



Subaerial terminoglacial fans II: a semi-quantitative sedimentological analysis of the middle and distal environments

T. Zieliński¹ & A.J. van Loon²

¹*Silesian University, Department of Earth Sciences, Będzińska 60, 41-200 Sosnowiec, Poland, e-mail: zielu@us.edu.pl*

²*Geocom, PO Box 336, 6860 AH Oosterbeek, The Netherlands, e-mail: geocom@wxn.nl*

Received 11 January 1999; accepted in revised form 23 June 1999

Key words: facies analysis, fluvio-glacial sedimentation, glacial fan, ice-contact deposits, Poland, semi-quantitative analysis, terminoglacial zone, Weichselian

Abstract

Twenty-five fans in NE Poland, formed under subaerial terminoglacial (previously called 'ice-contact') conditions, were investigated to model the dominant genetic processes involved. These fans show, as do other types, a proximal, a middle and a distal subenvironment. It is found, however, that the characteristics of these subenvironments as present in subaerial terminoglacial fans differ in several respects from those in fans formed under other climatic conditions. The present study deals with the middle and distal subenvironments. These appear to be much less complex than the proximal subenvironment in this type of fan. The middle terminoglacial fan comprises two sandy facies, characterized by unchannelized transport (mainly sheet floods) and stream flows. The distal terminoglacial fan is characterized by one (sandy/silty) facies, resulting from unchannelized currents and from settling in ephemeral ponds; braided streams play a secondary part in this fan subenvironment. The characteristics of the middle and distal fan subenvironments are described and illustrated, as is the facies from the distal subenvironment. Their vertical and lateral relationships are presented in a facies model.

Introduction

The small (commonly 500–1000 m long, exceptionally up to 2 km long) subaerial fans formed just in front of an ice sheet, in the relatively narrow zone where ice-related processes directly affect the sedimentary surface, are termed 'terminoglacial fans' (cf. Brodzikowski & Van Loon 1987, 1991). They are fed with water and sediment from mainly supraglacial sources, as indicated by frequent flowtill intercalations and cappings. They thus have some characteristics in common with 'hochsanders' (Gripp 1975, Heim 1992, Krüger 1997), but they are true fans, no outwash plains. The analysis of subaerial terminoglacial fans formed during former glaciations helps in the reconstruction the previous extent of ice sheets or glaciers and therefore plays a significant part in palaeogeographic reconstructions. Yet, 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. We carried out such a study in NE Poland (Figure 1), where 25 of such fans of Weichselian age were investigated as far as the exposures (mainly sand and gravel pits) allowed. These investigations showed that the fans have characteristics that are, in some respect, different from those of fans formed under other climatic conditions.

The subaerial terminoglacial fans are characterised by spatially distinctly different processes and resulting deposits in, respectively, a proximal, a middle and a distal subenvironment. The deposits of the proximal subenvironment were described in a previous contribution (Zieliński & Van Loon 1999), in which the genesis of the six proximal facies were also analysed. The reader is referred to the just mentioned contribution for further details and introductory re-

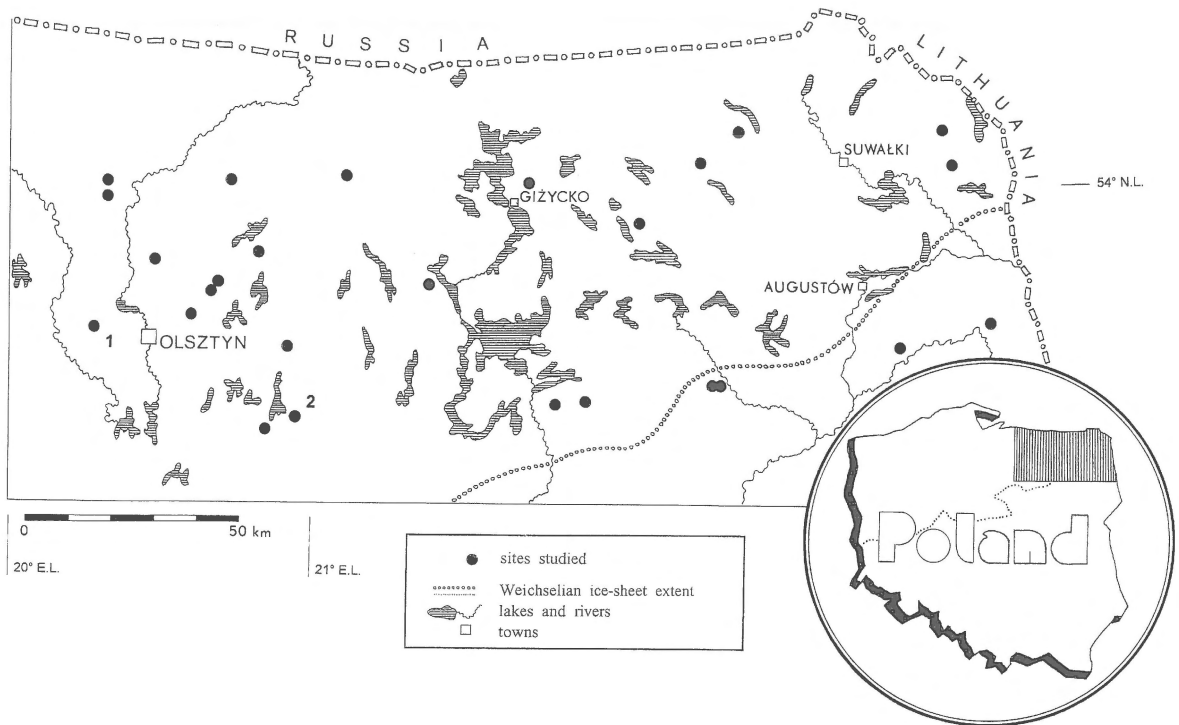


Figure 1. Location of study area and of sites investigated; 1 = Warkały site; 2 = Romany site. The fans described are much too small to show their extent on the present map. The Weichselian ice cover reached its maximum approx. 21 ka ago (Poznan–Lezno stage), leaving a distinct morainic belt, indicated by the open circles. Another morainic belt was left during the Pomeranian stage (approx. 16 ka ago), which can be correlated with the Dryas I stage in Western Europe.

marks concerning the general conditions under which subaerial terminoglacial fans are formed.

The present study focuses on the middle and distal subenvironments, with the objective to increase knowledge of the development of the facies in these subenvironments and to understand their genesis. The final objective is to establish a depositional model for these fans, on the basis of their lithological and structural characteristics. Such a model will be presented in the near future (Zieliński & Van Loon, in press).

