

Subaerial terminoglacial fans III: overview of sedimentary characteristics and depositional model

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Abstract

A general model is presented for the small type of fans (not to be confused with sandurs) that develop subaerially in the zone immediately before an ice front. These fans have in common with other fans that a proximal, a middle and a distal subenvironment – with distinctly different sedimentary facies – can be distinguished. The characteristics of these fans differ in several respects, however, from those formed under other conditions, particularly by the high proportion of mass-flow deposits in the proximal part, by the relative scarcity of fine particles in the middle fan, and by the relatively uniform character of the sediments in the distal fan.

The special character of this type of fan is ascribed to the interaction of a continuously changing distance between the ice front and the fan (as a result of alternating phases of ice advance and ice retreat), its position that may be surrounded by ice for a large part, and the irregular supply of debris-laden meltwater that comes sometimes even in the form of more or less catastrophic floods.

Due to the fact that terminoglacial fans have a good preservation potential only during phases of ice retreat, these fans tend to show a slight fining-upward tendency. The slope of terminoglacial fans tends to be more gentle (rarely over 2-5°) than that of fans formed under different conditions.

Keywords: depositional model, facies analysis, glacial fan, Poland, terminoglacial zone, Weichselian

Introduction

The analysis of fans formed in the narrow zone just in front of an ice mass ('terminoglacial fans', following the nomenclature of Brodzikowski & Van Loon, 1987, 1991) helps in the reconstruction of the previous extent of such ice masses. Analysis of terminoglacial fans of Pleistocene age therefore plays a significant part in palaeogeographic reconstructions of Pleistocene glaciations, particularly in previously glaciated lowland areas.

It appears that much confusion exists regarding the term 'fan', and also that terminoglacial fans are confused with sandurs (see, for instance, Leeder, 1999). There are, however, important differences between sandurs (also known as 'glacial outwash plains') and terminoglacial fans. Good overviews with useful dis-

cussions about what fans are (and of what they are not) have been provided by Blair & McPherson (1994a,b). We want to emphasize that our investigations were restricted to fans and did not deal with sandurs.

We carried out sedimentological analyses of twenty-seven fans in NE Poland (Fig. 1), with emphasis on semi-quantitative investigations of grain size and sedimentary structures. The fans had been formed just in front of the Weichselian ice sheet. In two earlier contributions, we presented the semi-quantitative analyses carried out in the proximal subenvironment (Zieliński & Van Loon, 1998) as well as in the middle and distal subenvironments (Zieliński & Van Loon, 1999). In these contributions, we distinguished three sedimentary facies of the proximal terminoglacial fan. Facies *P-1* is dominated by diamicts and contains two

