sand and mud; *7* — ripple cross-lamination; *8* — climbing ripple-drift cross-lamination; *9* — mud flasers in ripple-laminated sand; *10* — structureless intervals in sand and mud; *11* — normal and inverse grading; *12* — erosion surface; *13* — scale of mean vector magnitude

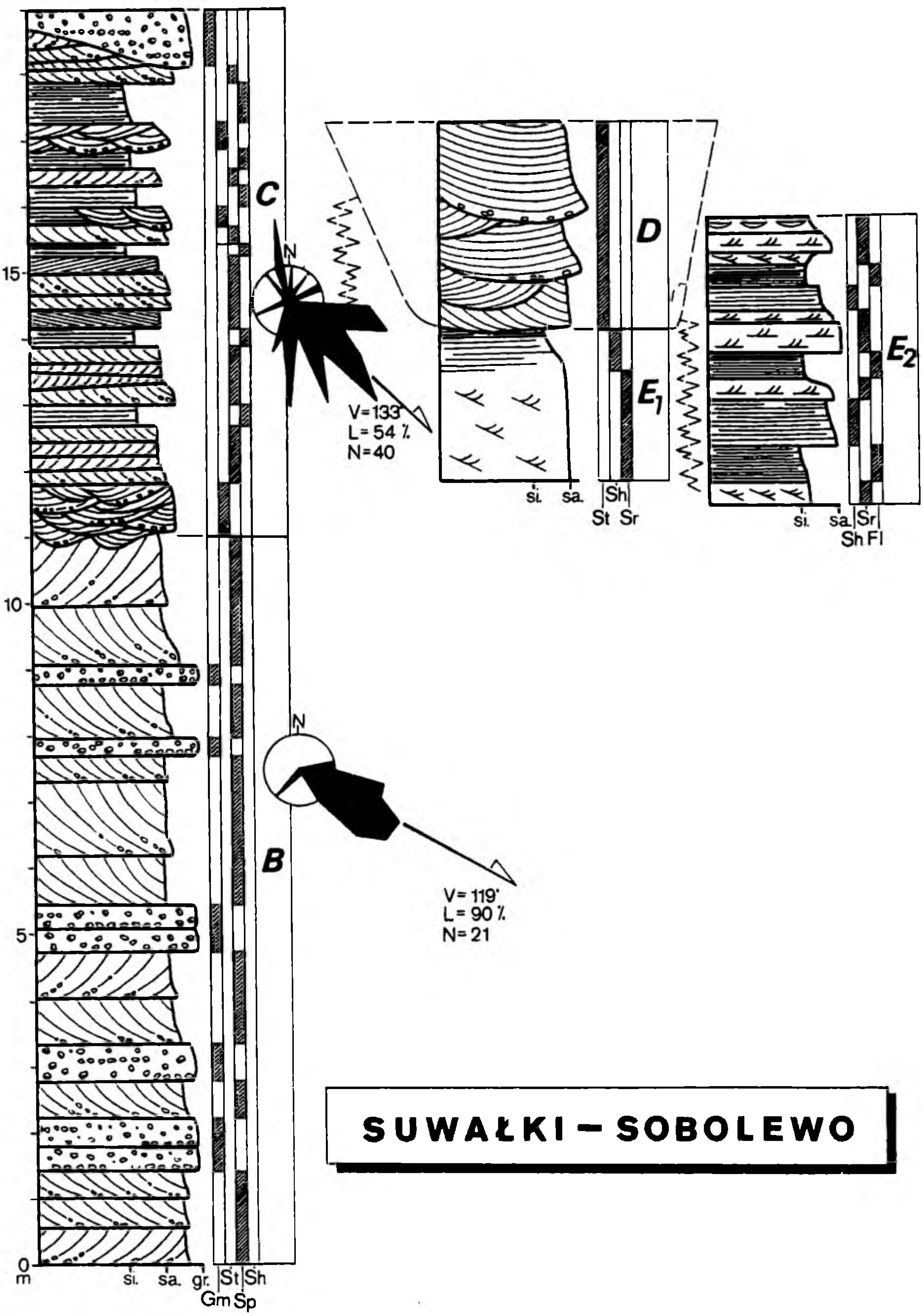

Fig. 4. Synthetic log of Sobolewo section. *V*, *L* – azimuth and magnitude of mean vector derived from orientation of cross-strata, *N* – number of readings; for explanation of other graphs and symbols, see caption of Fig. 3

(Williams, 1971) and common clast imbrication on weakly inclined bar faces (Gustavson, 1974; Boothroyd & Ashley, 1975; Teisseyre, 1975, 1977; Rust, 1978; Vos & Tankard, 1981).

The *Gm* beds undoubtedly represent deposits of a high-energy environment. Williams and Rust (1969) emphasized a genetic relationship of longitudinal bars with strong discharges. Furthermore, Fahnestock (1963) considered indistinct, flat stratification or massive structure, together with poor sorting of the gravel, as features indicative of rapid deposition from high-velocity flows.

The gravel beds of facies *Gm*, occurring as thin intercalations within the sandy sediment, may be interpreted as gravel sheets veneering the floor of a sand-bed channel during high-energy floods. Such veneers are comparable to "diffuse gravel sheets" which are thought to form embryonal cores of longitudinal bars (Smith, 1974; Hein & Walker, 1977).

Lithofacies *Gp*: Planar cross-stratified gravel

Lithofacies *Gp* occurs mainly in the Suwałki-NE locality (Fig. 3), where it alternates with massive gravel units (*Gm*). Beds of lithofacies *Gp* show clast-supported frameworks of cobbles and pebbles and a matrix composed of coarse sand. Beds are up to 1 m thick, several m in length, and commonly exhibit normal grading. Internally, the beds display planar cross-stratification, rarely wedge-shaped cross-sets. In the Sobolewo and Krzywólka sections, beds of this lithofacies average 20 – 30 cm in thickness, are up to 10 m in length, and occur as uncommon intercalations within the sandy sediment (Figs. 4 and 5, Pl. I: 2).

The thick planar cross-stratified beds (Suwałki-NE) are interpreted as genetically related to longitudinal bars. During a falling flood stage, longitudinal bars may grow through foreset accretion, directed both laterally (Costello & Walker, 1972; Smith, 1974; Rust, 1978; Ramos & Sopeńa, 1983) and streamwise (Leopold & Wolman, 1957; Smith, 1970; Boothroyd & Nummedal, 1978). Vos and Tankard (1981) found secondary bedforms, similar to linguoid bars, superimposed on the margins of longitudinal bars. The suggested relationship between the *Gp* and *Gm* units is also supported by their similar thickness ranges, common lateral transitions of one into another, and by the slightly finer gravel size of the *Gp* units (lateral accretion deposits) than that of the *Gm* beds which are interpreted as the cores of longitudinal bars (comp. Smith, 1974; Boothroyd & Ashley, 1975).

The thin, planar cross-stratified beds (Sobolewo and Krzywólka sections) are interpreted as foreset gravel-bar deposits. Such bars must have orginated within sand-bed channels during rising flood conditions. The increased flow's competence maintained transportation of the gravel, while the channel floor developed relief high enough to promote a local foreset accretion. Similar planar cross-stratified gravels were reported from transverse bars (McDonald & Banerjee, 1971; Vos & Tankard, 1981).