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/smaller than 6 cm, as this size forms a common transition between low-energy, small structures (e.g., current ripples) and larger ones of a higher energy level (e.g., dunes); '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.

Description and interpretation of the sediments formed on the middle fan

The deposits found in the middle part (called 'middle fan subenvironment' in the following, commonly indicated as the '*M*-subenvironment') of fans formed under terminoglacial conditions are represented by two facies, which both show a predominance of sands. The sands are found in units that show the configuration of braided channels, and in units that show no channeling (unchannelized current). Gravels – which predominate in the proximal (*P*) subenvironment – are of secondary importance (Figure 3).

The two facies are distinguished on the basis of their most common sedimentary structures (Figure 3). Facies *M-1* is characterised by a frequent occurrence of cross-bedding. Facies *M-2* shows predominantly beds with parallel stratification.

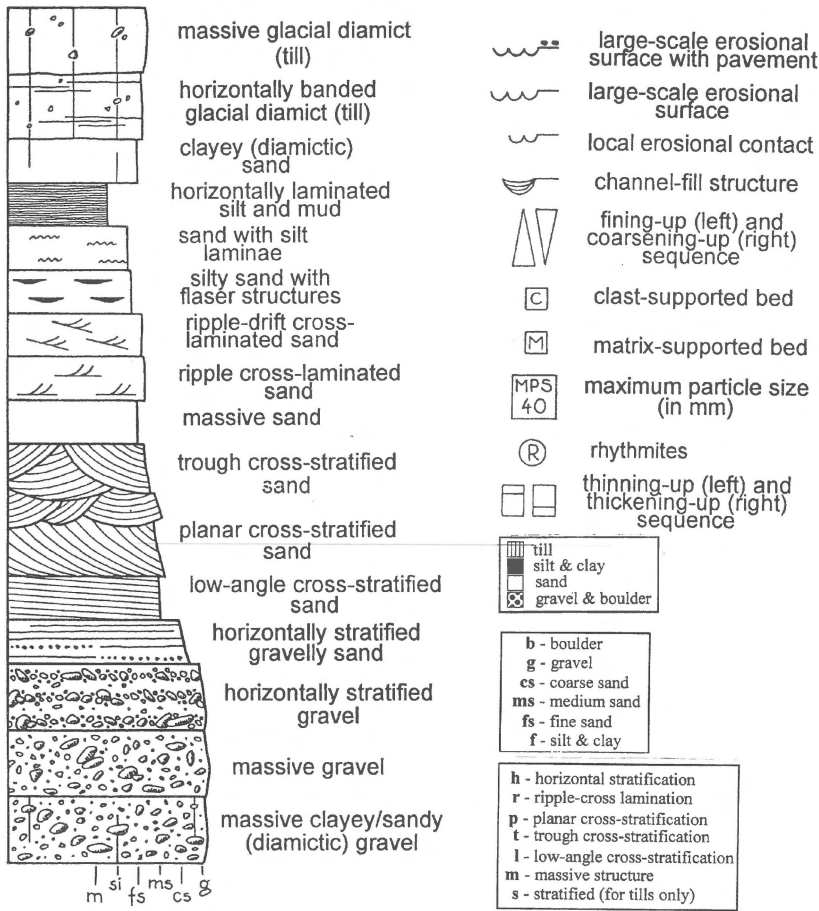


Figure 2. Legend for Figures 3, 5, 7, 10 and 11.

Facies M-1: the middle fan deposits dominated by cross-bedding

Description

The deposits of facies *M-1* consist almost entirely of cross-bedded sands (Figure 4), with part of the cross-bedding filling up ill-defined channels. Most of these channels are shallow, with shoals in between, but more deeply incised channels also occur, characterised by cross-stratified sands with a much larger amplitude than those in the shallow channels.

Medium-grained sands predominate where the channels are shallow; coarse sands play a secondary part. The sands are horizontally stratified or show low-angle cross-stratification. In general, the beds have an intermediate thickness; sometimes they are thick. Gravels are rarely present in this type of channel. Most of the gravels are lag deposits. Besides these coarse-

grained beds, thin beds consisting of horizontally laminated sandy silt are locally present.

The deposits with more deeply incised (though still fairly shallow) channels consist mostly of sand, but thick gravel beds are sometimes present. Trough cross-stratification becomes more frequent towards the top. Large-scale erosional surfaces occur but are fairly rare; if present, they occur most commonly at the erosive bases of matrix-supported, massive sandy gravels. These erosional surfaces are remarkably planar.

Interpretation

The domination of channels, in combination with their predominantly sandy infillings, indicates that a channelised current is the main transporting agent in facies *M-1* (Figure 5).

The sandy sediments with large-scale, tabular cross-bedding form owing to progradation of sandy foreset (transverse) bars (cf. Smith 1971, Church

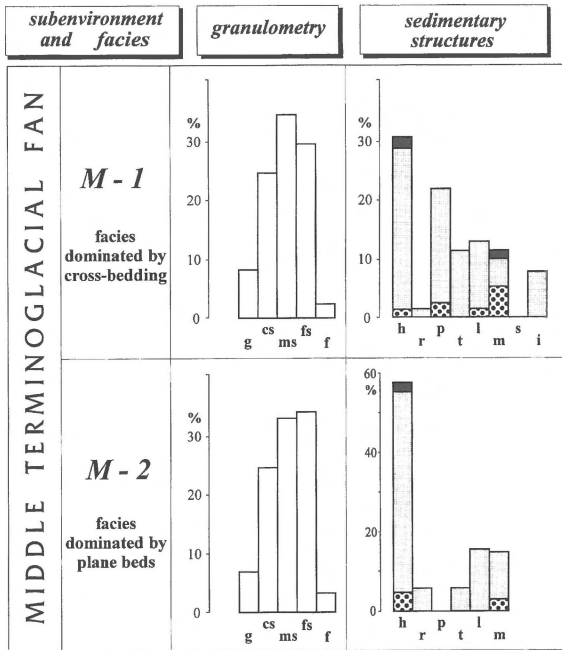


Figure 3. Sedimentological characteristics of the two facies in the middle subenvironment (see Figure 2 for legend). The grain sizes are based on macroscopic analyses in the field, with a 5–10% accuracy. Several dozens of beds were analysed for their grain size at each location, thus yielding an overall accuracy of 3–5%.

& Gilbert 1975, Rundle 1985); these are generally regarded as characteristic of braided channels. The direction of the dip of the lee sides of the bars is remarkably constant, which indicates that the sinuosity of the channels was low to very low. Most of the other sedimentological data point in the same direction. The field observations are consistent with Friend's (1978) conclusion that the depth of braided channels on fans decreases with distance.