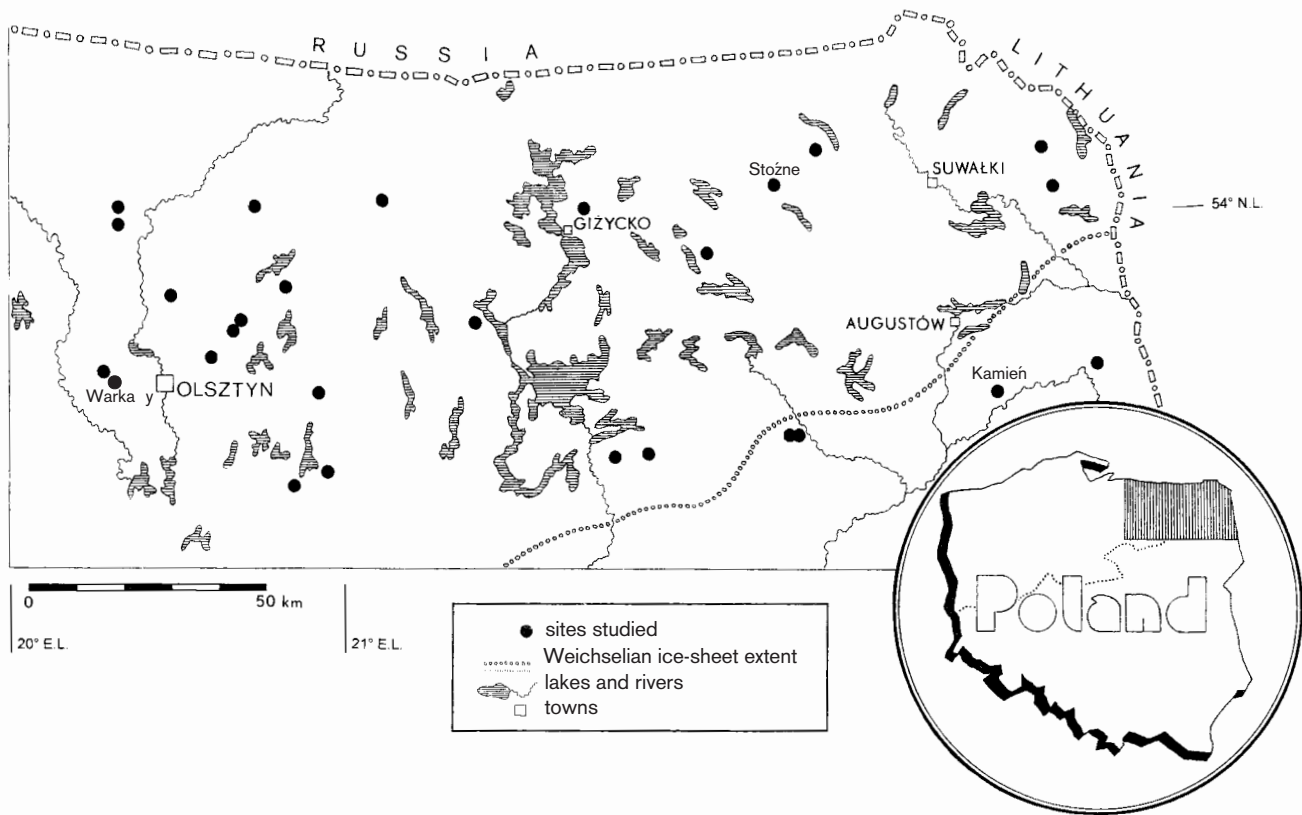


Fig. 1. Location of study area and of sites investigated.

subfacies: *P-1a* formed by flowtills and gravel-bed streams, and *P-1b* consisting of reworked flowtills. Facies *P-2* is built up by beds of gravelly sand and is subdivided into two subfacies: *P-2a* is formed by sheetflows and *P-2b* by sheetflows and channelized flows. Facies *P-3* includes gravel and sand beds; its subfacies were formed by catastrophic, hyperconcentrated flows (*P-3a*) and in gravel-bed channels (*P-3b*) (Fig. 2). The middle fan environment comprises two – mainly sandy – facies: *M-1* is formed in sand-bed braided channels (Fig. 3), and *M-2* is formed by

sand-bed sheetflows. Only one fan facies is found in the distal environment (*D*). This facies consists of fine sands and silts (Fig. 4) deposited by low-energy sheetflows and by settling in ephemeral ponds. We refer the reader to the just mentioned contributions on these fans for more details about the granulometric data, the sedimentary structures and the interpretation of the processes involved, as well as for further details and introductory remarks concerning the general conditions under which subaerial terminoglacial fans are formed.



Fig. 2. Deposit characteristic of subfacies *P-3b*. Medium-scale gravel beds (both massive and crudely stratified) intercalate with sheet-shaped beds consisting of horizontally laminated sands. The scale is 0.5 m long. Stożne site.



Fig. 3. Deposit characteristic of relatively proximal deposits of facies M-1. The gravels and sands were deposited in braided channels. Section approx. 3 m high. Kamią site.

Most terminoglacial fans are 10-30 m thick, most commonly 20-25 m. They show comparable vertical developments, but rarely completely or exactly according to an 'ideal' scheme. Combining data makes it possible, however, to establish composite sections that show all the relevant aspects in a logical (often repeated) succession. Such successions comprise several facies and show characteristic features that reflect the qualitative and quantitative changes in the transporting and depositional agents, and thus in the de-

positional environment. It should be noted that sedimentary and erosional processes in the terminoglacial subenvironment are exceptionally changeable.