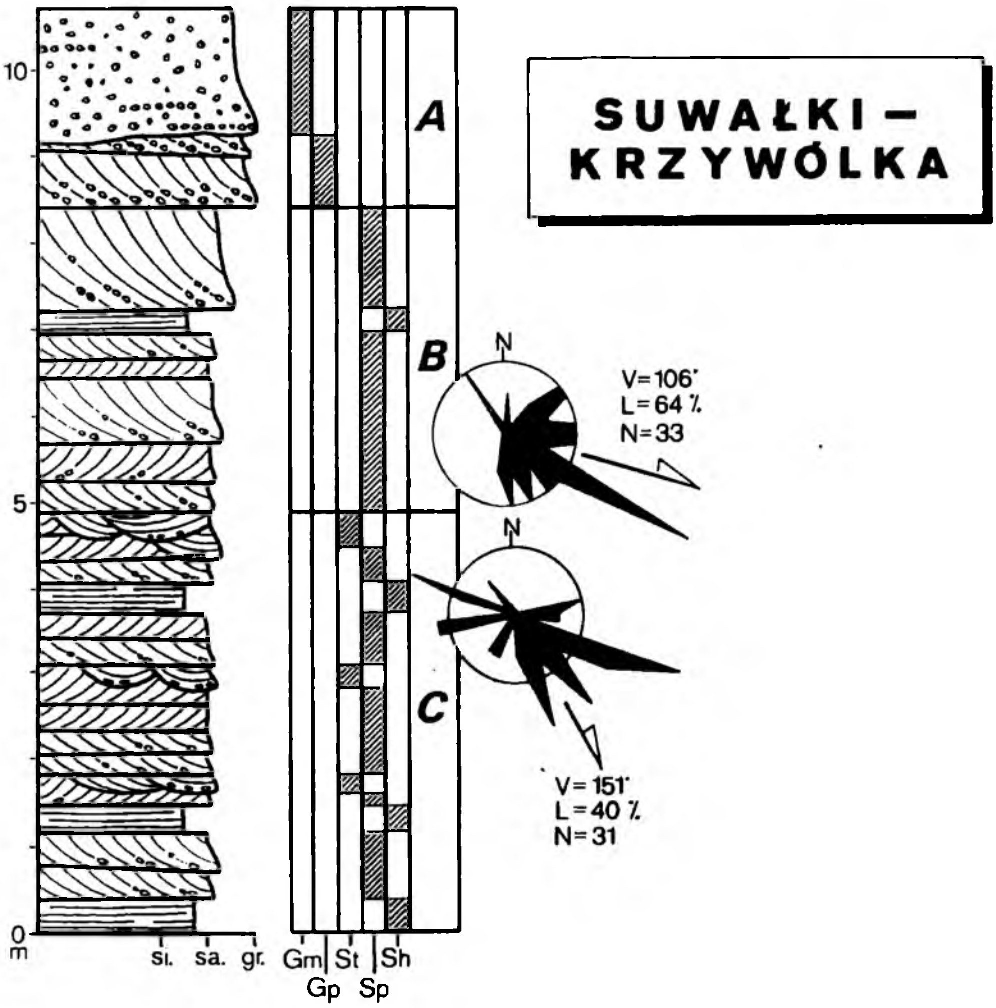

Fig. 5. Synthetic log of Krzywólka section. For explanation see caption of Fig. 3

Lithofacies *St*: Trough cross-stratified sand

Trough cross-stratified sand beds were encountered in the Sobolewo and Krzywólka sections (Figs. 4 and 5). The beds consist of sand and pebbly sand and reveal trough cross-sets, 20 cm thick on the average, and up to 2 m long. In the Sobolewo section there occur also large-scale trough cross-sets, 0.75 – 1.20 m thick and 5 – 7 m long (Pl. II: 2). The floors of these trough scours are lined with gravel, the grain size decreases upwards throughout the trough infill which, itself, may consist of several cross-sets.

The medium-scale (6 – 30 cm thick) trough cross-stratified sand beds are interpreted as produced by migrating three-dimensional dunes. Such dunes are commonly related to the upper part of a lower flow régime. The large-scale variety of lithofacies *St* is interpreted as the product of infilling of local, deep scours. These scours may have orginated in the zone of concentrated flows, possibly in a thalweg. Similar scours were reported from braided streams (Hein & Walker, 1977). Both varietes of lithofacies *St* can be taken as indicative of deposition in deep stream channels.

Lithofacies *Sp*: Planar cross-stratified sand

Lithofacies *Sp* consists of beds of planar cross-stratified pebbly sands (Pl. II: 1). Cross-sets are up to 1.5 m thick, 50 cm on the average, and 10–20 m long. This lithofacies is the dominant element of the Sobolewo and Krzywólka sections (Figs. 4 and 5).

Large-scale planar cross-sets in sand and gravelly sand (Pl. III: 1) represents a bar-derived lithofacies formed due to progradation of the downcurrent slopes of bars. The height of the bars could have reached 1.1 m in Krzywólka and minimum 0.6 m in Sobolewo (see *Appendix*). Their length approached 20 m, as suggested by the downstream extents of the cross-stratified beds. The beds are interpreted as produced by frontal accretion of large transverse bars. This interpretation is consistent with little spread of cross-set dip azimuths, reflected in the values of vector mean magnitude (Curray, 1956) 90 and 64% for the Sobolewo and Krzywólka sections, respectively (Figs. 4 and 5).

Transverse bars are produced in highly unsteady flow conditions which accompany falling flood stages (McGowen & Groat, 1971; Williams, 1971), when the flow becomes overladen with transported sediment (Smith, 1971). Transverse bars are thought to be diagnostic bedforms of sand-bed braided channels (Collinson, 1970; Smith, 1970, 1971, 1972).

Lithofacies *Sh*: Horizontally laminated sand

Sand showing horizontal lamination was encountered in all the sections examined. In the Sobolewo section, horizontal lamination averages 20 cm in thickness and 10 m in lateral extent (Fig. 4, Pl. I: 2) and occurs in medium- and fine-grained sand. In the Krzywólka section lithofacies *Sh* consists of medium, fine and muddy sands that occur in laminated units *c.* 20 cm thick and a few m in lateral extent (Fig. 5). In the Suwałki-NE section, beds of lithofacies *Sh* are rare and include mainly fine-grained sand units showing the same thickness and persistency ranges as those described above (Fig. 3, Pl. I: 1).

The horizontally laminated sand orginated from shallow, relatively fast flows in upper plane-bed conditions and is interpreted as indicating deposition within stream shallows.

Lithofacies *Sr*: Ripple cross-laminated sand

Lithofacies *Sr* was identified in the upper part of the Sobolewo section (Fig. 4), where in occurs in distinct two varietes. The first variety consists of medium and fine-grained sand beds showing ripple-drift cross-lamination (Pl. III: 2). Climbing-ripple sets of A and B_1 types predominate. Cross-laminated sets occur commonly as a part of graded sequences up to 1 m thick. Such a graded sequence commences with erosion surface which is overlain by a horizontal laminae-set (or coset). This passes up, in turn, into a ripple-drift cross-lamination which records the succession of climbing-ripple types: $A \rightarrow B_1 \rightarrow B_2 \rightarrow S$.

The second variety of lithofacies *Sr* comprises fine- and medium-grained sands showing ripple cross-lamination. Cosets are 10–20 cm thick and form lower segments in two-part sequences with silt cappings (Fig. 6).

The ripple-drift cross-laminated beds record predominantly suspension deposition of sand in zones of increased net aggradation. Such zones experienced strong flow-velocity gradients. The trough cross-laminated sand beds reflect predominantly tractional deposition in ripple-phase bed flow conditions.

