Geologie en Mijnbouw **77:** 1–15, 1999.

Subaerial terminoglacial fans I: a semi-quantitative sedimentological analysis of the proximal environment

T. Zieliński[1] & A.J. van Loon[2]
[1]*Silesian University, Department of Earth Sciences, Będzińska 60, 41–200 Sosnowiec, Poland (zielu@us.edu.pl);* [2]*Geocom, PO Box 336, 6860 AH Oosterbeek, the Netherlands (geocom@wxs.nl)*

Received 25 March 1998; accepted in revised form 21 October 1998

Key words: facies analysis, glacial fan, Poland, Vistulian, Weichselian

Abstract

Fans formed under subaerial terminoglacial (previously called 'ice-contact') conditions have several characteristics that differ from those formed under other conditions. Twenty-five such fans in NE Poland were investigated to model the dominant genetic processes involved. These fans show, as do other types, a proximal, a middle and a distal environment. The present study deals with the proximal environment. The fans date from the last, i.e. Weichselian or Vistulian, glacial. The proximal terminoglacial fan comprises abundant gravelly sediments, resembling the glacial deposits from which they were derived. Three facies, each subdivided into two subfacies, can be distinguished; these are dominated by mass flows, unchannelised flows, and stream (= channelised) flows, respectively. The characteristics of the facies are described and illustrated. It is concluded that the irregular supply of water by the nearby ice masses dominates the sedimentary processes.

Introduction

Terminoglacial fans, i.e. fans formed in the relatively narrow zone in front of an ice sheet where ice-related processes directly affect the sedimentary surface (cf. Brodzikowski & Van Loon 1991), are, together with end moraines, the most prominent morphological features of many glaciated areas. They help in analysing the previous extent of ice sheets or glaciers and therefore play a significant part in palaeogeographic (but also stratigraphic) reconstructions. Although the morphological characteristics of moraine-related terminoglacial fans have been examined in detail (e.g. Ritter et al. 1993), relatively little is known about their internal structure and depositional history. Even less is known about the aggradation of such fans as a result of transport by meltwater and by mass flow.

It should be emphasised here that terminoglacial fans are neither sandurs nor outwash plains, which have been studied in detail (see, among others, Boothroyd 1972, 1976, Boothroyd & Ashley 1975, Boothroyd & Nummedal 1978, Cherven 1984, Maizels 1989, 1993, Zieliński 1989, and references therein). Sandurs and outwash plains are characterised by much lower gradients, by a much more regular shape, and by, in general, a much larger extent than terminoglacial fans. The genesis of subaerial terminoglacial fans depends mainly on debris supply, irregular water supply with occasionally large outbursts, and slope conditions.

The prime objectives of our study are to increase knowledge of the development of the facies in subaerial terminoglacial fans and to understand their genesis. Closely related objectives are to find out if sequences exist in these deposits and, if so, if different sequences are present in different parts of the fans. The final objective is to establish a depositional model for these fans, on the basis of their lithological and structural characteristics. For the purpose, 25 moraine-related fans were studied in NE Poland, in the Suwałki Lake District and the Masurian Lake District (Figure 1). This region was affected by the ice of the last Scandinavian glaciation, named 'Weichselian glaciation' in western Europe and 'Vistulian glaciation' in Poland. Moraines and associated fans of this glacial are common in this region and still have a distinct mor-

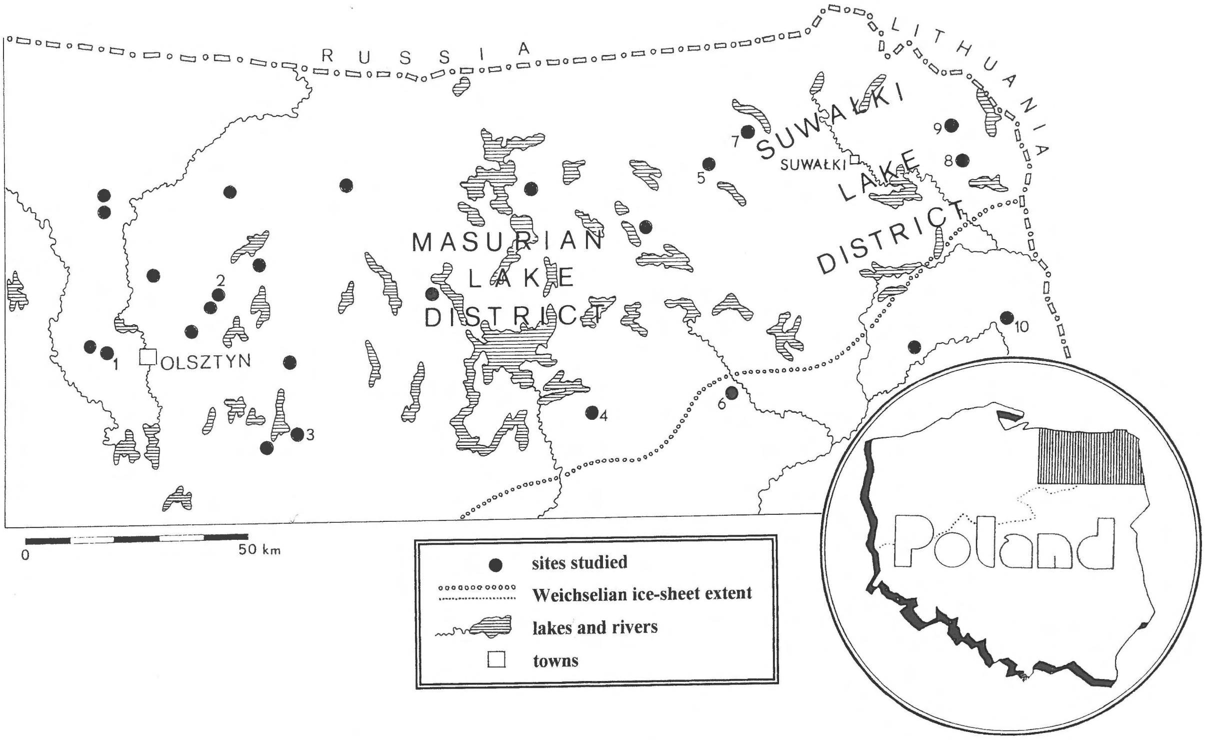


Figure 1. Location of study area and of sites investigated. The numbered sites are: 1 = Warkały; 2 = Kronowo; 3 = Romany; 4 = Kaliszki; 5 = Stożne; 6 = Grajewo; 7 = Filipów; 8 = Posejanka; 9 = Klejwy; 10 = Lipsk.

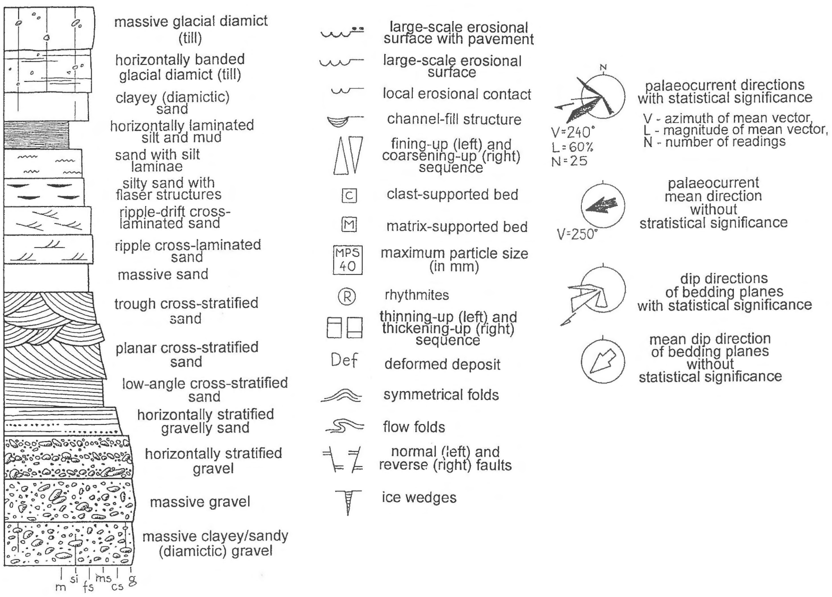


Figure 2. Legend for Figures 5 and 7 to 13 (grain-size symbols are explained in Figure 3; si = silt, m = mud).