The present study focuses on the framework in which the processes took place that must be held responsible for the aggradation of the terminoglacial fans. The objective is the development of a model that will improve the understanding of the genesis of fans formed under these conditions, facilitate their recognition in the field, and deepen the insight into the erosional and depositional processes that play a part in the transformation of true moraines (i.e., glacial tills) into fans.

General model

Debris left behind by stagnant and retreating glaciers is affected by a number of superficial processes that result, partly during and partly after the building up of marginal moraines, in the formation of fans under terminoglacial conditions. The main process involved is transport under the influence of meltwater – both hydraulic transport of individual grains by meltwater currents and transport by various types of mass-flow processes.

Subenvironments and energy conditions

The processes in the terminoglacial zone responsible for the formation of fans, like those under other environmental conditions, result in the surface of the fan having a decreasing slope. The energy conditions therefore diminish from the apex downwards. This is reflected in a gradual decrease in grain size, which allows three subenvironments to be distinguished: a



Fig. 4. Deposit characteristic of subenvironment D, showing a rhythmic alternation of sands with ripple-derived cross-lamination and horizontally laminated silts. The section is approx. 30 cm thick. Warkaty site.

proximal subenvironment in which gravels dominate, a middle subenvironment with mainly sand (but with some gravel), and a distal subenvironment of predominantly sand and finer material. The sediments in the three subenvironments differ in their sedimentological characteristics (bedforms, structures, etc.), thus reflecting the various transporting and depositional conditions.

The proximal subenvironment is represented by the coarsest sediments (gravel and coarse sand). Mass-flow processes (both subaerial and subaqueous) play a dominant part (cf. Selby, 1994), due to the water-saturated character of most sediments under these conditions. The resulting clayey flowtills and gravelly debris-flow deposits commonly undergo subsequent reworking by currents (Fig. 5). High-energy conditions during large meltwater floods, in combination with steep slopes, result in unchanneled transport of meltwater rich in gravel. Sudden outbursts of huge amounts of meltwater result in high-density streams through the channels, which sometimes be-

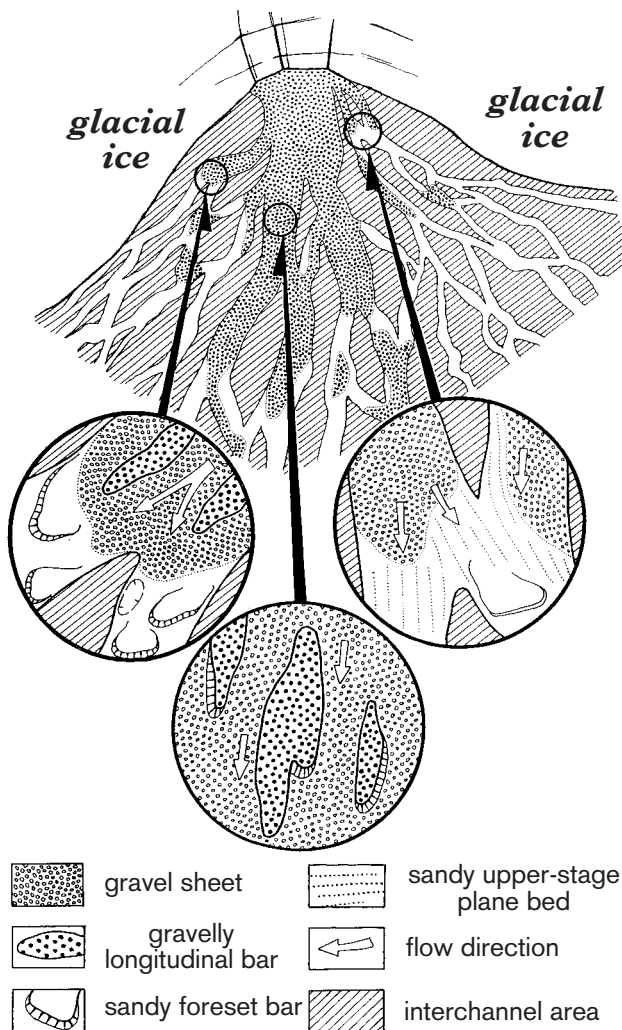


Fig. 5. Generalised palaeoenvironmental model of the proximal fan dominated by gravel-bed streams (subfacies P-3b).

come deeply incised. In such channels with transport transitional between mass flow and stream flow instantaneous deposition can develop. Quieter conditions result in braided streams, but are of minor importance with respect to the aggradation of the fan.