The shoals found within the braided channels are sandy and show an upper plane-bed configuration. This combination of data indicates conditions of the upper part of the lower flow regime alternating with transitions to the upper flow regime.

The less common fine sediments presumably form during stages with a small discharge, when short-lived settling from suspension can take place in the abandoned channels. Another possibility is that the fine particles settle in stagnant waters that are dammed off in the wide braided stream.

Some central parts of the braided channels are apparently deeper than most of the channels, because

sand beds of intermediate thickness can develop owing to the formation of dunes. These dunes become flattened during conditions of increasing energy (so-called 'diminished dunes' or 'wash-out dunes': see Allen 1984, Røe 1987), when sands with low-angle cross-stratification develop.

The less common coarse sediments do not fit well in this 'hydrodynamic field'. The sometimes thick gravel beds might be attributed to sudden melt-water floods resulting in accretion of longitudinal bars within deeply eroded channels; the thinner massive sheet-shaped gravel beds are deposited from gravel-rich unchannelised transport close to the braided stream (cf. Boothroyd & Ashley 1975, Hein & Walker 1977, Fraser 1993, Nemeč & Postma 1993).

Facies M-2: the middle fan deposits dominated by plane beds

Description

The most impressive characteristic of facies M-2 is the sheet-like appearance of almost all the beds. Another obvious feature is the uniform character, due to the dominance of sands. Most of the sand beds show a well developed horizontal stratification (Figure 6). Other sands (and some gravels) are massive. Horizontally stratified, matrix-supported sandy gravels occur locally, alternating with horizontally laminated silty sands.

Low-angle cross-stratified sand beds are also present. They tend to have plane boundaries and are intercalated between massive sands. Sand beds with cross-lamination due to current ripples are rare in between but do occur, whereas they do not occur in any of the proximal and middle facies of terminoglacial fans.

Interpretation

The plane character of the beds in facies M-2 is so obvious that only few sedimentary processes need be considered. The combination of grain size and structures in these sands leaves shallow currents of a transitional to upper-flow regime as the most likely possibility. These conditions must be interpreted as being due to sheetfloods that gradually lose their impetus and change into shallow, unchannelised transport over a sandy surface.

This facies is spatially closely related to subfacies P-2a (a sandy/gravelly facies with rhythmities; see Zieliński & Van Loon 1999), in general somewhat more distal, but also laterally and vertically interfin-

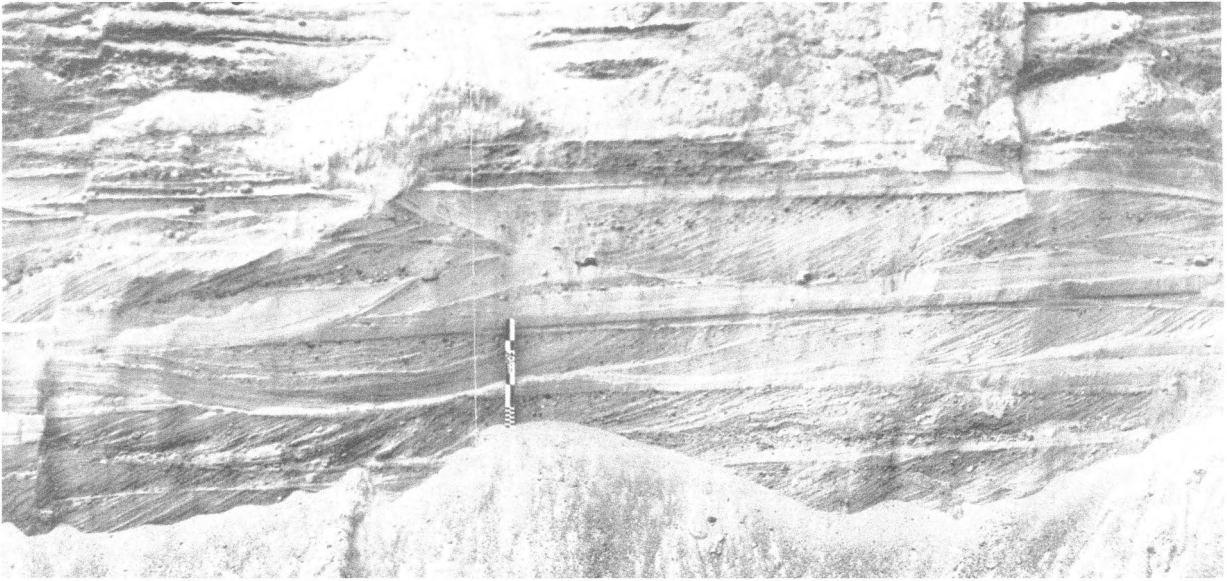


Figure 4. Deposit characteristic of facies M-1. Sandy beds with well developed cross-stratification and shallow channels dominate. Scale = 0.5 m.

gering. Abdullatif (1989) even pointed out that such sands are typical of unchannelised transport in the middle alluvial fan. Todd (1989) also related this lithofacies association to the middle alluvial fan.

Both the morphology of the fan and the hydraulic properties of the currents (discharge, unsteadiness, sediment load) favour the development of sheetfloods. Bull (1972), Wasson (1977, 1979), Heward (1978) and Blair and McPherson (1994) even characterised sheetflood deposits as being typical of the middle alluvial fan. Abdullatif (1989) found in present-day semi-arid fans that channelised currents proceeding on to the outer fan become transformed into unchannelised ones. This was also noticed by Heward (1978) for alluvial fans of Carboniferous age. Sheetflood facies were also found to characterise Pleistocene outwash deposits (Fraser, 1993).

The horizontally stratified sands can thus be interpreted as being classical sheetflood deposits, formed entirely under conditions of the upper plane-bed stage. There are also, however, some intercalations of massive sands. Heward (1978) stated that such massive sands are characteristic of sheetflood deposits; the lack of internal structure may be a primary feature but may also be due to postdepositional fluidisation. Rare intercalations of coarser material are present in this sandy facies. These gravelly sands and sandy gravels must be attributed to major ablational floods resulting in unchannelised currents with

sufficient competence to transport pebbles or even cobbles.

The distribution of the above sediments and the extent of the separate beds indicate that the water masses do not follow channels. The geometry of individual beds with distinct cross-stratification indicates that these sediments form on a flat base, with incisions occurring only locally. In such – elongated – incisions, dunes develop, indicating infrequent currents of relatively deep water. Other beds show cross-stratification of a smaller type; this must be attributed to shallower water currents with lower energy.