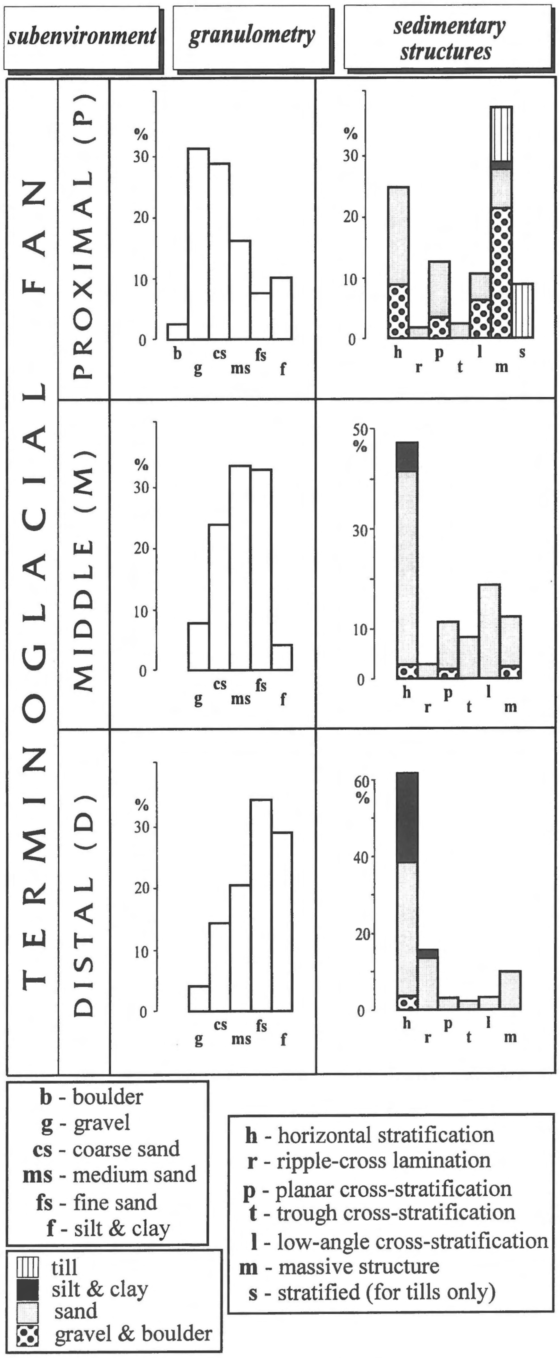


Figure 3. Schematic arrangement of lithofacies in the proximal, middle and distal subenvironments of Weichselian terminoglacial fans in NE Poland, showing the differences in average grain size and sedimentary structures in the three subenvironments.

phological expression. The forms consist commonly of undeformed (or only slightly deformed) deposits, and their internal structures can be studied in detail. The depositional processes involved could therefore be analysed precisely.

The present study is concerned with the proximal parts of fans formed by reworking, sometimes contemporaneous with ongoing deposition, of ablational moraines. The fans and moraines therefore interfinger: the particles removed from the moraines were deposited as fans at their feet (or even further away) during periods of high-capacity meltwater streams. In the present study, the term 'terminoglacial fan' is therefore used to indicate the fan-shaped landform that was apparently formed as (part of) an end moraine, and that was subsequently reworked, during and/or after deposition of the parent material. The intermediate and distal environments will be dealt with in a forthcoming contribution.

The lithological descriptions in the present study are based on field observations, not on analyses of grain size in the laboratory. A layer is termed 'thin' and a sedimentary structure is termed 'small-scale' if it is thinner or smaller than 6 cm, as this size forms a commonly used transition value between low-energy conditions or structures (e.g. current ripples) and high-energy phenomena (e.g. channel bars); 'thick' or 'large-scale' indicates more than 30 cm; for the 6–30 cm range, the term 'medium' is applied. The various symbols used in drawings are explained in Figure 2.

Vertical successions and lateral transitions between the fan environments

Comparison of the successions in the 25 fans that were investigated indicates that a number of lateral and vertical changes occur that must be attributed to common environmental changes in space and time.

Most of the fans studied are 10–30 m thick. They show comparable vertical developments, but rarely according to an 'ideal' scheme. Combining data of 'incomplete' successions allowed, however, to establish composite sections that show all the relevant aspects in a logical, often cyclic, succession. Such successions comprise several facies and show characteristic features that reflect the qualitative and quantitative changes in the transporting and depositional agents (mass flow or particle transport; amount of water and particles available), and thus in the depositional en-

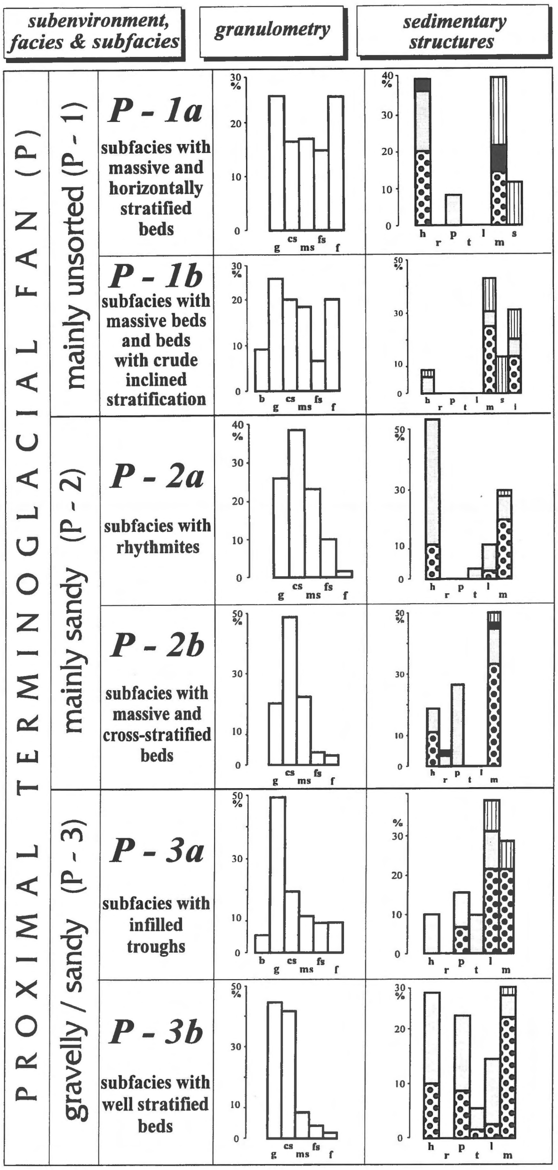


Figure 4. Sedimentological characteristics of the various lithofacies and subfacies in the proximal subenvironment. For symbols: see Figure 3.

vironment. It should be noted that sedimentary and erosional processes in the region immediately affected by the nearby ice (the terminoglacial subenvironment in the sense of Brodzikowski & Van Loon 1987, 1991) are exceptionally variable in time.

Differences in the overall grain size of the deposits and in their relative amounts of specific sedimentary structures make it possible to distinguish three, spatially more or less separated, environments: the proximal, the middle and the distal fan environments (Figure 3). This is consistent with other sedimentological analyses of fans (cf. Bull 1972, Kochel & Johnson 1984, Went et al. 1988, Sah & Srivastava 1992, Brierley et al. 1993, Blair & McPherson 1994a, b). The proximal environment is coded here as the *P* environment.

Description and interpretation of the sedimentary facies

Description of the facies

Field observations at the 25 sites showed that three facies can be distinguished in proximal terminoglacial fans, primarily on the basis of their grain-size distribution and the relative frequency of specific sedimentary structures (Figure 4). These three facies are dominated by unsorted deposits (facies *P-1*), predominantly sandy deposits (*P-2*) and gravelly/sandy deposits (*P-3*).

Facies *P-1* comprises two subfacies. Subfacies *P-1a* (Figures 5–6) shows frequent massive beds but equally frequent beds showing horizontal stratification, without large-scale inclined stratification. Subfacies *P-1b* is dominated by massive beds, with frequent beds showing crude (= without finely developed foresets), inclined stratification and almost no horizontal stratification.

Facies *P-2* comprises two subfacies. Subfacies *P-2a* is characterised by gravels and sands in rhythmites that only rarely show cross-bedding. Subfacies *P-2b* lacks the rhythmite character but is made up of mainly massive beds, although cross-bedding is also common. The sheet-like bodies of this subfacies are separated from each other by planar erosional surfaces.

Facies *P-3* also comprises two subfacies (Figure 7), although these were never encountered together in the field. Subfacies *P-3a* contains frequent troughs with infillings of diamictic material. Subfacies *P-3b* is characterised by the common occurrence of both gravel and sand beds, usually with distinct stratification, although massive beds may be intercalated.