The middle subenvironment consists predominantly of sands. These are deposited by both sheetfloods and braided streams (Fig. 6). Transport and deposition take place in a more uniform way than in the proximal subenvironment (as the effects of sudden outbursts of meltwater from the ice-sheet become less catastrophic with distance regarding both discharge and stream power), but still largely under upper plane-bed conditions.

The distal subenvironment is characterised by accretion of sandy/silty sediments. Ephemeral, shallow streams and ponds are the main depositional sites (Fig. 7). The energy of the flows has decreased so much in this subenvironment that many sands show current ripples formed in the lower flow regime, though some sands are still deposited under upper

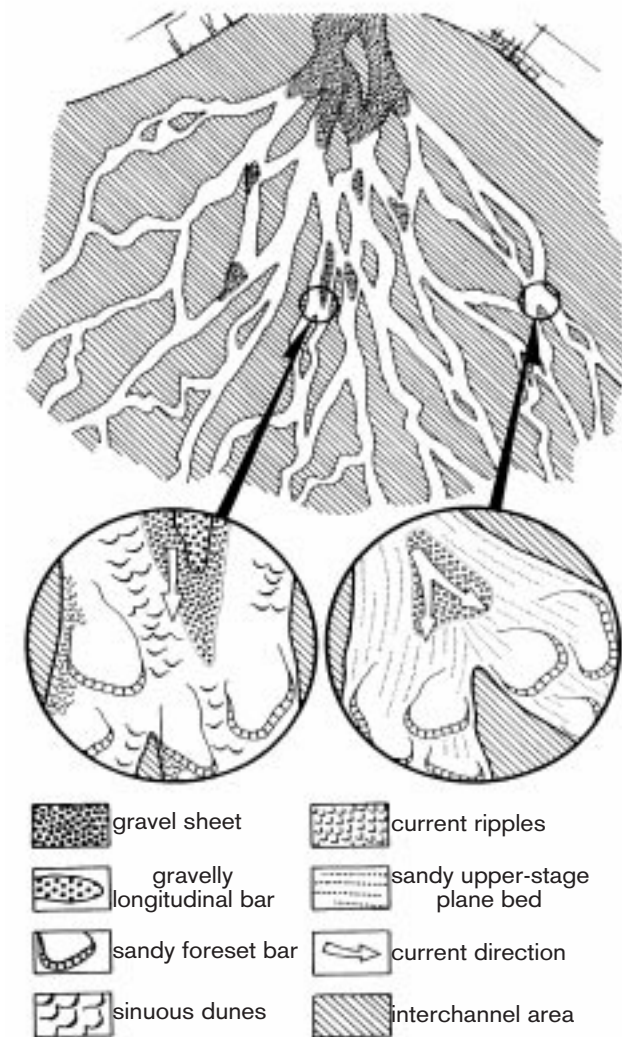


Fig. 6. Generalised palaeoenvironmental model of the middle fan dominated by sand-bed streams (facies M-1).