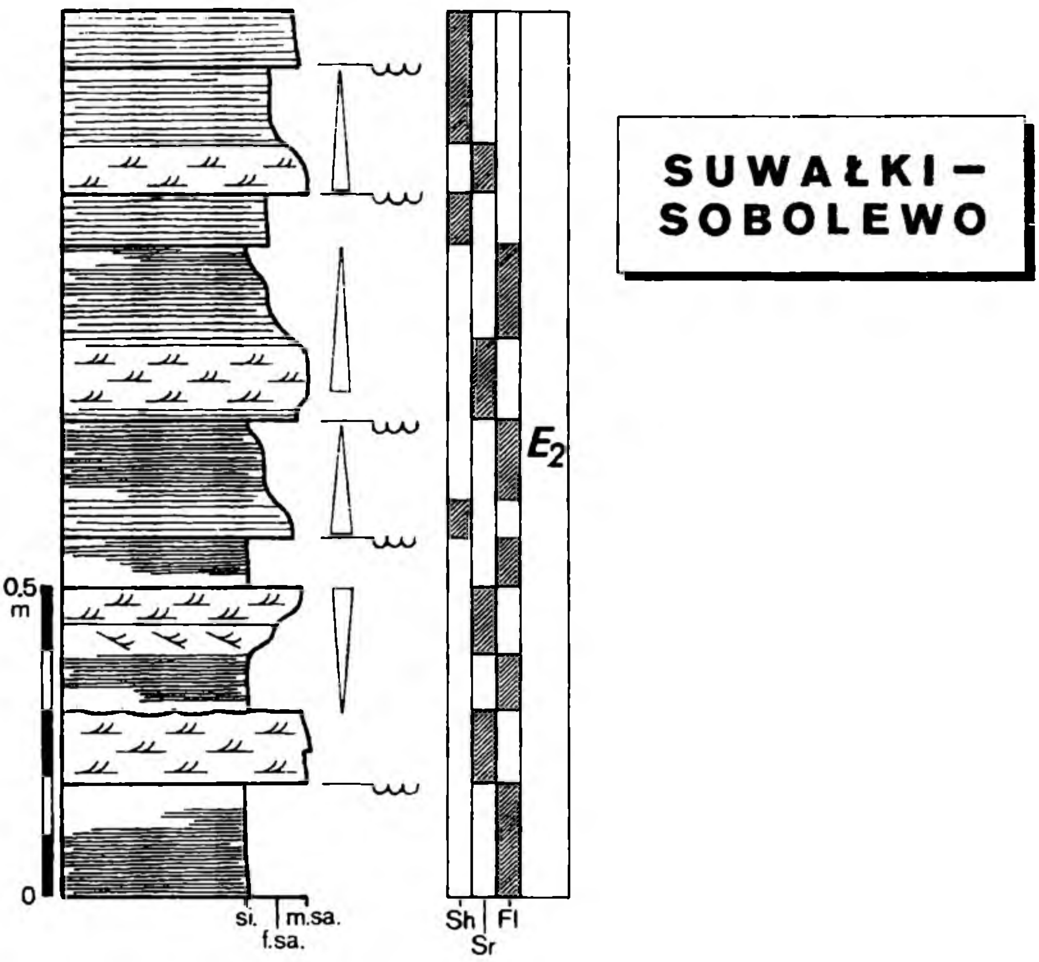

Fig. 6. Detailed log through lithofacies subassociation E_2 in Sobolewo section, showing stacked fining-up cyclothems, each bounded by erosion surface at the base. For explanation see caption in Fig. 3

Lithofacies *Fl*: Laminated mud

Lithofacies *Fl* consists of sandy to clayey muds which are horizontally to wavy laminated. Cosets, 10–30 cm thick, are often normally graded. This lithofacies was encountered in the Sobolewo section where it is intimately associated with lithofacies *Sr* (Fig. 4). Cross-laminated sand units are commonly followed by wavy laminated mud which, in turn, is overlain by horizontally laminated mud. Thus, lithofacies *Fl* forms an upper, fine-grained part of graded rhythms *Sr*→*Fl* (Fig. 6).

The laminated mud orginated from slow suspension fall-out in bodies of stagnant waters. Such bodies typified by high concentrations of suspended fines, should be identified with floodbasin ponds, such as abandoned channels.

LITHOFACIES ASSOCIATIONS

The lithofacies distinguished were assembled into three major facies associations (*A*, *B*, and *C*) and two subordinate ones (*D* and *E*) which are less common and make-up lithosomes of limited lateral extents.

Association *A*: Main channel with longitudinal bar deposits

The association *A* consists of the massive to faintly stratified gravel (*Gm*) and planar cross-stratified gravel beds (*Gp*), with subordinate intercalations of the laminated sand (*Sh*). This association was identified in the Suwałki-NE section (Fig. 3). Palaeohydraulic analysis of the gravel beds from this section (Table 1 and *Appendix*) indicates that these deposits orginated within a deep channel (1.4 – 2.4 m) typified by high discharges (flow velocity 3.0 – 3.9 m s^{-1}; shear stress 42 – 73 N m^{-2}; stream power 126 – 282 N $m^{-1}s^{-1}$).

Deposition of the gravel beds took place at the transition flow conditions ($0.80 < Fr < 0.82$) within longitudinal bars. These developed probably in the main channel of the outwash system. The dominant lithofacies (*Gm*) of this association reflects mainly a vertical aggradation of the bars which were situated in the central parts of the channel. During a falling flood the longitudinal bars may have accreted laterally generating the planar cross-sets (*Gp*). The laminated sand (Sh) reflects upper plane-bed deposition at the bars toes during low water stages (comp. McDonald & Banerjee, 1971; Rust, 1972; Vos & Tankard, 1981).

Association *B*: Sand-bed braided channel with transverse bar deposits

The association *B* is characterized by the predominance of planar cross-stratified sands (*Sp*), subordinately interbedded with massive gravels (*Gm*) (Fig. 4, Pl. II: 1) and laminated sands (*Sh*) (Fig . 5). This association is thought to reflect deposition in a sand-bed braided channel carrying transverse bars. The gravel beds resulted from the development of thin, gravel sheets veneering the channel floor during frequent, short-term floods. The sheets were deposited at the transition to upper flow regime (see Table 1). It is also likely that the sheets orginated within zones of confined flows which existed between transverse sand bars. The common alternation of the *Sh* and *Gm* beds in the Sobolewo section testifies highly unsteady melt-out discharges and a strong topographic variability of the channel floors.

The association *B* orginated mainly due to progradation of transverse bars.

Table 1

Palaeohydraulic summary for the main lithofacies associations of the Suwałki outwash

Site	Litho-facies associa-tions	Lithofacies	Depth D [m]	Velocity V [m s^{-1}]	Froude number Fr	Shear stress τ [N m^{-2}]	Stream power (per unit width) ω [N m^{1} s^{-1}]
Sobolewo	D	*St* (pool fill)	<1.2	<1.8	0.52	<36	<66
	C	*Sp* (transverse bar)	0.4	0.9	0.45	12	11
		St (3-dimensional dunes)	0.8	1.5	0.55	24	38
	B	*Sp* (transverse bar)	≥0.6	≥1.1	0.45	≥18	≥20
		Gm (upper plane bed)	0.7	2.1	0.83	20	43
Krzywólka	B	*Sp* (transverse bar)	1.1	1.6	0.51	33	54
	C	*Sp* (transverse bar)	0.3	0.8	0.45	10	8
		St (3-dimensional dunes)	0.7	1.6	0.60	21	33
Suwałki NE	A	*Gm* (longitudinal bar)	1.4–2.4	3.0–3.9	0.80–0.82	42–73	126–282

Such macro-bedforms are commonly considered as the main factor contributing the braiding of channeled discharges. Therefore, the association *B* is interpreted as the deposit of a classical braided channel.

Association *C*: Shallow braided channel deposits

The association *C* is dominated by planar cross-stratified sands (*Sp*), interbedded with horizontally laminated sands (*Sh*) and, subordinately with trough cross-stratified sands (*St*) (Figs. 4 and 5). It differs from the association

B in having the *St* interbeds, showing lower bed thicknesses, and in displaying a greater dispersion of cross-set dip azimuths (Figs. 4 and 5).

Major depositional forms of the association *C* were transverse sand bars. They were smaller than those inferred from the *Sp* beds in the association *B*. The height of the former bars did not probably exceed 40 cm, suggesting that the bars orginated in relatively shallow channels (see Table 1). This conclusion is also consistent with the high proportion of the laminated sand beds, whose shallow depth was probably the main contributing factor to high Froude number values. The trough cross-stratified beds (*St*) resulted from migration of three-dimensional dunes which developed in deep channel flows, possibly in the thalweg. The relatively low concentration of palaeoflow directions in the association *C* may be explained by deposition of sand in a shallow channel during low-stage flows. In such conditions the bar tops became emerged and the single, large braided channel was replaced by a series of small channels of a higher sinuosity.

The medium-scale trough cross-cosets occurring at the top of some planar cosets (see Fig. 5) are indicators of local changes in hydrodynamic conditions. The trough-shaped scours were generated on the bar-tops during a falling flood stage, when the lateral accretion was limited already. This structural superposition is one of very few ordered sequences identified in the channel deposits of the Suwałki outwash.

It is thus concluded that the association *C* orignated from deposition in shallow, sand-bed braided channels. Their floors were dominated by upper plane-bed zones separated by transverse bars, whereas the channel pools contained three-dimensional dunes.

Association *D*: Catastrophic flood channel-infill

The association *D* consists almost exclusively of large-scale trough cross-beds (*St*), intercalated sporadically by smaller-scale trough cross-sets (Pl. II: 2). This association was identified in the upper part of the Sobolewo section, where it occurs as ribbon sand bodies incised within fine-grained deposits of the association *E* (Fig. 4).

These deep scour infills are interpreted as fossil palaeochannels which orginated during meltwater peak floods. Such floods represented short-lived, catastrophic events during evolution of the Suwałki outwash plain. They were probably comparable with the peak discharges of modern, summer proglacial floods which are known to exceed 20 to 50-times the low-water flows (Fahnestock, 1963; Smith, 1974; Forbes, 1983).

Association *E*: Abandoned channel deposits

The association *E* consists of fine-grained lithofacies and was identified in the Sobolewo section (Fig. 4). It is subdivided into two varieties differring each other in the bulk grain size.