Interpretation of facies P-1: proximal fan dominated by unsorted deposits

The sedimentary characteristics of the diamictic (= badly sorted) deposits in facies *P-1* can be explained satisfactorily only if a mass-flow origin is assumed. This type of deposit is also common in proximal

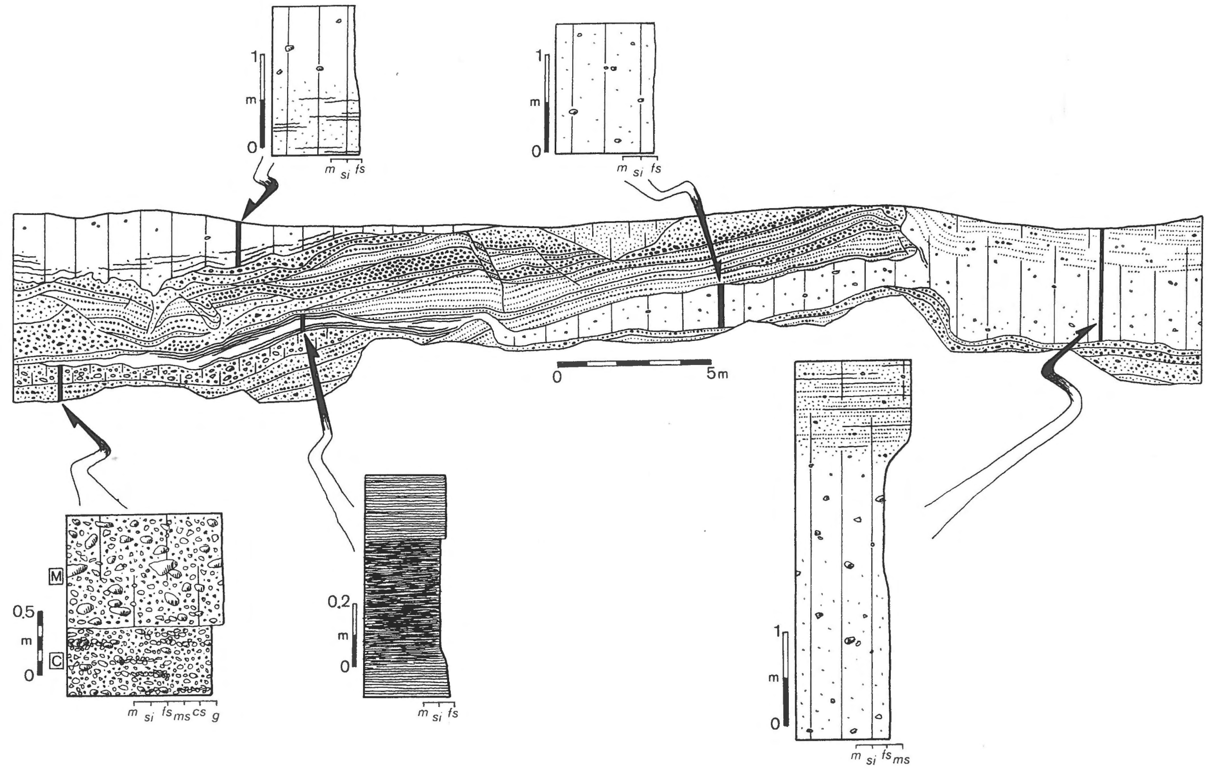


Figure 5. Characteristic appearance of subfacies *P-1a*, with two massive, locally banded, flowtills embedded between horizontally stratified sands and gravels and rare silty clays (Kronowo site). See Figure 2 for legend.

fans formed in other environments, e.g. in the tropics (Brierley et al. 1993). The deposits represent a wide variety of transporting and depositional processes, but the main distinction is between deposits that underwent subaerial mass transport and those that underwent subaqeous mass transport.

Subfacies dominated by massive beds and beds with horizontal stratification (P-1a)

The general characteristics of the gravelly subfacies *P-1a* indicate an environment with high-energy streams and an irregular supply of meltwater. This resulted in shallow channels of low sinuosity with longitudinal bars and gravel sheets (Figure 8). Sedimentation from currents was frequently interrupted by mass-movements that resulted in the deposition of massive and stratified diamicts. Subaerial gravity flows of water-saturated material resulted in the frequent formation of flowtills. The material was apparently transported downwards on the fan's surface as relatively continuous, sheet-shaped mudflows.

The flowtills form irregular beds covering the surface of the braided system. The current activity eroded the previously deposited flowtills, changing their character, at least locally, into that of reworked alluvium. Sorting during this process was minimal, so that the resulting deposits often kept their diamictic character: matrix-supported gravels with a considerable admixture of sand and, particularly, clay, and massive diamictic gravels (Figure 8). The ratio between flowtills and glaciofluvial sediments possibly reflects the changes in the melting of ice: the coarse-grained cosets of predominantly stream deposits might represent periods of large water supply (summer), whereas the levels with predominantly diamictic beds might represent periods of rapid alternations of frost and thaw (autumn and spring). In winter time hardly any meltwater will have been available, so the winters are presumably represented by hiatuses. The massive nature of most beds, the poor sorting, the considerable thickness of the facies, the abundant sedimentary deformations due to loading, and the lack of erosional surfaces are strong arguments for rapid aggradation.

A comparable environmental interpretation has been provided for other marginal moraines in Poland, where Kozarski (1990) analysed some end moraines

Figure 6. Detail of right-hand section in Figure 5. Note the grain-size contrast between the fluvially reworked, bedded diamictic gravel (bottom part) and the massive flowtill (top part). The scale is 0.5 m long.

where flowtills are intercalated with stream deposits, representing a similar situation as subfacies *P-1a*. Polish end moraines dominated by flowtills were also described by Ruszczynska-Szenajch (1982).

Subfacies characterised by massive beds and beds with crude, inclined stratification (P-1b)

The environmental and depositional conditions of subfacies *P-1b* were fairly similar to those of *P-1a*. The main difference was the larger abundance of currents. This is deduced from the fact that the debris-flow deposits included in this subfacies were almost always reworked by superficial streams. These streams eroded and transported previously formed deposits usually over only short distances, as shown by the diamictic character of the sediments. The somewhat coarser character of the latter indicates, however, that some of the fine material has been washed out.

In spite of the frequent presence of deposits formed as a result of reworking by superficial streams, mass flows seem to have contributed most to the vertical accretion (Figure 9). Similar gravels and boulders that have been reworked under the influence of gravity and that 'float' in a clayey/sandy matrix have been described from proximal parts of alluvial fans formed under synorogenic conditions (DeCelles et al. 1991), in the tropics (Lin & Crook 1992) and in high mountain regions (Sah & Srivastava 1992). Several researchers emphasise that proximal fan sediments are characterised by a massive structure or ill-defined sedimentary structures, as well as by the thickness of their beds (Fraser 1982, Ruszczynska-Szenajch 1982). They, too, attribute proximal fan beds to gravity sediment flows.

The few sediments that do not show a debris-flow character were usually formed by unchannelised flows in shallow, ephemeral streams. They consist mainly of clayey sands or gravels with a horizontal stratification that indicates deposition under upper plane-bed conditions. These better sorted, stratified deposits often cover entire mass-flow deposits, which is considered characteristic of syndepositional or penecontemporaneous reworking of the mass-flow deposits by unchannelised flows (Broscoe & Thomson 1969, Nemec & Steel 1984, Hubert & Filipov 1989, Blair & McPherson 1992, 1994a).

Interpretation of facies P-2: proximal fan dominated by mainly sandy deposits

The energy in facies *P-2* must, on the average, have been lower than in the *P-1* facies. This is deduced from the fact that gravel-sized and larger clasts are no longer the most common constituents, even though they still occur frequently; sand is instead. The high-energy conditions prevailing during the transport of the sands are reflected in the sedimentary structures. These structures are the main reason for the distinction of two subfacies.