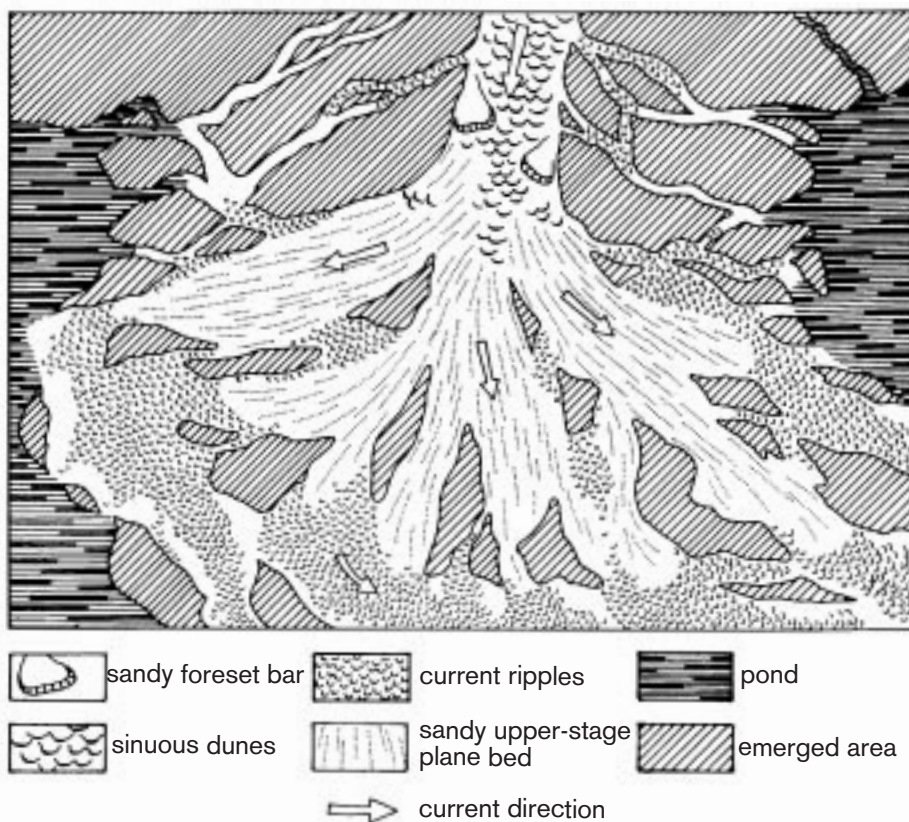


Fig. 7. Generalised palaeoenvironmental model of the distal fan (subenvironment D).

plane-bed conditions (very shallow, distal sheetflows). Silts settle in standing waters. As a rule, these relatively fine-grained deposits cap the successions of the fans and form their margins.

Bed thickness and frequency of erosional surfaces

The proximal, middle and distal subenvironments have different average bed thicknesses (calculated on the basis of 600-800 measurements per subenvironment): 85 cm, 25 cm and 15 cm, respectively. This decrease is primarily due to an energy decrease of the currents with increasing distance and thus in their transport capacity; a secondary reason is the increase in the length of the respective subenvironments and thus, because of the cone-like configuration of the fan, the more than exponential increase in the surface area of the three successive subenvironments. In the third place, many beds in the proximal fan are formed by debris flows. Such flows are, as a rule, non-erosional and thus contribute to vertical aggradation. The depositional rate over the entire fan thus decreases gradually from the apex of the fan to its margins.

The difference in sedimentation rate is also expressed in another way: the average energy of currents and floods decreases in a downward direction, yet erosion is relatively unimportant in the proximal fan. This is mainly due to the high concentration of particles in the currents on the proximal fan; such cur-

rents have a low erosional capability. An additional reason is that even small decreases in the slope, as well as minor decreases in the current's velocity, induce deposition of particles, so that sedimentation is the dominant process. Erosional processes consequently have a larger net effect in the middle than in the proximal subenvironment. In the distal subenvironment the current's velocity is much lower than that in the proximal and middle subenvironments, so the erosional power becomes so small that its influence is more than compensated for by the – also diminished – sedimentation (Fig. 8). The frequency of erosional surfaces consequently increases from the proximal subenvironment in a down-fan direction to reach an optimum in the middle fan subenvironment, lessening again further down-fan.

Types of transport and sedimentation

Transport and sedimentation on the fan take place by, in order of decreasing importance, unchannelized transport (including sheetfloods), channelized braided streams and mass transport. Settling from suspension is responsible for most of the other deposits. Other processes are of minor importance or do, in a strict sense, not belong to the sedimentation on fans (e.g. deposition from melting ice after temporary ice advance over the fan).