The subassociation E_1 consists of ripple cross-laminated fine sands (*Sr*) interbedded with horizontally laminated muddy sands (*Sh*). It was laid down in a low-energy environment dominated by suspension sedimentation from low-competence flows (climbing ripple, wavy and flat lamination). Such flows, overladen with fine sand and mud, could have been induced by floods in the areas lying off main glacifluvial tracts. The subassociation E_1 may therefore result from a terminal filling of cut-off channels as well as from deposition in the distal reaches of subaqueous fans growing into abandoned channels. Similar lithofacies assemblage was recorded in glacifluvial fans prograding into an ice-crevasse lake (Lewandowski & Zieliński, 1980).

The association E_2 consists of laminated muds (*Fl*) and cross-laminated fine sands (Sr) arranged into stacked, fining-up sequences *Sr*→*Fl* (Fig. 6). These two-part sequences orginated due to a repeated inflow of melt-waters into abandoned outwash channels. Each melt-water flood cycle included a similar series of events, involving sand deposition from a low-energy flow in ripple-phase bed conditions, followed by waning of the flow and slow-suspension settling of mud in standing waters. The common stacking of these sequences is easily explicable in terms of outwash-plain hydrology which is typified by the high recurrence of melt-out floods, both in a daily and seasonal cycle.

It is likely that the both subassociations identified in the Sobolewo section orginated simultaneously in different reaches of the same abandoned channel – E_1 in its proximal (nearshore) part and E_2 in its central, deeper part.

THE SUWAŁKI OUTWASH PLAIN

The lithofacies associations described above are the product of an outwash channel system. The Sobolewo and Krzywólka sections are similar in being dominated by the associations *A* and *B*. These deposits orginated in the sand-bed braided channels, mainly due to lateral accretion of transverse bars. The high thickness variability of the planar cross-sets (*Sp*) within these sections points to highly variable melt-out discharges.

The facies associations *B* and *C* are comparable to the alluvial sequence inferred from the Platte River – a classical sand-bed braided stream (*cf.* Smith, 1970). This similarity lies mainly in the abundance of the transverse bar-derived lithofacies *Sp*. The outwash plain in the Sobolewo-Krzywólka areas was dominated by deposition within transverse bars – a common feature of modern sand-bed outwash channels (McDonald & Banerjee, 1971; Boothroyd & Nummedal, 1978; Casshyap & Tewari, 1982; Fraser & Cobb, 1982). The sand-bed, commonly shallow channels, inferred for the Sobolewo and Krzywólka sections, are interpreted as secondary streams of the Suwałki outwash.

Particular subenvironments were highly transient within the outwash system. This is suggested by an "inversion" of stratigraphic positions of the associations *B* and *C* in the sections considered (Figs. 4 and 5). Furthermore, the Sobolewo section shows a number of lateral transitions between the (sub)associations *C*, *D*, E_1 and E_2 (Fig. 4). Within a short distance, the shallow channel deposits (*C*) contact laterally with abandoned channel infills (E_1 and E_2) which, in turn, are dissected by deep-scours filled with the deposits of catastrophic floods (*D*). This close coexistence of the deposits representing subenvironments of drastically different energy levels also evidences the high transiency of particular subenvironments of the outwash system.

The main associations of the Suwałki outwash are typified by the remarkable scarcity of fine-grained suspension deposits and those generated in ripple-phase bed configurations. This is consistent with Church and Gilbert's (1975) view on the high-energy nature of glacifluvial environment.

Table 1 shows results of palaeohydraulic analysis performed for the Sobolewo and Krzywólka sections. The association *C* in both sections shows the lowest values of stream depth, flow velocity and stream power. The association *D* (catastrophic flood channel-fill) reveals the highest values of these parameters among all sand-dominated associations of the Suwałki outwash.

The association *A* (Suwałki-NE) is interpreted as having been related to the main, gravel-bed channel of the outwash system. Palaeohydraulic characteristics (Table 1) support earlier conclusion that these deposits orginated within a deep channel from high-energy flows. The massive bed accreted as low-relief longitudinal bars in conditions of the upper plane-bed flow. The comparison of stream power (per unit width) values calculated for the main associations clearly reflects a strong contrast in the energy level between the associations *B* and *C* and the association *A*. ω values for the former are 6-times lower than for the latter (Table 1). This difference can be explained by the hydrological nature of a dispersed channel system. Outwash plains normally have one to three main channels and many secondary ones (Krigström, 1962; Boothroyd & Nummedal, 1978; Maizels, 1983).

Assuming a tri-partition of an outwash system into proximal, medial and distal zones, it can be concluded that the sections analysed were situated in the proximal segment of the Suwałki outwash plain. Such an interpretation is suggested by the high values of hydraulic parameters (especially for association *A*). These values correspond perfectly to those calculated for modern proximal streams of Alaska outwash plains (Boothroyd & Ashley, 1975).

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APPENDIX

For planar cross-stratified sands palaeohydraulic analysis starts with estimation of bedform height (h). Thickness of planar cross-sets (t_p), formed by lateral accretion of transverse bars, is comparable with bar height (h_b):

$$h_b \simeq t_p, \qquad \text{(Williams, 1971)} \qquad (1)$$

$$0.8h_b = t_p \text{max.} \qquad \text{(Saunderson \& Jopling, 1980)} \qquad (2)$$

The height of bars was estimated as the mean obtained from Eqs. 1 and 2.

The *depth* (D) of depositional channel was taken as equal to the height of channel bars:

$$D \simeq h_h \qquad \text{(Friend \& Moody-Stuart, 1972; Klimek, 1972; Eynon \& Walker, 1974)} \qquad (3)$$

For trough cross-stratified sands another method of channel depth estimation was used. Trough cross-sets of medium scale (i.e. 6—30 cm in thickness) reflect erosional-depositional processes on the channel bed covered with three-dimensional dunes. The height of dunes (h_d) was estimated as the mean obtained from equations:

$$h_d = 2\ t_t, \qquad \text{(Simons \& Richardson, 1962)} \qquad (4)$$

$$h_d = 1.5\ t_t, \qquad \text{(Cant, 1978)} \qquad (5)$$

where t_t — thickness of trough cross-sets.

After Simons & Richardson (1962) and Harms & Fahnestock (1965), it was taken that the depth of flow over three-dimensional dunes is approximately twice as the height of the dunes:

$$D \simeq 2\ h_d \qquad (6)$$

Mean flow velocity $\bar{V}$ [m s^{-1}] was estimated according to Manning's formula:

$$\bar{V} = n^{-1} R^{2/3} S^{1/2}, \qquad (7)$$

where: n [dimensionless] — Manning's roughness coefficient; R [m] — hydraulic radius, for shallow and broad braided channels $R \simeq D$; S [dimensionless] — channel slope. Roughness régime was evaluated according to bedforms interpreted from sedimentary structures. n values corresponded to the appropriate bedforms were taken from data of Simons & Richardson (1961) and Albertson & Simons (1964). Slope of outwash channels was assumed to be the same as the slope of glacifluvial terrace in the Czarna Hańcza valley ($S = 0.0031$). It seems that such approach is justified, because (1) the analysed sediments make up a near-surface part of the glacifluvial body, and (2) outwash channels are normally characterized by a low-sinuosity pattern, hence their slope is comparable with the slope of the present-day surface of the outwash plain.

Values of depth and velocity of palaeoflow, obtained from Eqs. 3, 6 and 7, were used to estimate *Froude number*:

$$Fr = \bar{V}(g\bar{D})^{-0.5}, \qquad (8)$$

where g [m s^{-2}] — acceleration of gravity. From Fr values it was possible to establish flow régimes and to verify former paleohydraulic calculations. Flow régime fields can be identified from a bed state and the latter be deduced from sedimentary structures. Thus it could easily be tested, if Fr values estimated from Eq. 8 correspond to those (*cf.* Simons & Richardson, 1966).

Stream power (per unit width) ω [N m^{-1} s^{-1}] defines energy level of flow:

$$\omega = \tau\bar{V}. \qquad (9)$$

Shear stress τ [N m^{-2}] was evaluated from Shields' graph (see Church & Gilbert, 1975, fig. 17b). The 90th percentile read from cumulative grain-size plots was taken as d. Shear stress was also estimated from equation:

$$\tau_{cr} = \gamma RS, \qquad (10)$$

where γ [N m^{-3}] – specific weight of water (for proglacial streams $\gamma = 9820$ N m^{-3} after Boothroyd & Ashley, 1975).