Subfacies with rhythmites (P-2a)

The beds of subfacies *P-2a*, starting with massive sandy gravel or gravelly sand at the base and ending with horizontally laminated (sometimes cross-bedded) sands, reflect the effect of alternating periods with more and less melting of ice. Each of these sheet-like beds may represent a cyclic, short-term flood, during which the entire bed was deposited under conditions of transitional or supercritical flow (the upper plane-bed stage). The extent of the sheet-like beds, the lack of channel structures and the radial pattern shown by palaeocurrent indicators point to sheetfloods as the transporting agent (Figure 10; cf. Ruszczynska-

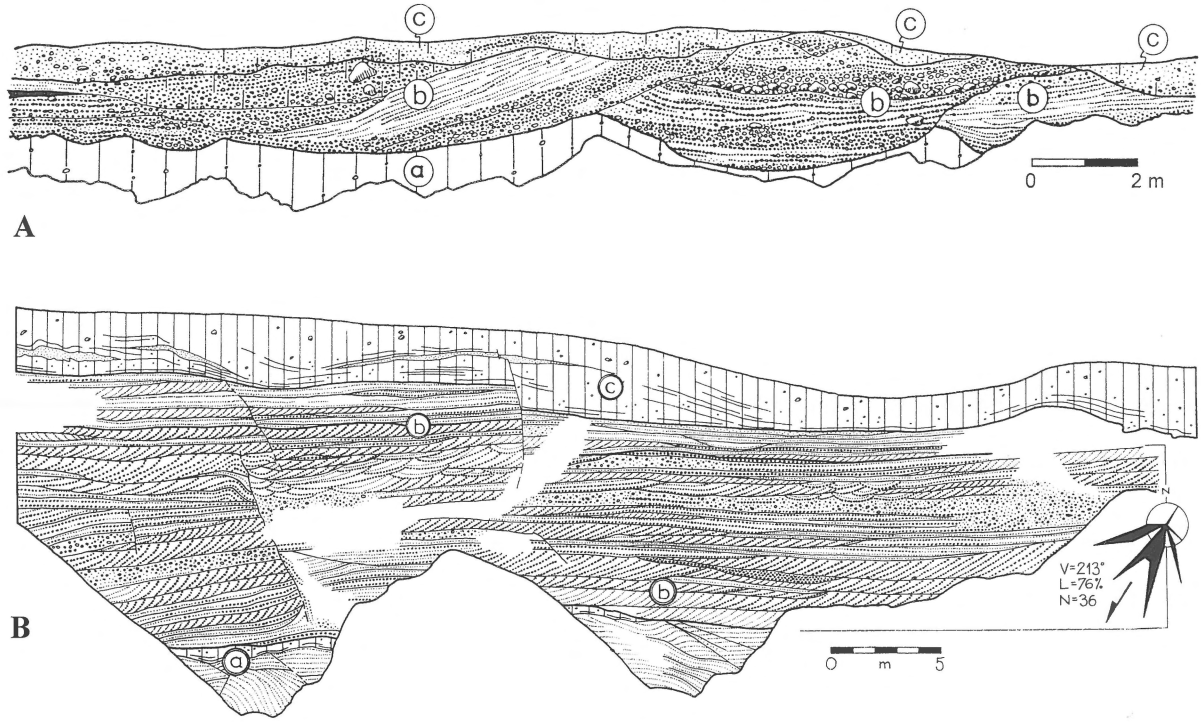


Figure 7. Subfacies of facies *P-3*. A: Section (Grajewo site) showing spatial relationships between the various deposits of subfacies *P-3a*. a = till of moraine core; b = infilling of large-scale troughs; c = upper cover of diamictic sands. B: Section (Kronowo site) showing the geological context of the deposits of subfacies *P-3b*. a = glacially deformed glaciofluvial sands and tills from an older phase of ice advance; b = stratified gravels and sands of subfacies *P-3b*; c = flowtill cover. Legend in Figure 2.

Szenajch 1982, Wells 1984; Blair & McPherson 1994b).

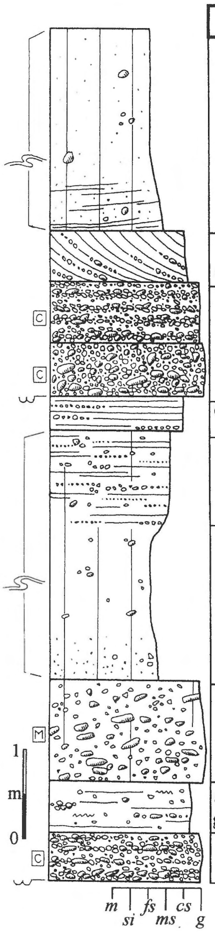
The massive, poorly sorted gravels at the base of the graded beds resulted from accumulation from fluid flow of high-density currents with a high sediment load. Nemec & Muszynski (1982) termed such deposits 'sheet-flood slurries' and interpreted the transporting agent as being intermediate (according to the density criterion) between a debris flow and a stream flow. The lowermost, gravelly part of the bed represents transport by a sheetflood. Such gravelly parts in fans formed under other than terminoglacial conditions may form up to 30% of the fan (Harvey 1984, Al-Sulaimi & Pitty 1995).

The upper part of the rhythmites consists of sands with horizontal lamination or low-angle cross-bedding. An analogous development was described by Southard et al. (1984) for sediments of a proglacial alluvial fan (a fan not directly influenced by the nearby ice front) dominated by sheetfloods. The horizontal lamination represents upper plane-bed conditions during deposition; the low-angle stratified sands must be low dunes, formed at the transition between the lower and the upper flow regime. Bull (1972) considered this low-angle cross-stratification to be typical of sheetfloods. Subfacies *P-2a* is most commonly found in small-scale, steep terminoglacial fans. Palaeogeographic and geomorphological reconstructions (Zieliński 1989) suggest that such fans tend to accumulate in depressions surrounded by dead-ice masses.

It is still uncertain what timespan is represented by a single layer in the succession of graded rhythmites. The poor sorting of the sediment makes a high aggradation rate likely. A single rhythmite thus probably represents a very short time: it is possible that it represents a one-day cycle, or perhaps a cycle of a few days. Roberts et al. (1994) presumed a timespan of hours to weeks for deposition of material under fairly comparable conditions. Klimek (1972) and Ruszczynska-Szenajch (1982) assumed a diurnal genesis.

Subfacies with common cross-stratified beds (P-2b)

The most obvious deposits of subfacies *P-2b* are massive gravelly longitudinal bars and gravelly/sandy



P-1a

LITHOLOGY	INTERPRETATION	
sandy/clayey massive diamict with interspersed gravel; the basal part is sandier and shows vague stratification	deposits of clay-rich, dense subaerial debris flow that developed on the ice front during a phase of limited ablation	**apex of the terminoglacial fan dominated by an alternation of sediment gravity flows and high-energy floods**
(relatively rare) sands with interspersed gravel; tabular cross-bedding	sandy foreset bar formed locally by meltwater currents	
thick beds with clast-supported cobbles and pebbles; massive or horizontal stratification	gravelly longitudinal bars formed during stages of meltwater outbursts	
(relatively rare) sands with interspersed gravel; horizontal stratification	sediment of meltwater current (upper plane bed stage)	
clayey (diamictic) sand with interspersed gravel; vague horizontal stratification, flow folds; gradual transition into:	upper part of subaerial debris flow, reworked by sheet floods	
massive clayey diamict with interspersed gravel	deposit formed by a subaerial debris flow during a period of limited ablation	
massive gravel interspersed in sandy/clayey (diamictic) matrix	initial reworking (torrential meltwater currents) by short-distance transport of moraine debris	
slightly clayey sand with interspersed gravel; vague horizontal stratification	sandy bed formed during flood (upper flow regime)	
clast-supported gravel, sometimes clayey; horizontal stratification	accretion of gravelly longitudinal bar in high-energy stream	

Figure 8. Composite lithological column and palaeoenvironmental interpretation of subfacies *P-1a* (see Figure 2 for legend).

sheets (Figure 11). The characteristics described above indicate that they resulted from frequent, high-energy meltwater floods that were almost sheetfloods. During flood peaks, supercritical and transitional flows developed (gravelly upper plane-bed stage). During lower discharges, the streams became increasingly channelised. Sandy foreset bars of the transverse type were formed in sandy, braided channels. The alternation of high-stage sheetfloods with mean-stage, channelised stream flows does not seem to be uncommon hydrologically. McKee et al. (1967) and Williams (1970) emphasised the easy transition of stream flow into sheetflood.