It is deduced that this facies mainly reflects a transition zone between the (proximal) subenvironment with high-energy, channelised and unchannelised transport and the (distal) subenvironment with low-energy currents and sandy/silty deposition (Figure 7). Some parts of this facies are probably formed in very shallow, braided channels, as some finer deposits are found that are probably formed at places of relative quietness (dammed off wide channels, etc.).

Conclusions with respect to the middle fan subenvironment

The predominance of sand indicates that the average competence of the currents reaching this subenvironment is lower than that in the proximal subenvironment. Floods with a high discharge may reach this part of the fan, but only exceptionally. Transport and

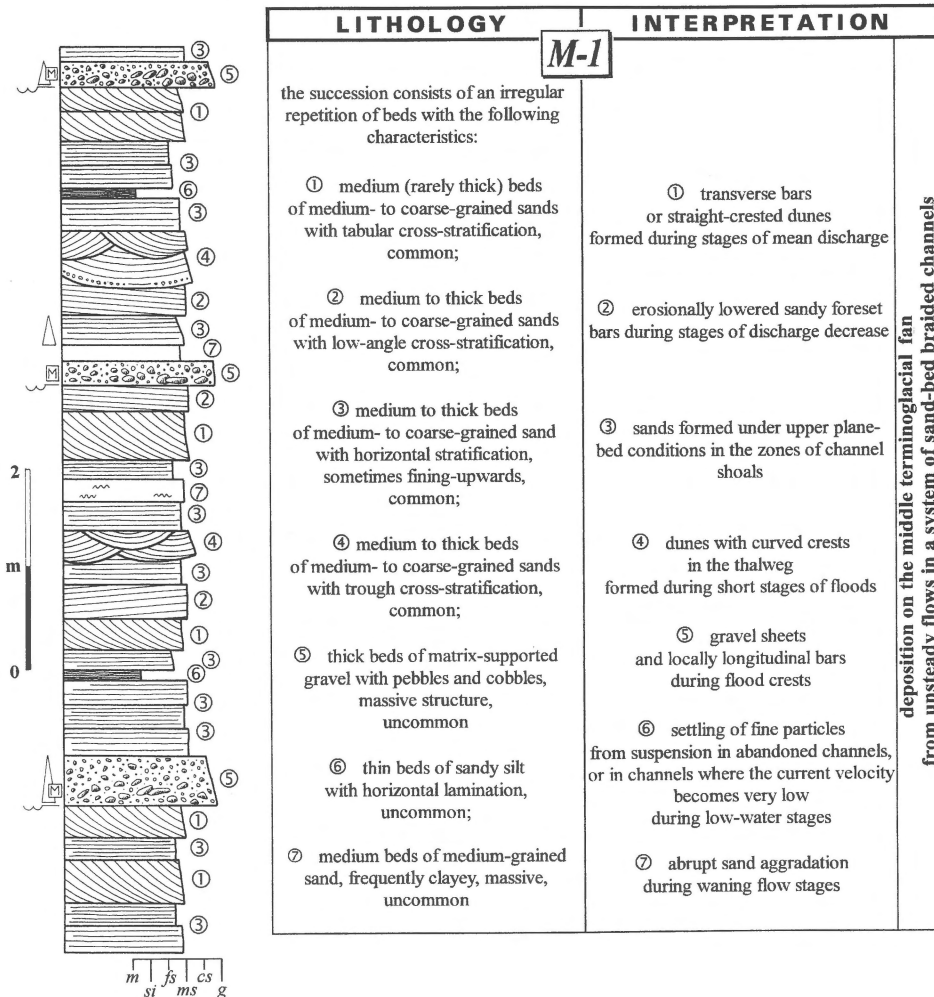


Figure 5. Representative (composite) lithological log and palaeoenvironmental interpretation of facies *M-1* (see Figure 2 for legend).

deposition of particles take place by streams in braided channels with a sandy bottom, and by unchannelised transport. The two facies distinguished in this subenvironment are determined by, respectively, the predominance of bedforms and structures related to channelised transport (facies *M-1*) and plane beds (facies *M-2*).

Rather similar, purely sandy sediments have been reported in other middle fans (e.g., Abdullatif 1989). McGowen & Groat (1971) attributed such sediments, with a minor contribution of laminated fines, to a braided distributary. Zieliński (1989) examined a Pleistocene outwash fan with analogous deposits from a shallow braided channel. Brierly et al. (1993) identified the facies with slightly channelized flows (which they termed 'stratified sheet deposits') in alluvial fans.

The predominance of sand in this subenvironment reflects the intermediate position within the fan. The slopes are still steep enough for transport of sand-sized material but are in general insufficiently steep to generate mass flows (although some low-density flows reach this subenvironment in the form of stream slurries). Sheetfloods, however, are still common.

Shallow braided channels with currents of alternately high and low energy are common.

The distinction between two facies in the middle terminoglacial fan is supported by differences in the frequencies of the various architectural elements (Figure 8).



Figure 6. Deposit characteristic of facies M-2. The uniform sheet-like sand layers display well developed horizontal stratification and lamination. Romany site.

Overview of processes and deposits in the mid-fan subenvironment

In the mid-fan (*M*) subenvironment, many authors (e.g., Amajor 1986) interpret abundant deposits as being a result of grainflow. We did – surprisingly – not recognise any of such sediments, however. Some inversely graded beds (the most conspicuous criterion of grainflow deposits) occur, particularly in facies *M-2*, but ‘grainflow freezing’ can also take place in high-energy sheetflows (Lowe 1982), in the near-bottom zone where the sediment concentration is high enough to induce non-Newtonian (i.e., nonhydraulic) transport and deposition (the thus formed traction carpet and the high-energy sheetflow form what is called a ‘sheetflood slurry’). The basic support mechanism in a traction carpet is intergranular collision, fairly similar to that in ‘true’ grainflow (cf. Moss 1972, Allen & Leeder 1980, Todd 1989). The conditions required for such a process do not take place on the subaerial middle terminoglacial fan. One must deduce that grainflow deposits on the fans described here are most likely absent because the mass flows of till material are too cohesive owing to the high percentage of silt and clay (cf. Bertran et al. 1997), supplied by the meltwater flows; grainflows can develop only in ma-

terial with very little cohesion or no traceable cohesion at all.

In the middle subenvironment, where braided channels dominate, the currents follow a large number of shallow braided channels; this contrasts with the most common situation on other fans, where the main channel takes most water (cf. Friend 1978). Whereas Cherven (1984) and Amajor (1986) noted abundant channel-fills up to 2 m thick in the middle zone, such indications of deep channels are absent in terminoglacial fans. This is a logical consequence of the difference in the system of channels, but may – at least partially – also be a result of the aggradation ratio, which is, as a rule, higher on terminoglacial fans than on nonglacigenic fans.