* * *

Other equations were employed for gravelly deposits. Because these occur mostly in massive or horizontally stratified beds, Eqs. 1 to 6 were useless for paleoflow depth estimations. Thus Du Boys' equation (10) was employed, where R (i.e. D) was the sole unknown variable. τ_{cr} values were taken as the average from traditional Shields' formula and from the following empirical functions:

$$\tau_{cr} = 0.0801 d_{75}, \text{ for } d > 5 \text{ mm}, \quad \text{(Lane, 1953)} \quad (11)$$

$$\tau_{cr} = 0.0774\ d, \quad \text{(Bogardi, 1974)} \quad (12)$$

$$\tau_{cr}^{1.58} = d_{96}/18.28, \text{ for } d > 10 \text{ mm}, \quad \text{(Carling, 1983)} \quad (13)$$

where: τ_{cr} [kG m^{-2}], d [mm].

Palaeoflow velocities were estimated from Eq. 7 in which n was replaced by *grain roughness coefficient* n_g.

$$n_g = 0.03779 d^{1/6}, \text{ where } d \text{ [m]}. \quad \text{(Strickler, 1923)} \quad (14)$$

Froude number and stream power values (Fr and ω) were estimated from Eqs. 8 and 9.

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Streszczenie

LITOFACJALNA I PALEOŚRODOWISKOWA CHARAKTERYSTYKA OSADÓW SANDRU SUWALSKIEGO (PLEJSTOCEN, PÓŁNOCNO-WSCHODNIA POLSKA)

Tomasz Zieliński

Obiektem analizy sedymentologicznej są piaszczysto-żwirowe osady sandru suwalskiego związane z zanikiem lądolodu stadiału pomorskiego zlodowacenia Wisły. Analizie poddano trzy duże odsłonięcia: Suwałki-NE, Sobolewo, Krzywólka (Fig. 1, 2). W stanowiskach tych wyróżniono siedem litofacji, które określono symbolami kodu litofacjalnego wg Mialla (1977, 1978) i Rusta (1978). Wydzielone litofacje zgrupowano w pięciu zespołach, które odzwierciedlają subśrodowiska sedymentacyjne i stanowią podstawę w rekonstrukcji paleośrodowiskowej sandru suwalskiego.

Litofacje

Żwirowe ławice masywne lub o niewyraźnym warstwowaniu poziomym (Gm). Są to ławice płaskorównoległe wielkiej skali. Dominuje materiał frakcji żwiru średnio- i gruboziarnistego. Pospolite są sekwencje normalnego uziarnienia frakcjonalnego (Fig. 3), a materiał żwirowy często wykazuje ułożenie imbrykacyjne. Litofacja *Gm* powstała w efekcie depozycji żwirów w stanie górnego płaskiego dna. Głównymi formami depozycyjnymi ławic o dużej miąższości (Pl. I: 1) były odsypy (łachy) podłużne. Cieńsze ławice (Pl. II: 1) odzwierciedlają akumulację żwirowych pokryw dennych. Jest to litofacja powstała w warunkach zdecydowanie wysokoenergetycznego przepływu.

Żwirowe ławice o płaskich warstwowaniach przekątnych (*Gp*). Litofacja ta jest nieco bardziej drobnoziarnista w stosunku do *Gm*. Żwiry najczęściej wykazują strukturę przekątnego warstwowania tabularnego (Pl. I: 2). Litofacje *Gp* i *Gm* współwystępują ze sobą, przechodząc niekiedy obocznie nawzajem. Litofacja *Gp* interpretowana jest jako efekt bocznego (i dystalnego) przyrostu odsypów podłużnych w etapach opadania wód wezbraniowych.

Piaszczyste zestawy przekątnego warstwowania rynnowego (*St*). Piaszczyste i piaszczysto-żwirowe jednostki *St* są dwojakiego rodzaju: zestawy rynnowe średniej skali (o przeciętnej miąższości 20 cm) oraz wielkoskalowe (o miąższości 0,75 – 1,20 m). Zestawy *St* średniej skali powstały w efekcie procesów erozyjno-depozycyjnych zachodzących w warunkach dna pokrytego diunami (dużymi riplemarkami) trójwymiarowymi. Zestawy *St* wielkiej skali (Pl. II: 2) to efekt lokalnych, głębokich rozmyć dna powstałych w okresach intensywnych przepływów. Litofacja *St* została uznana jako wyznacznik depozycji w głębokim korycie.

Piaszczyste zestawy przekątnego warstwowania tabularnego (*Sp*). Są to najczęściej jednostki wielkiej skali (Pl. II: 1), a ich frekwencja w sandrowych osadach piaszczystych jest bardzo duża (Fig. 4, 5). Zestawy tabularne genetycznie związane są z odsypami poprzecznymi. Powstały w efekcie dystalnej progradacji frontów depozycyjnych tych odsypów typowych dla piaskodennych koryt roztokowych.

Piaski laminowane poziomo (*Sh*). Są to piaski średnio-, drobnoziarniste i mułowe. Litofacja *Sh* powstała w warunkach przepływów nadkrytycznych lub doń przejściowych (stan górnego płaskiego dna). Wysoka wartość liczby Froude'a spowodowana były zapewne małymi głębokościami przepływu. Litofacja *Sh* uznana jest więc jako wyznacznik depozycji w strefach płycizn korytowych.

Piaski o przekątnej laminacji riplemarkowej (*Sr*). Piaski średnio- i drobnoziarniste występują w formie wielozestawów laminacji riplemarków wstępujących. Często są to sekwencje normalnego uziarnienia frakcjonalnego, których architektura strukturalna (Pl. III: 2) sugeruje depozycję z zamierających przepływów. Występują również wielozestawy małoskalowej (riplemarkowej) laminacji rynnowej. Litofacja *Sr* reprezentuje warunki niskoenergetycznych, najprawdopodobniej płytkich przepływów,

Muły laminowane poziomo (*Fl*). Piaszczyste, bądź ilaste muły *Fl* powstały w warunkach depozycji zawiesinowej w wodach stagnujących. Duża koncentracja drobnoziarnistej zawiesiny utożsamiana jest z ośrodkiem wód powodziowych gromadzących się w obniżeniach równi aluwialnej (np. stagnujących w nieczynnych korytach).

Zespoły litofacji

Wyróżniono trzy dominujące zespoły (*A*, *B*, *C*) oraz dwa zespoły drugorzędne (*D*, *E*).

Zespół A składa się głównie z litofacji *Gm* i *Gp*, a podrzędnie zawiera litofację *Sh* (Fig. 3). Zespół *A* reprezentuje depozycję gruboziarnistą w głównym korycie roztokowego systemu fluwialnego. Wyniki analizy paleohydraulicznej (Tab. 1) wykazały, że osady te związane są z głębokimi, intensywnymi przepływami. Zespół *A* powstał głównie z pionowego przyrostu odsypów podłużnych (*Gm*), które niekiedy rozrastały się również na boki (*Gp*). W okresach stanów wód niskich deponowane były osady piaszczyste (*Sh*).

Zespół B jest zdominowany przez litofację *Sp*. W profilu Sobolewa (Fig. 4) wraz z litofacją *Sp* współwystępuje litofacja *Gm*. W korycie roztokowym dominowały piaszczyste odsypy poprzeczne (geneza litofacji *Sp*). W okresach częstych, krótkotrwałych wezbrań dochodziło do wyścielania dna koryta pokrywami żwirowymi (*Gm*). W Krzywólce zespół *B* wykształcony jest niemal wyłącznie w postaci wielozestawów tabularnych *Sp* (Fig. 5). Zespół *B* uznany jest jako osad klasycznego, piaskodennego koryta roztokowego.

Zespół C składa się z litofacji *Sp*, *Sh* i *St*. Zarówno w stanowisku Sobolewo i Krzywólka (Fig. 4, 5) dominują w tym zespole zestawy tabularne *Sp* — związane z odsypami poprzecznymi. Zarówno ich ograniczona miąższość, jak i współobecność litofacji *Sh* (identyfikowanej z przepływami o małej głębokości), dowodzą, że zespół *C* reprezentuje subśrodowisko płytkiego, piaskodennego koryta roztokowego. Depozycyjna rola diun (litofacja *St*) ograniczona była do centralnych, głębszych partii koryta.

Zespół D składa się niemal wyłącznie z zestawów *St* wielkiej skali (Fig. 4). Głębokie rozmycia dna powstały zapewne w okresach katastrofalnych wezbrań, które są typowe dla hydrologicznych reżimów fluwioglacjalnych.