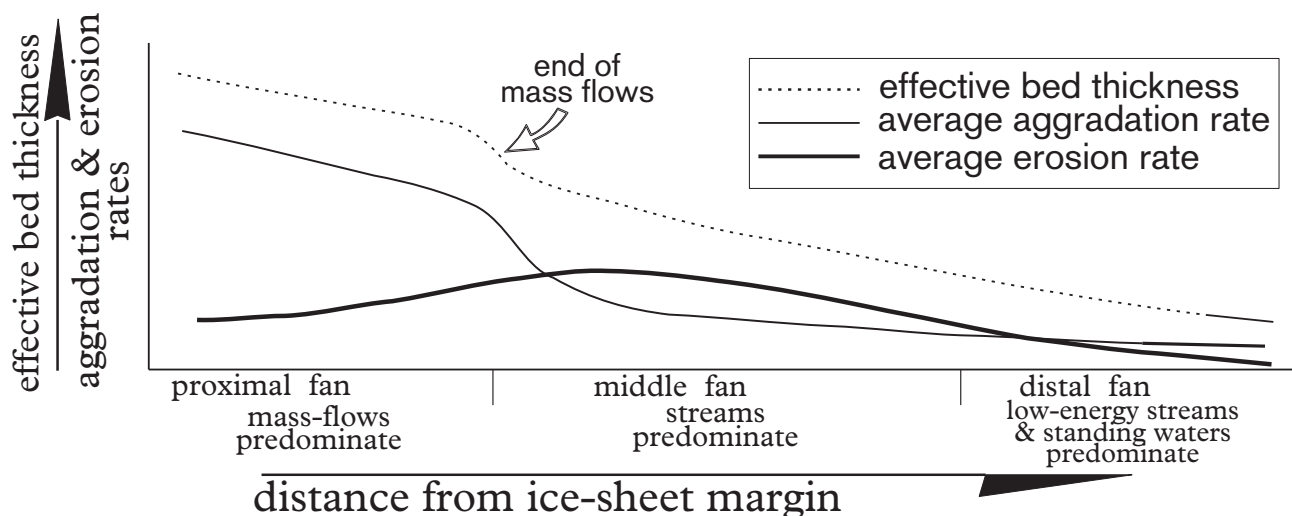


Fig. 8. Schematic diagram of average erosion and deposition rates, resulting in net vertical aggradation, in a longitudinal section of a subaerial terminoglacial fan. Not to scale.

Mass flows

Mass flows occur on terminoglacial fans under both subaerial and subaqueous conditions. In many cases, mass flows start subaerially and end in pools that develop on the irregular surface of the fan. The mass-flow process is facilitated by the slope of the fan, the water-saturated character of most sediments, and the presence of sufficient silt- and clay-sized material to act as a lubricant.

The mass flows in the proximal subenvironment are characterised by the frequent presence of large clasts; both the maximum size and the average size of the material transported by mass flow decrease distally. In the most proximal zone, true debris flows prevail; they result in flowtills. The lower-concentration mass flows (fluidal flows) characterise the more distal parts, i.e. the transitional area between the proximal and the middle subenvironments, and result in hyperconcentrated-flow deposits within the channel pattern (see also Zieliński & Van Loon, 1996).

Unchannelized flows

A relatively large number of sheet-like layers have a rhythmic character. This may be due to cycles in the ablation, which are characteristic of the terminoglacial zone. The rhythmic successions encountered in a terminoglacial fan are diagnostic of sheetfloods; such frequent, short-lived floods are the dominant transporting agent on these fans – unlike on fans formed under most other conditions, even if the water supply is irregular, as is often the case in an arid climate (see, for instance, Viseras & Fernández, 1995). The predominance of sheetflows is found particularly in small subaerial terminoglacial fans (up to about 1 km long).

The rhythmites are generally well developed and show a coarse (gravelly/sandy) character in the proximal subenvironment and a fine (sandy/silty) character in the distal subenvironment. This indicates that the sheetfloods gradually lose their competence when running down from the top of the fan, thus becoming low-energy unchannelized flows.

Channelized currents

Two types of channelized transport can be distinguished: through relatively deep channels and through braided streams.

Currents in deeply incised channels are most common where sudden floods result in heavy, overloaded flows. Their deposits are found in particular in the proximal fan (subfacies *P-3b*). The channels of this type are usually filled with a mixture of massive, badly sorted gravels, resulting from accretion of coarse-grained sheets in the fan's apex, where channels are truncated frequently.

Other, irregular, channels are shallower and become filled almost exclusively with bars, dunes, plane beds and current ripples indicating a lower flow intensity. This type of channel occurs predominantly in the proximal subenvironment (facies *M-1*).