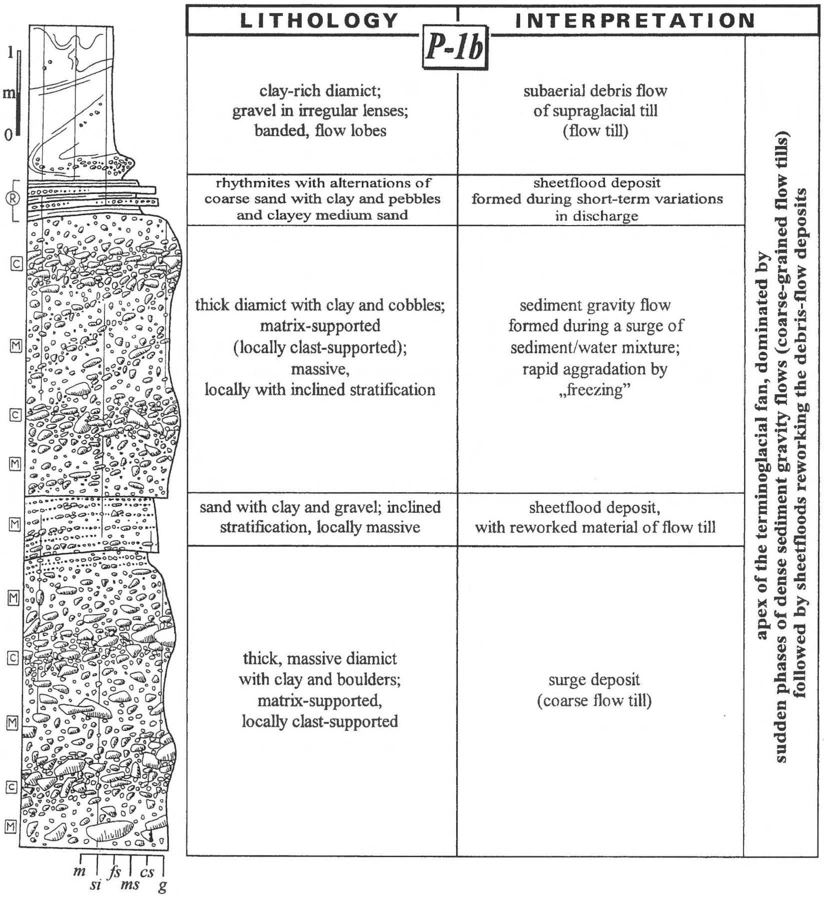
This subfacies can thus be interpreted as having formed under the influence of ephemeral strong floods. According to the present study, this subfacies is relatively rare in terminoglacial fans.

Interpretation of facies P-3: proximal fan dominated by gravelly, sandy deposits

Facies *P-3* is also characterised by high-energy conditions, as shown by the presence of coarse-grained material. The sediments are considered to reflect sudden outbursts of water, due to either suddenly increased ablation or to the breakthrough of an ice-dammed lake. The strongest outbursts eroded channel patterns. Floods with a lower discharge result in shallow, braided streams.

Subfacies with infilled troughs (P-3a)

The deep troughs that characterise subfacies *P-3a* indicate the catastrophic character of the floods (Figure 12). Similar large-scale troughs infilled by poorly sorted gravel have been noted also in proximal outwash fans (Fraser 1982). Apparently, the outbursts of floods stopped so abruptly that the troughs were not



LITHOLOGY	INTERPRETATION	
clay-rich diamict; gravel in irregular lenses; banded, flow lobes	subaerial debris flow of supraglacial till (flow till)	apex of the terminoglacial fan, dominated by sudden phases of dense sediment gravity flows (coarse-grained flow tills) followed by sheetfloods reworking the debris-flow deposits
rhythmites with alternations of coarse sand with clay and pebbles and clayey medium sand	sheetflood deposit formed during short-term variations in discharge	
thick diamict with clay and cobbles; matrix-supported (locally clast-supported); massive, locally with inclined stratification	sediment gravity flow formed during a surge of sediment/water mixture; rapid aggradation by „freezing”	
sand with clay and gravel; inclined stratification, locally massive	sheetflood deposit, with reworked material of flow till	
thick, massive diamict with clay and boulders; matrix-supported, locally clast-supported	surge deposit (coarse flow till)	

Figure 9. Composite lithological column and palaeoenvironmental interpretation of subfacies *P-1b* (see Figure 2 for legend).

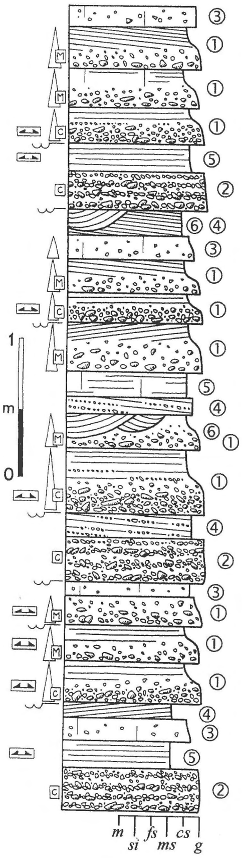
filled up with graded channel deposits. Instead, they were filled by coarse-grained diamictic sediments, most likely formed by ‘freezing’ from hyperconcentrated flows. From a rheological point of view, this implies fluid flow of high concentration for all grain sizes. The presence of such flows is very likely, because the concentration of particles, both as bedload and in suspension, must be high in the meltwater streams (up to 35%: Maizels 1989). This also explains the large-scale character of the beds and the poor sorting. The debris that builds up the trough infillings was supplied by gravity flows of tills (flowtills), which underwent some reworking by currents.

Sudden outbursts of meltwater as interpreted here are thus characterised by high sediment concentrations. The resulting diamictic infills by such floods have also been reported for proglacial channels (Brodzikowski & Van Loon 1991). They were also reported to form gravelly subaqueous dunes in channels after glacial outburst floods in Siberia (Carling 1996). One must assume that a similar type of deposition took place simultaneously outside the troughs on the planar, nonscoured sedimentary surface, presumably under conditions of high-density unchannelised flow. ‘Normal’ braided-stream deposition played a limited part during the accumulation of this subfacies.

Subfacies with well stratified beds (P-3b)

The alternating gravel and sand beds reflect cycles in the supply of meltwater. The beds show a well defined stratification, sometimes with cross-stratified units (Figure 13). The beds are not widespread. This, in combination with the grain-size distribution, is typical of braided streams, where the shoals alternate laterally with shallow channels.

During the floods, gravelly longitudinal bars and gravel sheets developed in the channels. They accumulated rapidly from transitional or supercritical flows



P-2a

LITHOLOGY	INTERPRETATION	
the succession consists of an irregular repetition of beds with the following characteristics: ① sheet-like beds consisting of massive clast- or matrix-supported gravel at the base, fining upwards into coarse sands with horizontal stratification (rarely low-angle cross-stratification); ② thick and medium gravel beds, clast-supported with horizontal stratification, sometimes fining upwards; ③ coarse sands, frequently with some clay and gravel (diamictic), sometimes fining upwards; ④ medium to thin sands with low-angle cross-stratification, sometimes scattered gravel; ⑤ medium to thin sands (locally clayey) with horizontal lamination or stratification; ⑥ coarse sand beds of medium thickness with trough cross-stratification (relatively rare)	① to ⑥ deposition under the influence of short-lived (day? a few days?) sheetfloods reworking previously deposited sediment gravity-flow deposits, deposition from currents in upper flow regime during main floods: transport as sliding beds, rapid vertical deposition of gravels as sheets (rarely as flat longitudinal bars) during periods of slowing down: deposition of sandy gravels and sands, forming sheets or diminished dunes (rarely flat bars or dunes with curved crests)	**sedimentation by sheetfloods on the apex of a small terminoglacial fan**

Figure 10. Composite lithological column and palaeoenvironmental interpretation of subfacies *P-2a* (see Figure 2 for legend).

(gravelly upper plane-bed stage). During periods with less ablation, deposition of sand prevailed within the channel. The flows affecting the shoals had a transitional character, resulting in horizontally laminated sands formed under upper plane-bed conditions. When the competence of the currents in the channels decreased, sandy transverse bars with abundant foresets were formed.

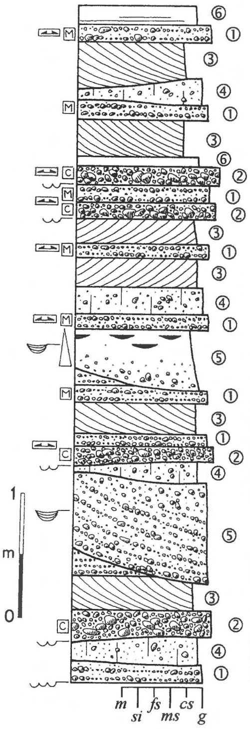
The sediments were thus formed by processes that led to four main depositional forms: gravel bar, gravel sheet, sandy foreset bar and sandy upper plane-bed (Figure 13). The fact that fluvially reworked tills (diamictic clayey gravels) are fairly rare – their frequency is lowest among all facies in proximal fans – might indicate that this facies develops further away from the ice margin than do the other facies in this subenvironment.

The sediments that characterise this subfacies have been found in more or less identical forms by others, e.g. in the braided, gravelly channels of outwash fans (J.Z. Fraser 1982, G.S. Fraser 1993, Zieliński 1989, Maizels 1993).