Zespół E utworzony jest przez drobnoziarniste litofacje *Sr*, *Sh* i *Fl*. Wyróżniono dwie odmiany tego zespołu: E_1 oraz E_2 (Fig. 4). Zespół E_1 współtworzą litofacje *Sr* i *Sh*. Osad ten w znacznym stopniu powstał z piaszczystej depozycji zawiesinowej (riplemarki wstępujące). Warunki dużych gradientów prędkości przepływu autor łączy ze strefami kontaktu wód powodziowych ze zbiornikami nieczynnych (odciętych) koryt. Zespół E_2 ma najczęściej postać frakcjonalnych cyklotemów *Sr*→*Fl* (Fig. 6). Każdy cyklotem jest efektem wpływu wód powodziowych na depozycję w nieczynnym korycie. Człon dolny (*Sr*) znaczy etap piaszczystej depozycji prądowej z ekstremum wezbrania, natomiast wyższy człon *Fl* powstał z depozycji zawiesinowej w rozlewisku wód stagnujących.

Środowisko sedymentacji sandru suwalskiego

Profile Sobolewa i Krzywólki (Fig. 4, 5) wykazują wiele podobieństw. Dominują tam zespoły *B* i *C*. Na ich genezie zaważyły odsypy poprzeczne — główne formy depozycyjne piaskodennych koryt roztokowych. Zespoły

B i *C* powstały w stosunkowo płytkich korytach, które identyfikowane są z drugorzędnymi arteriami roztokowego systemu fluwialnego.

Obraz litologiczny odsłonięć Sobolewa i Krzywólki sugeruje, że poszczególne subśrodowiska sedymentacyjne były silnie zmienne w obrębie sandru. Z tego powodu w profilach odsłonięć istnieje duża zmienność kolejnych zespołów litofacji, a w górnej części profilu Sobolewa (Fig. 4) mamy do czynienia z obocznym współwystępowaniem kilku zespołów: *C*, *D*, E_1, E_2. Na niewielkiej przestrzeni litosomu sandrowego zespół płytkiego koryta (*C*) przechodzi obocznie w niskoenergetyczne zespoły nieczynnych koryt (E_1 i E_2), a te rozcięte są korytami katastrofalnych wezbrań ablacyjnych (*D*).

Zespół *A* stanowiska Suwałki-NE (Fig. 3) kontrastuje wyraźnie z zespołami Sobolewa i Krzywólki. Należy go łączyć z subśrodowiskiem głównego, wysokoenergetycznego koryta sandrowego systemu fluwialnego. Główną rolę depozycyjną pełniły tam żwirowe odsypy podłużne.

Wspomniane różnice między zespołem *A* (Suwałki-NE) oraz zespołami *B*, *C* (Sobolewo, Krzywólka) znajdują odzwierciedlenie w wartościach parametrów paleohydraulicznych (Tab. 1). Różnice energetyczne między subśrodowiskiem drugorzędnych i głównych koryt obrazuje dobrze parametr jednostkowej mocy przepływu (ω). Dla zespołów *B* i *C* przyjmuje on wartość niemal 6-krotnie niższą w stosunku do zespołu *A*. Również parametry głębokości (*D*) i prędkości (*V*) przepływu oraz naprężenia ścinającego (τ) wyraźnie różnicują warunki hydrodynamiczne panujące w głównym i w drugorzędnych korytach.

Parametry hydrauliczne, wyliczone dla zespołu *A*, pozwalają stwierdzić, że paleoprzepływ głównego koryta sandru suwalskiego odpowiada warunkom hydrodynamicznym środowiska sandru proksymalnego (porównanie z danymi Churcha & Gilberta, 1975).

Autor sądzi, że główne zespoły litofacji sandru suwalskiego (tj. *A*, *B*, *C*) należy uznać za typowe dla środowiska koryt proglacjalnych. Co za tym idzie, mogą one być pomocne w określaniu fluwioglacjalnej genezy osadów występujących w innych, mniej czytelnych sytuacjach geologicznych.

EXPLANATIONS OF PLATES

Plate I

1 — Coarse gravel massive beds (*Gm*) intercalated with lense of horizontally laminated sand (*Sh*). Channel gravel lag is visible at top of photo. Association *A* in Suwałki-NE locality. Ruler is 30 cm long

2 — Planar cross-stratified gravel bed (*Gp*) overlain by sand bed showing horizontal lamination (upper plane bed) and low-angle cross-stratification. Association *C* in Sobolewo section. Ruler is 30 cm long

Plate II

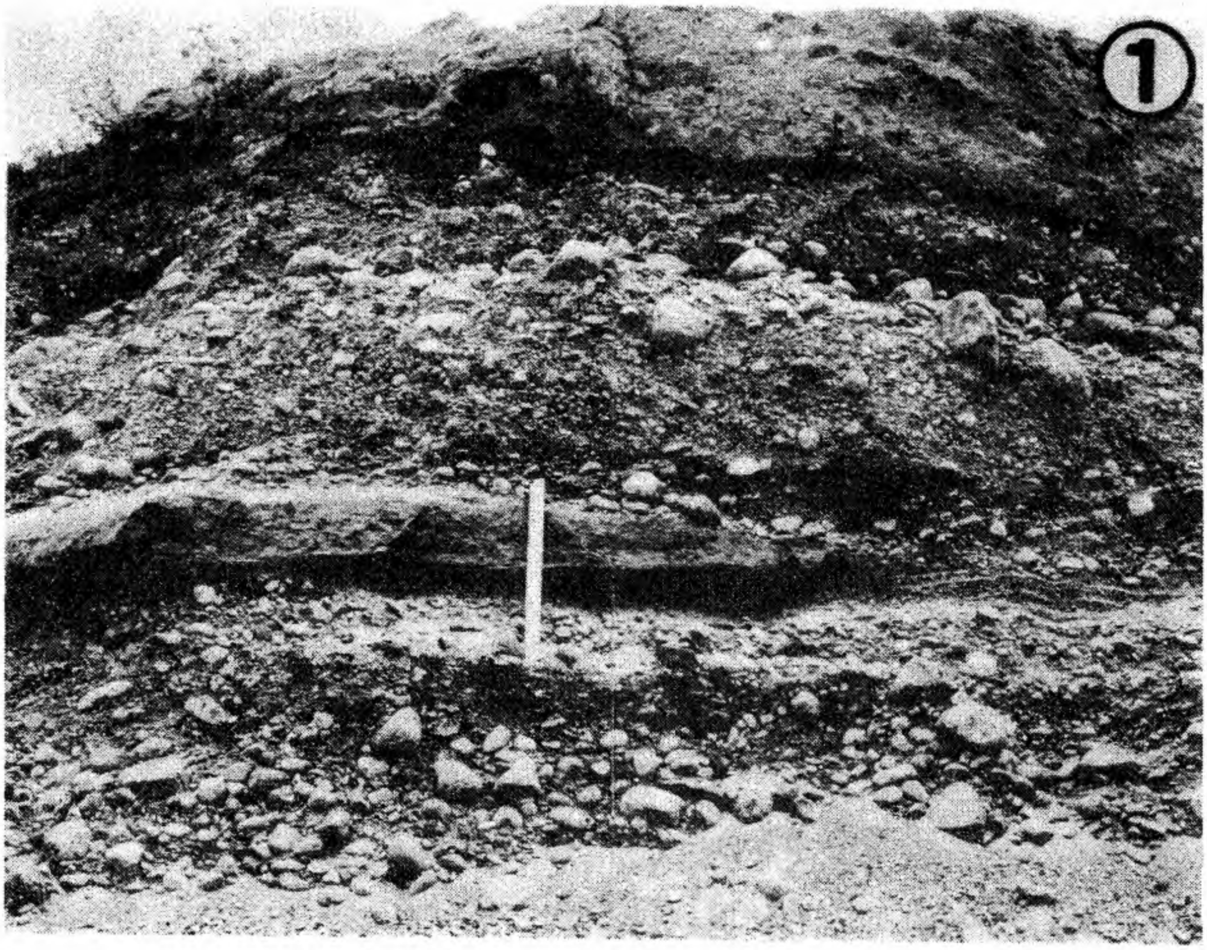
1 — Large-scale planar cross-stratified sand (*Sp*) followed upwards by gravel sheets showing massive structure or indistinct horizontal stratification (*Gp*). Association *B* in Sobolewo section

2 — Large-scale trough cross-coset (*St*). Association *D* in Sobolewo section

Plate III

1 — Planar cross-coset in pebbly sand (*Sp*) followed upwards by faintly horizontally stratified sandy gravel bed (*Gm*). Association *B* in Krzywólka section. Ruler is 30 cm long