Settling from suspension

Fine-grained sediments (mainly fine-grained sand to silt) are almost exclusively restricted to the distal fan. They are deposited from low-energy (generally shallow, unchannelized) currents or by settling from suspension in abandoned channels, ponds and small lakes. They obviously represent hydrodynamic conditions from the lower part of the lower flow regime and standing water.

Overview

Terminoglacial fans are the only type of fan where the sediments are almost continuously water-saturated owing to a large – though irregular – supply of melt-water, with frequent large floods, apart (perhaps) in winter time. This results in sheetfloods being responsible for most of the vertical accretion. These sheetfloods occur as hyperconcentrated flows in the proximal (rarely in the middle) part of the fans. Individual sheetflood deposits may extend from the highest to the lowest parts. The water-saturated character of the sediments and the abundant presence of debris result in mass flows being common on the proximal fan.

Currents on the proximal fan often have a catastrophic character, like they do – due to fairly similar conditions – on large outwash fans (cf. Smith, 1985; Fraser & Bleurer, 1988; Maizels, 1992, 1993). This character disappears gradually towards the lower parts, with the result that gravel-bed sheetflows and channels dominate the flows in the proximal fan, whereas sand-bed ones dominate the middle fan.

Discussion

The genesis of fans under terminoglacial conditions is strongly influenced by the specific situation as regards sediment and water supply, local morphology and granulometry of the parent material. This results in specific characteristics – dealt with below – which are fairly different from those of ‘wet’ fans, which tend to become shaped in the form of half a cone, with the outline of a Greek capital delta (Δ). Terminoglacial fans are, as a rule, more irregular because the locations from where water is supplied are highly variable.

Position, growth, size and morphology

The position of subaerial terminoglacial fans is determined by the ice front. A moving ice front thus results in lateral shifting of the area where the fans are formed. This has consequences for their growth (aggradation), the size that they may obtain, and their morphology; another consequence is the possible occurrence of cycles, due to alternating phases of ice advance and retreat (apart from cycles due to alternations in hydrological conditions and sediment supply).

Position

The position of a fan is less fixed under terminoglacial conditions than under more stable conditions: debris may be supplied from various directions (Fig. 9), which tends to make the shape of terminoglacial fans less regular. Since the shape affects the pattern of the distribution of sediment on a fan, the development of terminoglacial fans may differ from that of other alluvial fans.

Another important difference from most other fans is that terminoglacial fans are not static. The ice front moves continuously, however little, which implies that the area where a fan can develop shifts to and fro and that sedimentation at a specific place is more restricted in time than sedimentation on other fans. It is also important in this respect that advancing glaciers tend to destroy not only their marginal moraines (or at least part of them) but also the much less pronounced fans that develop in front of such ‘true’ moraines, i.e. moraines built of glacial till. Terminoglacial fans thus have a chance of surviving only when the ice front is stable (which is rare) or when it retreats. Retreat im-