Discussion

The proximal fans, which in general intercalate with moraine material that seems not, or only slightly, to have been reworked after their deposition by ice, contain abundant clasts, which show similar compositions and textural characteristics as those in the nearby moraines. It is therefore beyond doubt that the sediments in the proximal fan were derived from the marginal moraines that developed under terminoglacial conditions.

The irregular topography in the ice-contact area, the abundance of debris released by melting of the ice, and the availability of highly unsteady, sometimes vast and sudden outbursts of water flows explain



P-2b

LITHOLOGY	INTERPRETATION	
the succession consists of an irregular repetition of beds with the following characteristics:	① most common form of sheetflood with deposition of gravel and sand under upper plane-bed conditions;	sedimentation by sheetfloods and in braided channels on the apex of a terminoglacial fan
① sheet-like sandy matrix-supported gravel with pebbles, horizontal stratification;	② reworking of sediment-gravity flow deposits by high-energy sheetfloods with supercritical flow, capable of erosion, accretion of gravel sheets;	
② massive clast-supported gravel with cobbles, erosional base, sheet-like beds;	③ accumulation of sandy foreset bars in braided streams, during last phase of sheetflood when water followed a braided channel pattern;	
③ sands with tabular cross-stratification;	④ first stage of sheetflood, with reworking of previously deposited sediment gravity-flow deposits;	
④ massive clayey sands with dispersed gravel;	⑤ maximum discharge of meltwater outburst, resulting in erosion of troughs and subsequent filling with gravel and sand;	
⑤ usually thick beds with a distinctly erosive base, filled with sand and gravel, massive or with stratification following the base configuration, relatively rare;	⑥ sand aggradation during rapid decay of sheetflood	
⑥ sheet-like beds of massive sands, relatively rare		

Figure 11. Composite lithological column and palaeoenvironmental interpretation of subfacies *P-2b* (see Figure 2 for legend).

why mass transport and high-energy, mainly unchannelised, flows were the main transporting mechanisms.

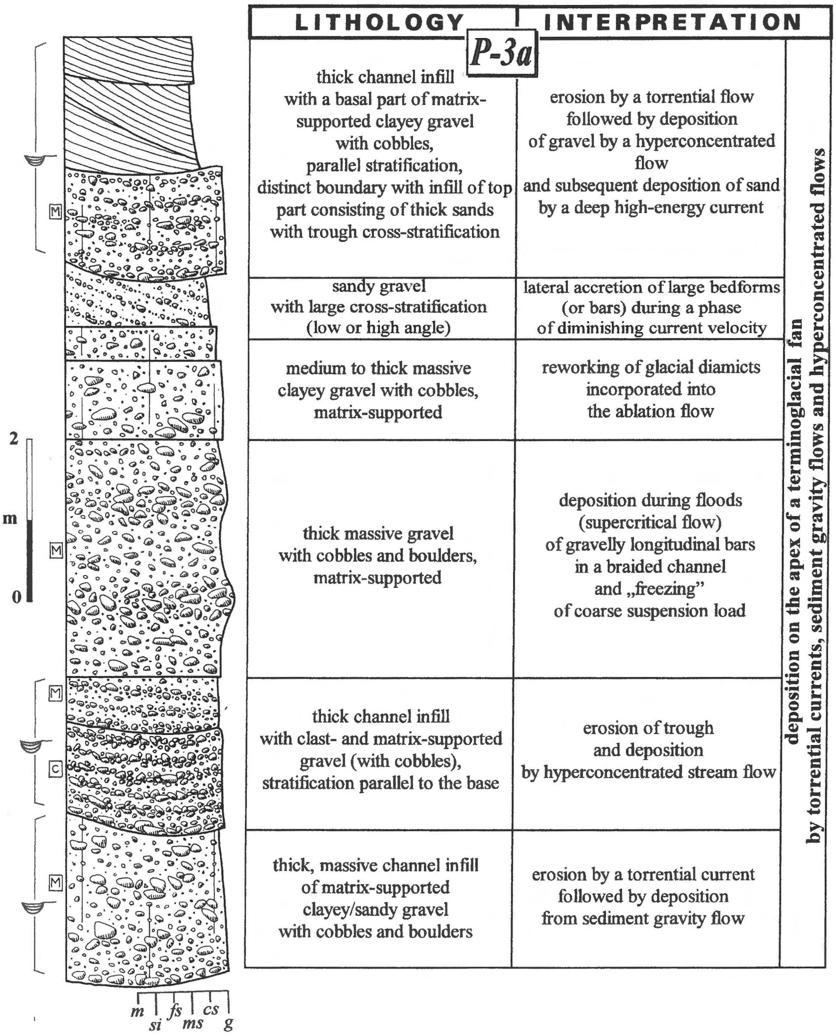
Not all transport took place by mass transport or through unchannelised flows. Sometimes the water followed channels; the currents in these channels had commonly a high energy, resulting in further erosion of the channels. A decrease in energy resulted in relatively fast vertical accretion, reflected by the thickness of the deposits (Figure 14).

The variation in relative frequency of the various architectural elements is of prime importance for the palaeoenvironmental interpretation. It should be noted in this context that fans are generally subdivided into ‘wet’ and ‘dry’ fans (Schumm 1977). The first group is dominated by braided channels, whereas the second group is dominated by mass flows. (Most fans show a mixture of predominant streamflow deposits and a smaller amount of mass-flow deposits, and others seem to consist almost entirely of streamflow deposits; see, among others, Jo et al. 1997.) A quantitative analysis of these elements in the proximal terminoglacial fans under study allows six subfacies to be distinguished, each of which is characterised by the predominance of one or more depositional processes (Figure 15).

The important role of debris flows in the proximal subenvironment contrasts with the models proposed for fans from other environments by Miall (1970), Gloppen & Steel (1981) and Kochel & Johnson (1984). On the other hand, Brierley et al. (1993) mentioned debris flows on proximal fans, together with hyperconcentrated flows that they consider characteristic of the proximal zone. We found, however, that hyperconcentrated flows on terminoglacial fans are also present in the middle subenvironment, as indicated by the occurrence of massive clayey sands and clayey, sandy gravels.

Conclusions

Fans formed under subaerial terminoglacial conditions, with marginal moraines as parent material, are different from most other types of fans. A specific characteristic of terminoglacial conditions is the irregular, and occasionally devastating, supply of water. In combination with the water-saturated character of the



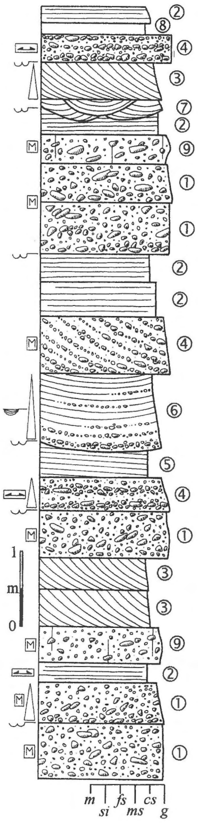
LITHOLOGY	INTERPRETATION	
thick channel infill with a basal part of matrix-supported clayey gravel with cobbles, parallel stratification, distinct boundary with infill of top part consisting of thick sands with trough cross-stratification	erosion by a torrential flow followed by deposition of gravel by a hyperconcentrated flow and subsequent deposition of sand by a deep high-energy current	deposition on the apex of a terminoglacial fan by torrential currents, sediment gravity flows and hyperconcentrated flows
sandy gravel with large cross-stratification (low or high angle)	lateral accretion of large bedforms (or bars) during a phase of diminishing current velocity	
medium to thick massive clayey gravel with cobbles, matrix-supported	reworking of glacial diamicts incorporated into the ablation flow	
thick massive gravel with cobbles and boulders, matrix-supported	deposition during floods (supercritical flow) of gravelly longitudinal bars in a braided channel and „freezing" of coarse suspension load	
thick channel infill with clast- and matrix-supported gravel (with cobbles), stratification parallel to the base	erosion of trough and deposition by hyperconcentrated stream flow	
thick, massive channel infill of matrix-supported clayey/sandy gravel with cobbles and boulders	erosion by a torrential current followed by deposition from sediment gravity flow	

Figure 12. Composite lithological column and palaeoenvironmental interpretation of subfacies *P-3a* (see Figure 2 for legend).

unsorted source material (diamicts constituting previously formed moraines), this facilitates mass movements. It is therefore interesting that these fans fit the general model of Kochel & Johnson (1984) for arid alluvial fans rather than the model for humid-glacial fans. Terminoglacial fans appear to form an intermediate category. In addition, terminoglacial fans differ from fans formed under other conditions in the exceptionally frequent occurrence of mass flow. The specific conditions of the terminoglacial environment initially result in almost equal amounts of mass-flow and fluvial deposits in the proximal subenvironment. Subsequent reworking of part of the mass-flow deposits changes this picture, but the original character of the reworked mass-flow deposits is usually still traceable, indicating that reworking is only slight in most cases.