2 — Climbing ripple-drift cross-lamination in fine sand, showing the vertical succession of climbing-ripple types $A \rightarrow B_1 \rightarrow B_2 \rightarrow S$. Subassociation E_1 in Sobolewo section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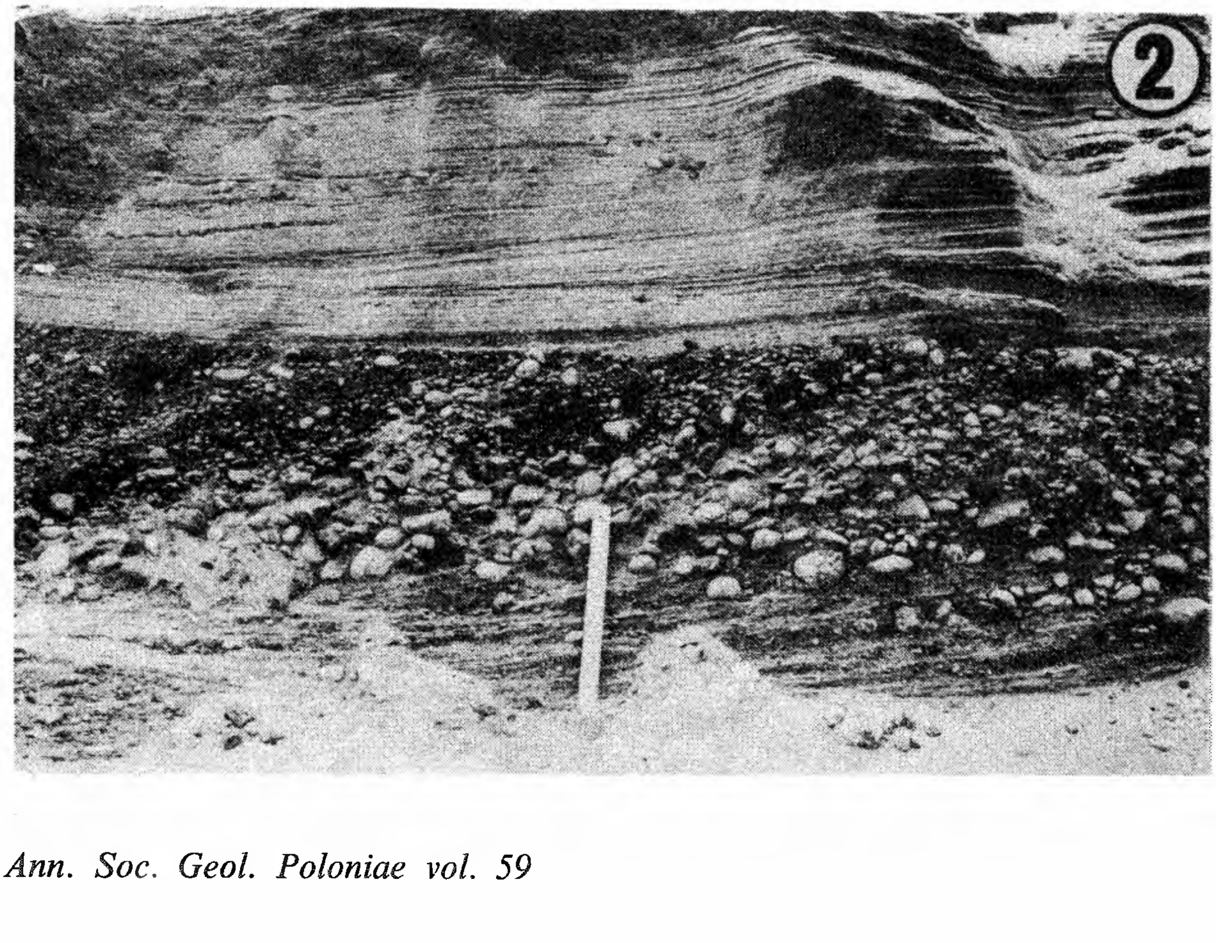
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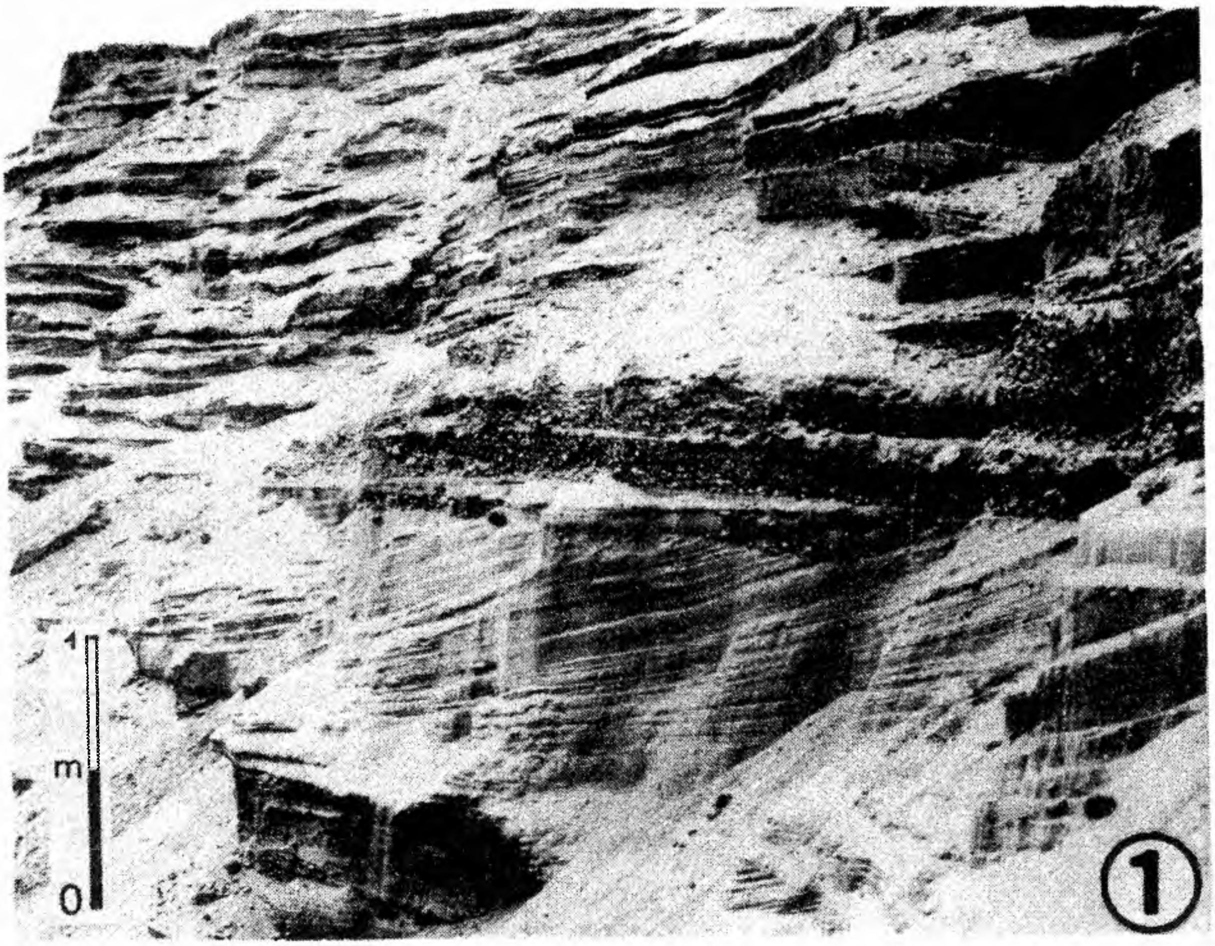
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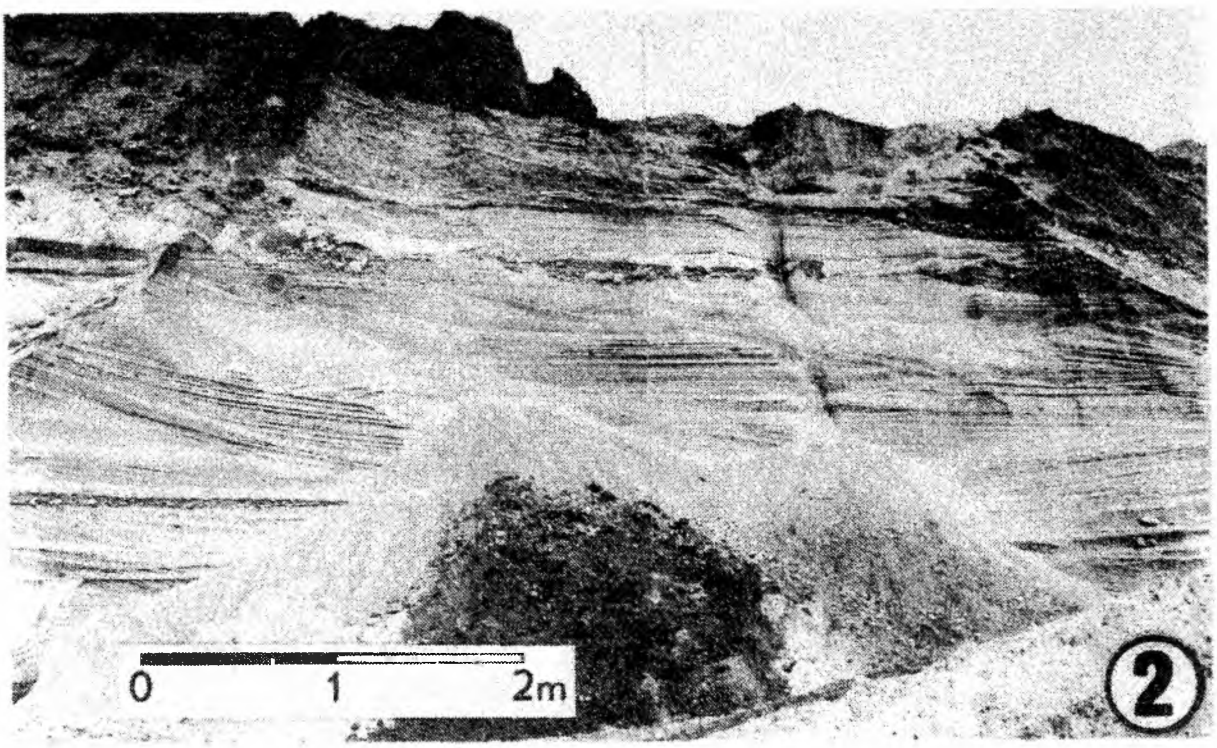
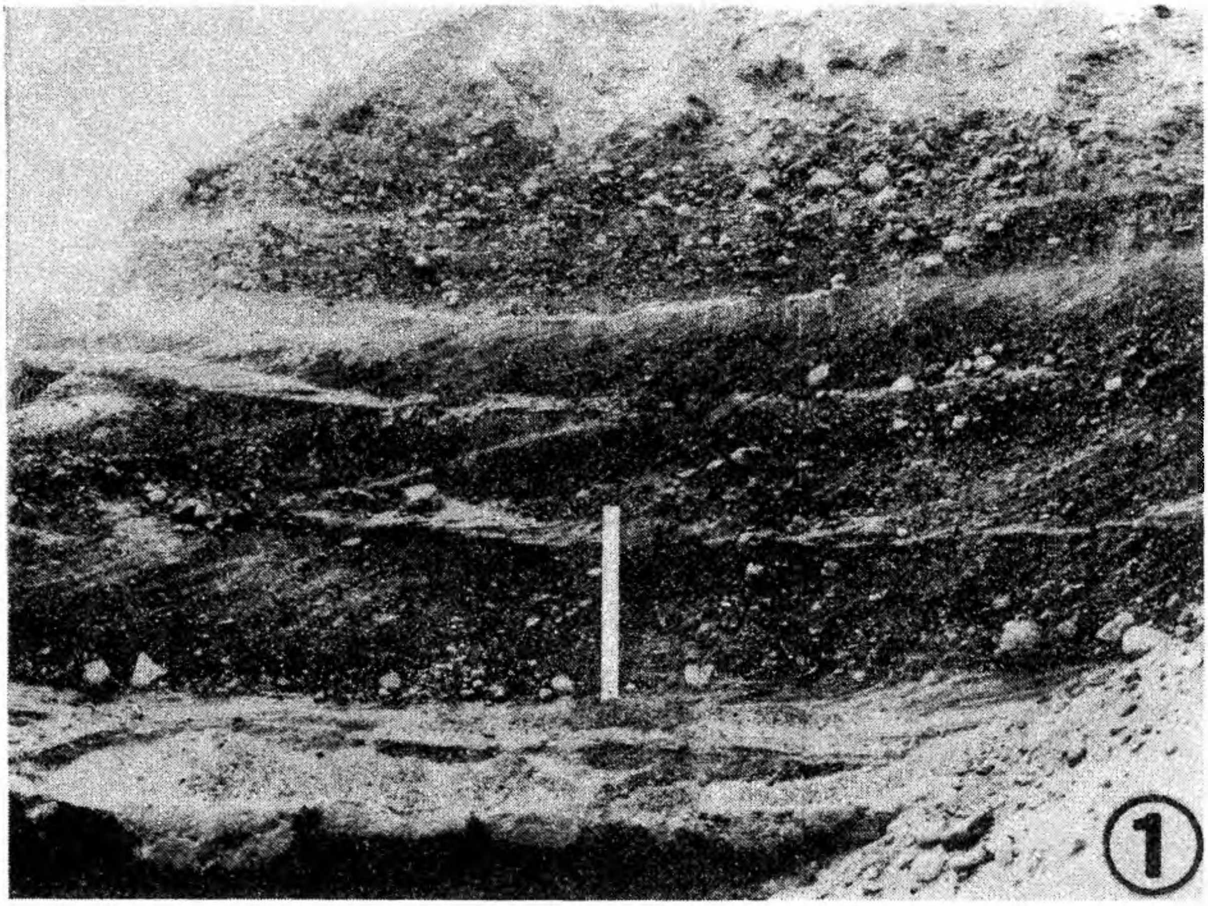