Description and interpretation of the sediments formed on the distal fan

The sediments in the distal parts of terminoglacial fans tend to form beds of limited thickness, consisting mainly of a mixture (or alternations) of sands and finer material. Although the sediments in this subenvironment show some differences, they have so much in

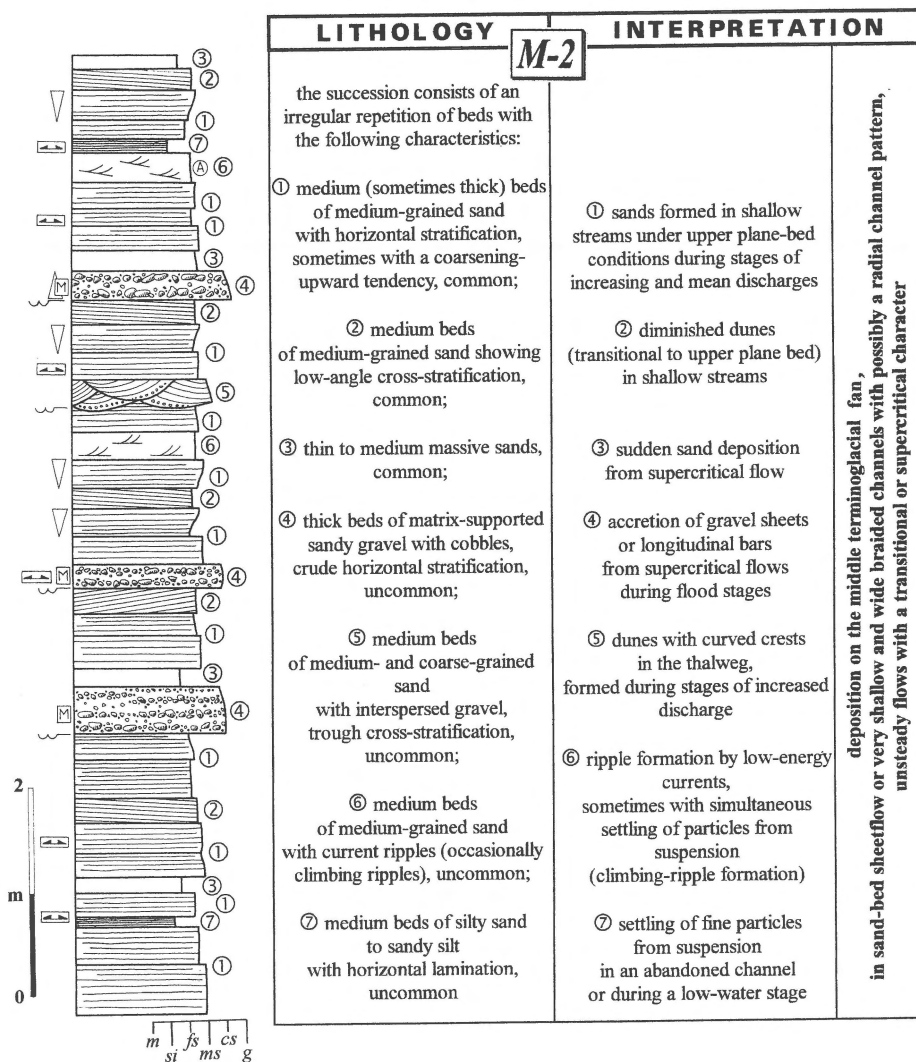


Figure 7. Representative (composite) lithological log and palaeoenvironmental interpretation of facies M-2 (see Figure 2 for legend).

common that it seems appropriate to consider them all as one single facies. Most of these deposits form sheet-like plane beds that consist mainly of fine sands and sandy silts. The beds often have a rhythmic character: medium-scale beds of horizontally laminated sands alternate with small-scale sandy/silty beds, which also show horizontal lamination. The medium-scale sandy beds sometimes show small-scale current ripples (Figure 9). These ripples tend to be concentrated in the basal parts of the beds, but do also occur at higher levels. There are also sets with climbing ripples; these commonly have an intermediate thickness.

The contacts between the individual beds are sometimes irregular but never erosional. Some small scour-and-fill structures are, however, present.

Interpretation

The generally small grain size (compared with that of the sediments of the proximal and middle fans) indicates that the competence of the flows must have been relatively low, although an upper plane-bed regime was commonly reached. The sandy, horizontally laminated, plane beds represent shallow, unchannelised transport of low power. Scott et al. (1969) and Amajor (1986) described sand beds formed under similar

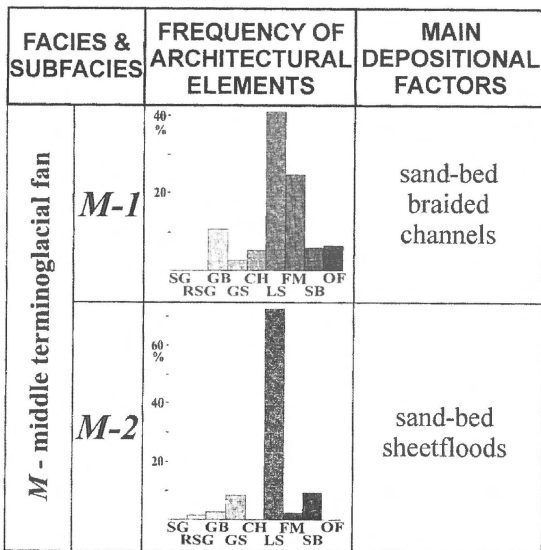


Figure 8. Overview of the architectural elements characteristic of the middle fan subenvironment. The elements were quantified by counting of the relevant parameters in several representative vertical profiles within each outcrop. The data thus obtained were added for all exposures and relative frequencies were then calculated.

conditions, with both horizontal and cross-lamination; these sands were intercalated with silt beds. They interpreted these beds as being distal, unchannelised flows. Fairly comparable facies were mentioned by Wu Chonglong et al. (1992), Dreyer (1993) and Hartley (1993), who interpreted the deposits as distal sheetfloods.

The beds of this facies are predominantly sandy, but silty sands and sandy silts are also present. Most of the beds show cross-lamination representing current ripples from the lower flow regime. The horizontal lamination in the fine-grained deposits represents phases of settling from suspension in relatively quiet water. The layering, the grain-size distribution and the sedimentary structures, in combination with the lateral extent of the layers and the vertical successions, indicate that deposition of such sediments took place in a very wide and very shallow braided stream. The silty material probably settles in abandoned channels or in small pools or lakes that can develop on the nearly horizontal surface of the distal fan.