Acknowledgements

The first author thanks Richard Collier (University of Leeds Univ., Department of Earth Sciences) for his helpful review of an earlier draft of this contribution. The suggestions by the late Prof. Dr Krzysztof Brodzikowski (University of Łódź , Department of Geography) are also greatly appreciated. We are much indebted to Liza Crossan (WriteItRight) for continuous support and for correcting the English text.



LITHOLOGY	INTERPRETATION	
P-3b the succession consists of an irregular repetition of beds with the following characteristics:		**deposition on the apex of a terminoglacial fan in a system of braided gravel-bed channels occasionally reached by mass-transported material**
① massive, thick matrix-supported sandy gravel with cobbles and pebbles, sometimes fining upwards, abundant;	① intensive aggradation of gravel and sand during the first phase of dramatic flood waning;	
② medium (rarely thick) sands with horizontal stratification, abundant;	② deposition of sand under plane-bed conditions in channel shoals during low-water stages;	
③ thick medium- and coarse-grained sands with tabular cross-stratification, abundant	③ formation of sandy foreset bars during low-water stages;	
④ thick matrix-supported sandy gravel with cobbles and pebbles, vague horizontal stratification or tabular cross-stratification, not uncommon;	④ formation of gravelly longitudinal bars during flood events	
⑤ medium- and coarse-grained sands with low-angle cross-stratification, not uncommon;	⑤ accretion of low erosionally modified sandy foreset bars during decreasing discharge	
⑥ deep erosive troughs filled with sandy gravel with pebbles, stratification parallel to the base, relatively rare	⑥ filling of deep local erosional troughs in the central zones of braided channels during the flood episodes;	
⑦ coarse sands with trough cross-stratification, relatively rare;	⑦ local erosion and deposition in front of sinuous dunes;	
⑧ medium- and coarse-grained massive sands, occasionally clayey, relatively rare;	⑧ sudden sand aggradation from supercritical flow;	
⑨ thick, massive matrix-supported diamictic cobbles and pebbles with sand and clay, relatively rare	⑨ initial fluvial reworking of sediment-gravity flows reaching channels	

Figure 13. Composite lithological column and palaeoenvironmental interpretation of subfacies *P-3b* (see Figure 2 for legend).

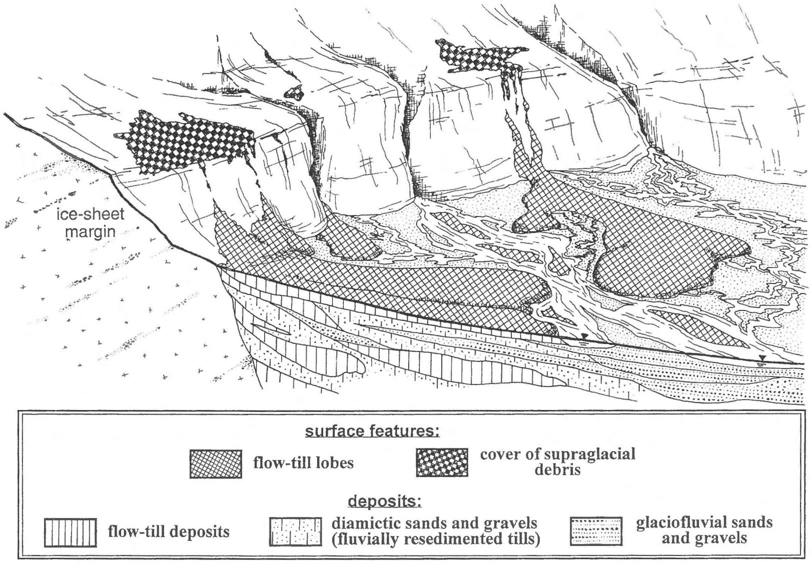


Figure 14. Environmental reconstruction of facies *P-1*.

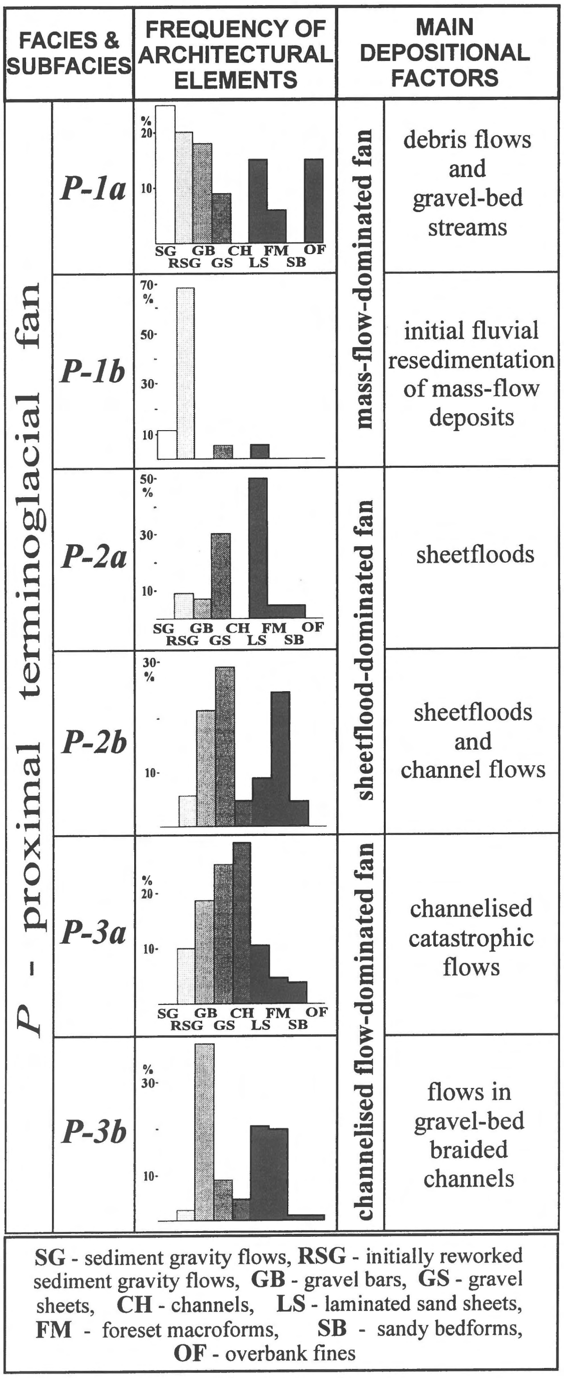


Figure 15. Overview of the sedimentary features characteristic of the proximal terminoglacial fan environment in the Weichselian of NE Poland.

References

Al-Sulaimi, J. & A.F. Pitty 1995 Origin and depositional model of Wadi Al-Batin and its associated alluvial fan, Saudi Arabia and Kuwait – Sediment. Geol. 97: 203–229

Blair, T.C. & J.G. McPherson 1992 The Trollheim alluvial fan and facies model revisited – Geol. Soc. Am. Bull. 104: 762–769

Blair, T.C. & J.G. McPherson 1994a Alluvial fans and their natural distinction from rivers basedon morphology, hydraulic processes, sedimentary processes, and facies assemblages – J. Sediment. Research 64: 450–489

Blair, T.C. & J.G. McPherson 1994b Alluvial fans – processes and forms. In: Abrahams, A.D. & A.J. Parsons (eds) Geomorphology of Desert Environments. Chapman & Hall, London: 354–402

Boothroyd, J.C. 1972 Coarse-grained sedimentation on a braided outwash fan, Northeast Gulfof Alaska – Techn. Rept. Coastal Res. Div., Univ. South Carolina (Columbia) 6: 127 pp

Boothroyd, J.C. 1976 Sandur plains, northeast Gulf of Alaska: a model for fan delta sedimentation in cold-temperature environments. In: Miller, T.P. (ed.) Recent and Ancient Sedimentary Environments in Alaska. Alaska Geol. Soc. N1–N13

Boothroyd, J.C. & G.M. Ashley 1975 Processes, bar morphology and sedimentary structures on braided outwash fans, Northeastern Gulf of Alaska. In: Jopling, A.V. & B.C. McDonald (eds) Glaciofluvial and Glaciomarine Sedimentation. Soc. Econ. Paleont. Min. Spec. Publ. 23: 193–222