0 1 2m
2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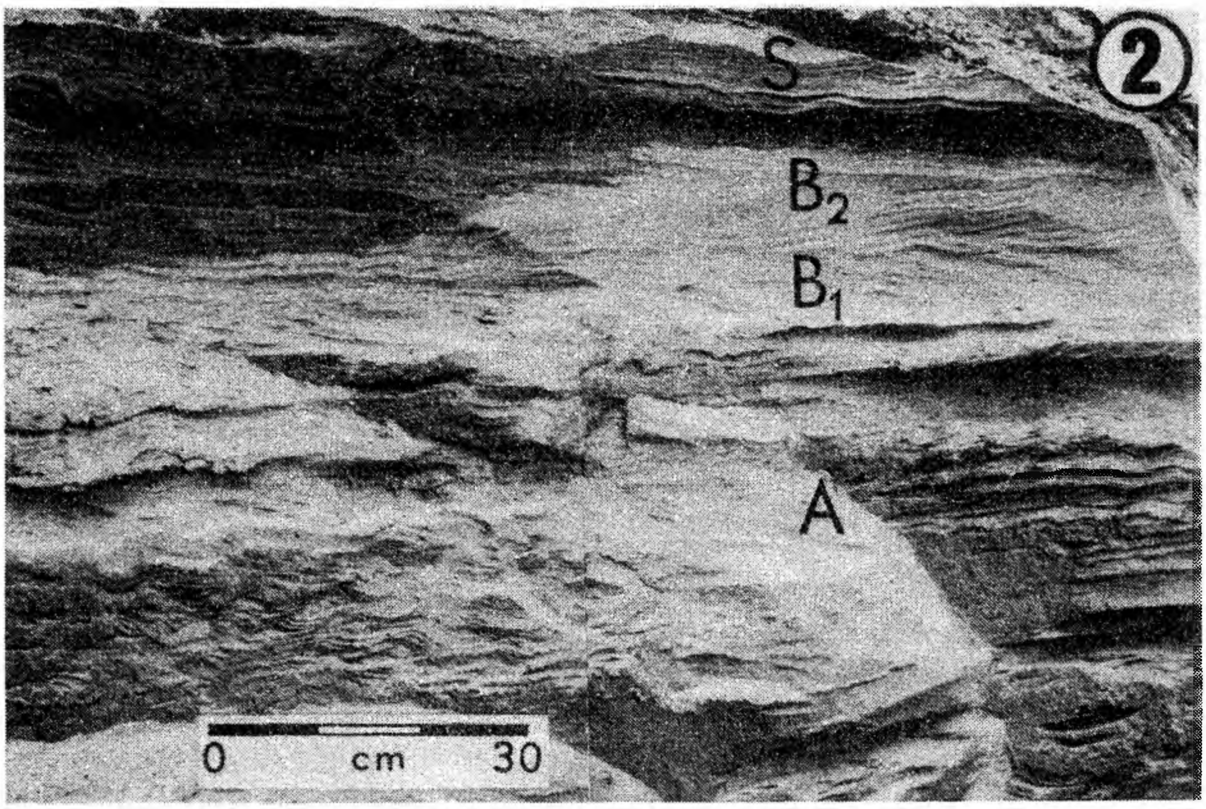
2
S
B2
B1
A
0 cm 30