The interpretation (ephemeral, wide braided streams in the marginal zone of a terminoglacial fan; see Figure 10) is consistent with other observations. Wasson (1977) described shallow channels with sandy infillings and an increase in a distal direction in the relative amount of fine material that had settled from sus-

pension. The currents in the channels presumably have an ephemeral character, which also holds for ponds or small lakes (cf. Mukerji, 1976). Ruszczynska-Szenajch (1982) described horizontally laminated silts and sands formed under comparable conditions and interpreted them as being marginal pond sediments of terminoglacial fans.

The most common grain sizes in this subenvironment (sand and finer) reflect the reduced competence of the water flows. Unchannelised flows – with a relatively low energy – dominate this subenvironment. Ephemeral, wide and very shallow braided streams are of secondary importance; their deposits are comparable to those formed by the unchannelised currents. Quantitative analysis of the characteristics of the deposits building up the distal fan confirms the palaeoenvironmental interpretation (Figure 11).

Overview of processes and deposits in the distal-fan subenvironment

Friend (1978) states that the distal (*D*) subenvironment of fans is characterised by a system of numerous distributary channels, which is consistent with our observations that this subenvironment is dominated by abundant low-energy, unchannelised currents and deposition in shallow, ephemeral ponds. Our findings are also similar to those of Beaty (1990), whose model of the distal subenvironment includes numerous sand-bed braided channels and overflows. This is, however, not consistent with the characteristics described by Krigström (1962) and Fahnstock (1963), who state that a single, broad channel dominates in this subenvironment, too; these studies, however, concern sandurs rather than true fans.

The large, deep channels described for distal fans under most climatic conditions explain why gravel beds are considered to be common and why alluvium can be repeatedly reworked by such channels (cf. Blair 1987). This must be considered in the context of the slope, which tends to be much steeper outside than inside the terminoglacial zone, as detailed above. The relatively steep slope in other climatic zones also explains why several researchers (among others, McGowen & Groat 1971, Harvey 1984) mention much higher energy levels for the distal fan than are justified for terminoglacial conditions; Harvey (1984) states that up to 80% of the sediments in the distal subenvironment may consist of fluvial gravel, whereas sand is the coarsest material found in distal terminoglacial fans.

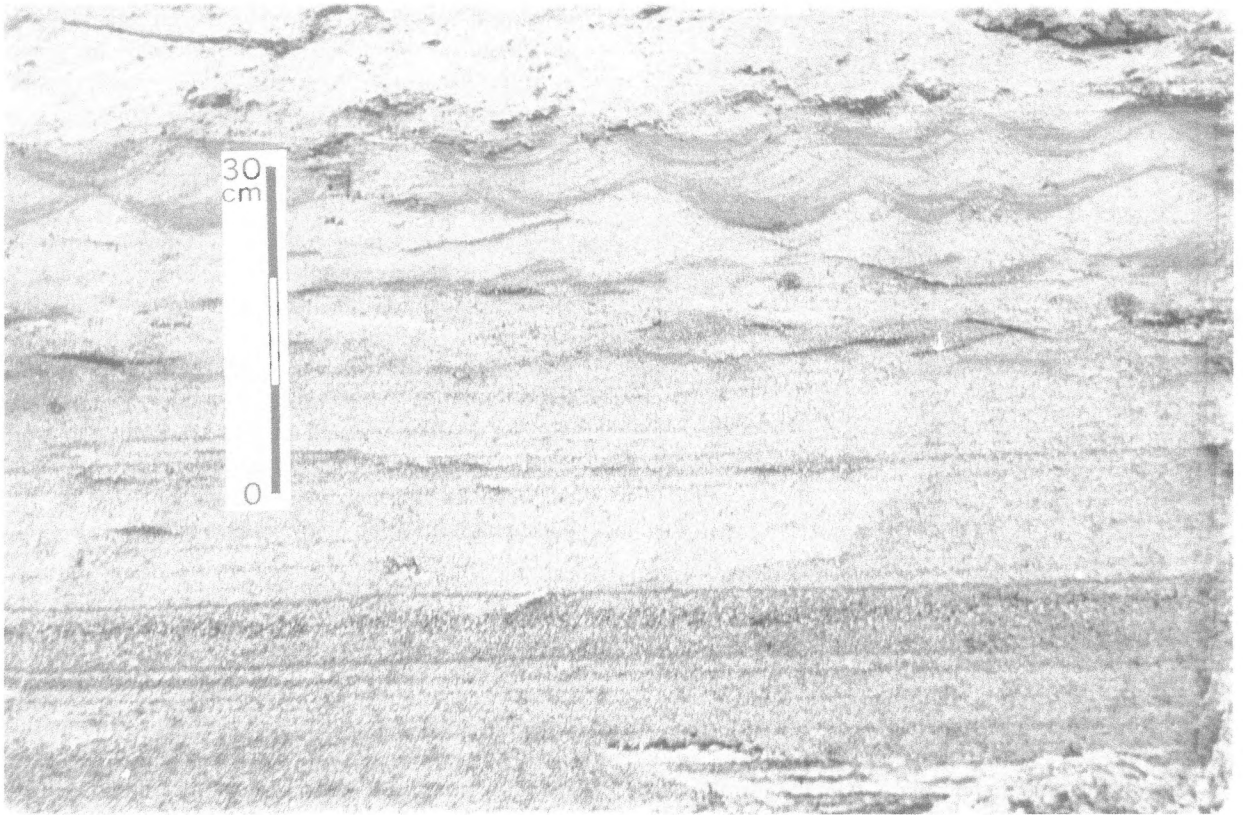


Figure 9. Deposits characteristic of subenvironment *D*, showing a rhythmic alternation of sands with ripple-derived cross-lamination and horizontally laminated silts. The scale is 0.5 m. Warkaly site.

The dominance of unchannelised flows and transport through numerous shallow channels explains why the distal subenvironment of terminoglacial fans does not contain pointbar deposits. Such deposits, which McGowen & Garner (1970) consider to be characteristic, require large rivers that can develop a sinuous course on exceptionally large fans (megafans).

Conclusions

The particles that build up these parts are supplied by flows with highly variable discharge, but the sedimentary dynamics are much less dynamic than in the proximal fan. Typical channel deposits are of minor importance, so that the sediments form part of an intermediate-type fan according to the classification by Harvey (1984).