Boothroyd, J.C. & D. Nummedal 1978 Proglacial braided outwash: a model for humid alluvial-fan deposits. In: Fluvial Sedimentology. Canad. Soc. Petroleum Geol. Mem. 5: 641–668

Brierley, G.J., K. Liu & K.A.W. Crook 1993 Sedimentology of coarse-grained alluvial fans in the Markham Valley, Papua New Guinea – Sediment. Geol. 86: 297–324

Brodzikowski, K. & A.J. van Loon 1987 A systematic classification of glacial and periglacial environments, facies and deposits – Earth-Science Reviews 24: 297–381

Brodzikowski, K. & A.J. van Loon 1991 Glacigenic Sediments (Developments in Sedimentology49). Elsevier, Amsterdam: 674 pp

Broscoe, A.J. & S. Thomson 1969 Observations on an Alpine mudflow, Steele Creek, Yukon – Canad. J. Earth Sciences 6: 219–229

Bull, W.B. 1972 Recognition of alluvial-fan deposits in the stratigraphic record. In: Rigby, K.J. & W.K. Hamblin (eds) Recognition of Ancient Sedimentary Environments – Soc. Econ. Paleont. Min. Spec. Publ. 16: 63–83

Carling, P.A. 1996 Morphology, sedimentology and palaeohydraulic significance of large gravel dunes, Altai Mountains, Siberia – Sedimentology 43: 647–664

Cherven, V.B. 1984 Early Pleistocene glacial outwash deposits in the eastern San Joaquin Valley, California: a model for humid-region alluvial fans – Sedimentology 31: 823–836

DeCelles, P.G., M.B. Gray, K.D. Ridgeway, R.B. Cole, D.A. Pivnik, N. Pequera & P. Srivastava 1991 Controls of synorogenic alluvial-fan architecture, Beartooth Conglomerate (Paleocene), Wyoming and Montana – Sedimentology 38: 567–590

Fraser, G.S. 1993 Sedimentation in an interlobate outwash stream – Sediment. Geol. 83: 53–70

Fraser, J.Z. 1982 Derivation of a summary facies sequence based on Markov chain analysis ofthe Caledon outwash: a Pleistocene braided glacial fluvial deposit. In: Davidson-Arnott, R. et al.

(eds) Research in Glacial, Glacio-Fluvial and Glacio-Lacustrine Systems. Proc. VI Guelph Symp. Geomorphology (1980), Geo Books, Norwich: 175–202

Gloppen, T.G. & R.J. Steel 1981 The deposits, internal structure and geometry in six alluvial fan-fan delta bodies (Devonian, Norway) – a study in the significance of bedding sequences in conglomerates. In: Ethridge, F.G. & R.M. Flores (eds) Recent and Ancient Non-Marine Depositional Environments: Models for Exploration – Soc. Econ. Paleont. Min. Spec. Publ. 31: 49–69

Harvey, A.M. 1984 Debris flows and fluvial deposits in Spanish Quaternary alluvial fans – implications for fan morphology. In: Koster, E.H. & R.J. Steel (eds) Sedimentology of Gravels and Conglomerates. Canad. Soc. Petroleum Geol. Mem. 10: 123–132

Hubert, J.F. & A.J. Filipov 1989 Debris-flow deposits in alluvial fans on the west flank of the White Mts., Owens Valley, California, U.S.A. – Sediment. Geol. 61: 177–205

Jo, H.R., C.W. Rhee & S.K. Chough 1997 Distinctive characteristics of a streamflow-dominatred alluvial fan deposit: Sanghori area, Kyongsang Basin (Early Cretaceous), southeastern Korea – Sediment. Geol. 110: 51–79

Klimek, K. 1972 Present-day fluvial processes and relief of the Skeidararsandur Plain, Iceland(in Polish, with English summary) – Prace Geogr. Polska Akad. Nauk 94: 1–139

Kochel, R.C. & R.A. Johnson 1984 Geomorphology and sedimentology of humid-temperatealluvial fans, central Virginia. In: Koster, E.H. & R.J. Steel (eds) Sedimentology of Gravels and Conglomerates. Canad. Soc. Petroleum Geol. Mem. 10: 109–122

Kozarski, S. 1990 Ablation sediments of the last glaciation in W. Central Poland: identification and palaeogeographical implications (in Polish, with English summary) – Acta Universitatis Wratislaviensis 1056: 41–60

Lin, K. & K.A.W. Crook 1992 Conglomerate dominated tropical fan-deltas (Pleistocene) from a collision zone, the Markham Valley, Papua New Guinea – Geol. Soc. Australia Abstracts 32: 147–149

Maizels, J. 1989 Sedimentology, paleoflow dynamics and flood history of jokulhlaup deposits: paleohydrology of Holocene sediment sequences in S. Iceland sandur deposits – J. Sediment. Petrology 59: 204–223

Maizels, J. 1993 Lithofacies variations within sandur deposits: the role of runoff regime, flow dynamics and sediment supply characteristics – Sediment. Geol. 85: 299–325

McKee, E.D., E.J. Crosby & H.L. Berryhill 1967 Flood deposits, Bijou Creek, Colorado, June 1965 – J. Sediment. Petrology 37: 829–851

Miall, A.D. 1970 Devonian alluvial fans, Prince of Wales Island, Arctic Canada – J. Sediment. Petrology 40: 556–571

Nemec, W. & A. Muszynski 1982 Volcanoclastic alluvial aprons in the Tertiary of Sofia district (Bulgaria) – Ann. Soc. Geol. Poloniae 52: 239–303

Nemec, W. & R.J. Steel 1984 Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits. In: Koster , E.H. & R.J. Steel (eds) Sedimentology of Gravels and Conglomerates. Canad. Soc. Petroleum Geol. Mem. 10: 1–31

Ritter, J.B., J.R. Miller, Y. Enzel, S.D. Howes, G. Nadon, M.D. Grubb, K.A. Hoover, T. Olsen, S.L. Reneau, D. Sack, C.L. Summa, I. Taylor, K.C.N. Touysinhthiphonexay, E.G. Yodis, N.P. Schneider, D.F. Ritter & S.G. Wells 1993 Quaternary evolution of Cedar Creek alluvial fan, Montana – Geomorphology 8: 287–304

Roberts, S.B., R.W. Stanton & R.M. Flores 1994 A debris flow deposit in alluvial, coal-bearing facies, Bighorn Basin, Wyoming, U.S.A.: evidence for catastrophic termination of a mire – Intern. J. Coal Geol. 25: 213–241

Ruszczynska-Szenajch, H. 1982 Depositional processes of Pleistocene lowland end moraines, and their possible relation to climatic conditions – Boreas 11: 249–260

Sadler, S.P. & S.B. Kelly 1993 Fluvial processes and cyclicity in terminal fan deposits: an example from the L. Devonian of SW Ireland – Sediment. Geol. 85: 375–386

Sah, M.P. & R.A.K. Srivastava 1992 Morphology and facies of the alluvial-fan sedimentation inthe Kangra Valley, Himachal Himalaya – Sediment. Geol. 76: 23–42

Schumm, S.A. 1977 The Fluvial System. Wiley & Sons, New York: 338 pp

Southard, J.B., N.D. Smith & R.A. Kuhnle 1984 Chutes and lobes: newly identified elements of braiding in shallow gravelly streams. In: Koster, E.H. & R.J. Steel (eds) Sedimentology of Gravels and Conglomerates. Canad. Soc. Petroleum Geol. Mem. 10: 51–59

Wells, N.A. 1984 Sheet debris flow and sheet-flood conglomerates in Cretaceous cool-maritime alluvial fans, S. Orkney Islands, Antarctica. In: Koster, E.H. & R.J. Steel (eds) Sedimentology of Gravels and Conglomerates. Canad. Soc. Petroleum Geol. Mem. 10: 133–146

Went, D.J., M.J. Andrews & B.P.J. Williams 1988 Processes of alluvial fan sedimentation, basal Rozel Conglomerate Fm., La Fête des Houghes, Jersey, Channel Islands – J. Geology 23: 75–84

Williams, G.E. 1970 Piedmont sedimentation and Lower Quaternary chronology in Biskraregion of the N. Sahara – Zeitschrift Geomorphol. Suppl. 10: 40–63

Zieliński, T. 1989 Lithofacies and palaeoenvironmental characteristics of the Suwałki outwash (Pleistocene, NE Poland) – Ann. Soc. Geol. Poloniae 59: 249–270

Zieliński, T. & A.J. van Loon 1996 Characteristics and genesis of moraine-derived flowtill varieties – Sediment. Geol. 101: 119–143