The middle part of subaerial terminoglacial fans has an extent intermediate between the larger proximal fan and the smaller distal fan. Sand accumulation dominates, partly in braided channels (facies *M-1*) but

more commonly as sand-bed sheetflows (facies *M-2*). Meltwater flows are commonly shallow in both facies, where sand is deposited mainly under the hydraulic conditions of the upper plane-bed flow regime, but the energy of the transporting agents is distinctly lower than described for most arid and semi-arid fans, which also tend to have a gravel-rich middle part (McCowen & Groat 1971, Blair 1987, Todd 1989, Viseras & Fernandez 1995). Another difference is the lack of deposition by grainflow that tends to dominate the sedimentation on middle fans developing in other environments, because water is transported on most middle fans – according to the literature – through channels.

The gradual transition zone between the middle and the distal fan is characterised by a decrease in bed thickness. This illustrates the distinctly different aggradation rates in the middle and the distal terminoglacial fan.

The – comparatively small – distal part of subaerial terminoglacial fans is more alike its distal counterparts formed under other conditions, although the propor-

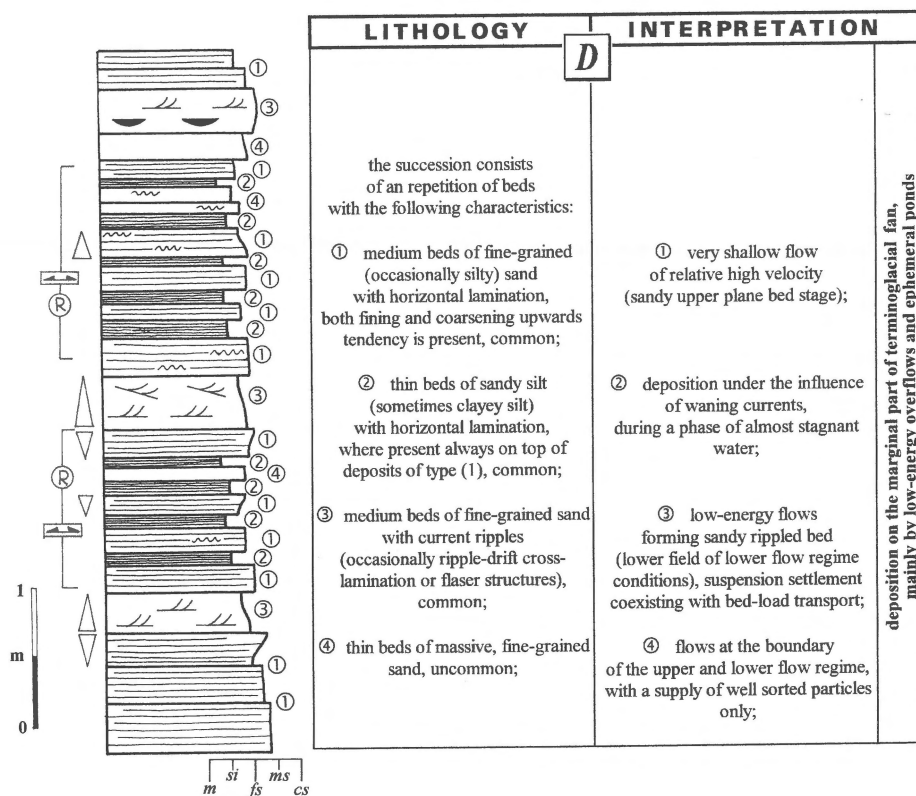


Figure 10. Representative (composite) lithological log and palaeoenvironmental interpretation of subenvironment *D* (see Figure 2 for legend).

tion of relatively coarse particles is much lower than the average value found in the literature for other distal fans (cf. Harvey 1984, Blair 1987). Accumulation of sandy/silty deposits takes place from low-energy sheetflows, in slow currents and in stagnant pools. The position of the sediments on top of deposits belonging to a proximal or middle fan facies underlines that subaerial terminoglacial fans commonly build up regressive sequences.

The rhythmic character of the successions in both the middle and the distal fan results from cyclic variations in the ablation rate of the nearby ice; it represents possibly a diagnostic criterion of these fans, since comparable cycles are not known from fans developed under other climatic conditions.

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

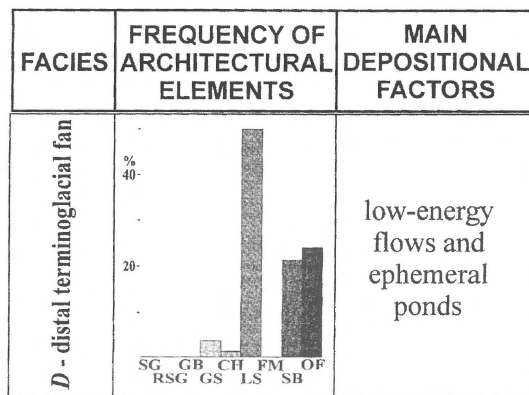


Figure 11. Overview of the architectural elements characteristic of the distal fan subenvironment (*D*). See Figure 2 for legend. Overview of the architectural elements characteristic of the middle fan subenvironment. The elements were quantified by counting of the relevant parameters in several representative vertical profiles within each outcrop. The data thus obtained were added for all exposures and relative frequencies were then calculated.

Brodzikowski (University of Łódź, Department of Geography) are also greatly appreciated. We are much indebted to Liza Crossan (WritelRight) for continuous support and for correcting the English text.

References

- Abdullatif, O.M. 1989 Channel-fill and sheet-flood facies sequences in the ephemeral terminal River Gash, Kassala, Sudan – *Sediment. Geol.* 63: 171–184
- Allen, J.R.L. 1984 Sedimentary structures, their character and physical basis (Developments in Sedimentology, 30). Elsevier, Amsterdam
- Allen, J.R.L. & M.R. Leeder 1980 Criteria for the instability of upper-stage plane beds – *Sedimentology* 27: 209–217
- Amajor, L.C. 1986 Alluvial fan facies in the Miocene-Pliocene coastal plain sands, Niger delta, Nigeria – *Sediment. Geol.* 49: 1–20
- Beaty, C.B. 1990 Anatomy of a White Mts. debris flow – the making of an alluvial fan. In: Rachocki, A.H. & M. Church (eds) *Alluvial Fans: A Field Approach*. Wiley & Sons, Ltd.: 69–89
- Bertran, P., B. Héту, J.-P. Texier & H. Van Steijn 1997 Fabric characteristics of subaerial slope deposits – *Sedimentology* 44: 1–16
- Blair, T.C. 1987 Sedimentary processes, vertical stratification sequences, and geomorphology of the Roaring River alluvial fan, Rocky Mt. National Park, Colorado – *J. Sediment. Petrol.* 57: 1–18
- Blair, T.C. & J.G. McPherson 1994 Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages – *J. Sediment. Res.* 64: 450–489
- Boothroyd, J.C. & Ashley, G.M. 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 Glaciolacustrine Sedimentation*. Soc. Econ. Pal. Min. Spec. Publ. 23: 193–222
- 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-Sci. Rev.* 24: 297–381
- Brodzikowski, K. & A.J. van Loon 1991 *Glacigenic Sediments* (Developments in Sedimentology, 49). Elsevier, Amsterdam
- Bull, W.B. 1972 Recognition of alluvial-fan deposits in the stratigraphic record. In: Hamblin, W.K. & J.K. Rigby (eds) *Recognition of Ancient Sedimentary Environments*. Soc. Econ. Paleont. Mineral. Spec. Publ. 16: 63–83
- 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
- Church, M. & Gilbert, R. 1975 Proglacial fluvial and lacustrine sediments. In: Jopling, A.V. & B.C. McDonald (eds) *Glaciofluvial and Glaciolacustrine Sedimentation*. Soc. Econ. Pal. Min. Spec. Publ. 23: 22–100
- Dreyer, T. 1993. Quantified fluvial architecture in ephemeral stream deposits of the Esplugafreda Fm. (Paleocene), Tremp-Graus Basin, N Spain – *Int. Ass. Sediment. Spec. Publ.* 17: 337–362
- Fahnestock, R.K. 1963 Morphology and hydrology of a glacial stream – White River, Mount Rainer, Washington – *U.S. Geol. Surv. Prof. Paper* 422-A
- Fraser, G.S. 1993 Sedimentation in an interlobate outwash stream – *Sediment. Geol.* 83: 53–70
- Friend, P.F. 1978 Distinctive features of some ancient river systems. In: A.D. Miall (ed.) *Fluvial Sedimentology*. Can. Soc. Petrol. Geol. Mem. 5: 531–542
- Gripp, K. 1975 Hochsander-Satzmoräne-Endmoränen Vertreter – *Zeitschr. Geomorphol.* NF 19: 490–496
- Hartley, A.J. 1993 Sedimentological response of an alluvial system to source area tectonism: the Seilao Member of the Late Cretaceous to Eocene Purilactis Fm. Of N Chile – *Int. Ass. Sediment. Spec. Publ.* 17: 489–500
- 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*. Can. Soc. Petrol. Geol. Mem. 10: 123–132
- Heim, D. 1992. Sandergene und Gletscherentwässerung am Kötluökull (Höfðabrekkjukull), Südisland – *Polarforschung* 62: 95–128
- Hein, F.J. & R.G. Walker 1977 Bar evolution and development of stratification in the gravelly, braided, Kicking Horse River, British Columbia – *Can. J. Earth Sci.* 14: 562–570
- Heward, A.P. 1978 Alluvial fan and lacustrine sediments from the Stephanian A and B (La Magdalena, Ciñera-Matallana and Sabero) coalfields, N. Spain – *Sedimentology* 25: 451–488
- Krigström, A. 1962 Geomorphological studies of sandur plains and their braided rivers in Iceland – *Geogr. Ann.* 44: 328–346.
- Krüger, J. 1997 Development of minor outwash fans at Kötluökull, Iceland – *Quat. Sci. Rev.* 16: 649–659
- Lowe, D.R. 1982 Sediment-gravity flows. II. Depositional models with special reference to the deposits of high-density turbidity currents – *J. Sediment. Petrol.* 52: 279–297
- McGowen, J.H. & L.E. Garner 1970 Physiographic features and stratification types of coarse grained point bars: modern and ancient examples – *Sedimentology* 14: 77–111
- McGowen, J.H. & C.G. Groat 1971 Van Horn Sandstone, W. Texas: an alluvial fan model for mineral exploration – *Univ. Texas Rept. Invest.* 72: 1–57
- Moss, A.J. 1972 Bed-load sediments – *Sedimentology* 18: 159–219
- Mukerji, A.A. 1976 Terminal fans of inland streams in Sutlej-Yamuna Plain, India – *Z. Geomorph.* N.F. 20: 190–204
- Nemec, W. & G. Postma 1993 Quaternary alluvial fans in SW Crete: sedimentation processes and geomorphic evolution. In: Marzo, M. & C. Puigdefabregas (eds) *Alluvial Sedimentation*. Int. Assoc. Sediment. Spec. Publ. 17: 235–276
- Røe, S.L. 1987 Cross-strata and bedforms of probable transitional dune to upper-stage plane-bed origin from a L. Precambrian fluvial sandstone, N. Norway – *Sedimentology* 34: 89–101
- Ruszczynska-Szenajch, H. 1982 Depositional processes of Pleistocene lowland endmoraines, and their possible relation to climatic conditions – *Boreas* 11: 249–260
- Scott, A.J., R.A. Hoover & J.H. McGowen 1969 Effects of hurricane 'Beluah' 1967 on Texas coastal lagoons and barriers. In: *Sobre lagunas costeras*. UNESCO Simp. Intern.: 221–236
- Smith, N.D. 1971 Transverse bars and braiding in the lower Platte River, Nebraska – *Geol. Soc. Amer. Bull.* 82: 3407–3420
- Todd, S.P. 1989 Stream-driven, high-density gravelly traction carpets: possible deposits in the Traberg Conglomerate Fm., SW Ireland and some theoretical considerations of their origin – *Sedimentology* 36: 513–530
- Wasson, R.J. 1977 Last-glacial alluvial fan sedimentation in the Lower Derwent Valley, Tasmania – *Sedimentology* 24: 781–799
- Wasson, R.J. 1979 Sedimentation history of the Mundi alluvial fans, W. New Wales – *Sediment. Geol.* 22: 21–51

- Wu Chonglong, Li Sitian & Cheng Shoutian 1992 Humid-type alluvial-fan deposits and associated coal seams in the L. Cretaceous Haizhou Fm., Fuxin Basin of NE China. In: McCabe, P.J. & J.T. Parrish (eds) Controls on the Distribution and Quality of Cretaceous Coals. Geol. Soc. Amer. Spec. Paper 267: 269–286
- 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 1999 Subaerial terminoglacial fans I: a semi-quantitative sedimentological analysis of the proximal environment – Geol. Mijnbouw 77: 1–15
- Zieliński, T. & A.J. van Loon (in press) Subaerial terminoglacial fans III: overview of sedimentary characteristics and depositional model – Geol. Mijnbouw.