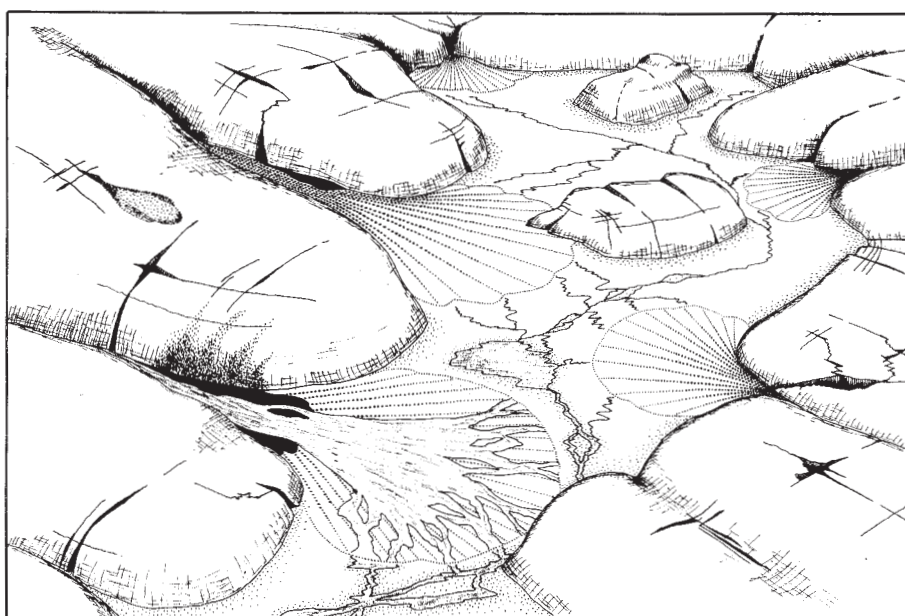


Fig. 9. Characteristic, irregular positions of fans developing in front of the main ice cover (left) and from dead-ice blocks (right).

plies a relatively short supply of sediment; this is reflected in the generally relatively small size of terminoglacial fans (10-30 m thick, usually 20-25 m; rarely longer than 1.5 km).

During the formation of a fan, dead-ice blocks that are covered with and/or contain debris may melt away in the fan area and leave heaps of sediment; in addition, irregular masses of sediment may be left by debris-flows, etc., thus forming new sources of sediment that can be distributed over the fan. This contributes to both the irregular distribution and the irregular character of terminoglacial fans.

Growth rate

Several authors (among others, Bull, 1964; Beaty, 1970; Graham, 1983; Sadler & Kelly, 1993; Mackey & Bridge, 1995; Viseras & Fernández, 1995) provide estimates of the aggradation rate of the alluvial fans that they studied. All these researchers found relatively low values, in the range of 0.002-2 cm a year. Only a few authors mention much higher values: Pierson (1980), Langford & Bracken (1987) Abdullatif (1989) and Beaty (1990) mention 10-100 cm a year. These higher values are ascribed by the investigators to the particle-rich, high-energy slurries that contribute to the rapid vertical aggradation of debris-flow-dominated fans.

Obviously, the growth rate of the terminoglacial fans under study depends on a wide variety of parameters, important ones being the thickness of the nearby ice (Warren & Ashley, 1994), the slope of the ice surface (Matthews, 1973; Shreve, 1985), the ablation rate during phases of ice-front stagnation (Sharp, 1951; Gustavson & Boothroyd, 1987). We estimate the aggradation rate of the small type of terminoglacial fans studied here to be highly variable, with a value of 50-100 cm a year as a likely average. This estimate is based on the above data, the thickness of the fans (usually 20-25 m) and the period needed for an ice front to retreat so far that it will no longer contribute to the same fan; from observations by the second author in Canada, Iceland and several glaciated mountain ranges, carried out during a timespan of some 25 years, we estimate this period to be 20-50 years.

Cyclicity in terminoglacial fans

Cyclicity is a feature typical of fans. Three types are commonly distinguished.

Mega-scale cycles (hundreds of metres thick) are common (Frostic & Steel, 1993; Kelly, 1993; Leeder, 1993) and large-scale cycles (of several dozens of metres) are even more abundant (Ridgway & DeCelles, 1993; Lopez-Gomez & Arche, 1993). Such cycles are

usually developed as inversely graded successions (Steel et al., 1977; Crews & Ethridge, 1993), representing prograding fans. These are long-term allogenic cycles controlled as a rule by tectonic and climatic changes. Such cycles have, to our knowledge, not been described from Pleistocene glacial sediments.

Medium-scale cycles are several to a few dozens of metres thick and often show a fining-upward tendency (Casshyap & Tewari, 1982; Blakey & Gubitosa, 1984; Sing & Banerjee, 1991; Fraser, 1993). Most of them are interpreted as an effect of lateral shifting of sedimentary subenvironments on the fans, such as channels and overbank areas (Viseras & Fernandez, 1995; Jo et al., 1997), channels and playas (Hubert & Hyde, 1982) or channels and mass-flow areas (Cavache et al., 1997). These cycles can be regarded as records of the evolution of braided channels and their infillings (the so-called channel cycle of Godin, 1991). This type has been described frequently from both Pleistocene and pre-Pleistocene successions (by, among others, Mader & Teyssen, 1985; Rust & Gilbing, 1990; Singh et al., 1993). They should be considered as autogenic cycles because both depositional evolutions and the avulsion of braided channels are autocyclic phenomena (cf. Heward, 1978b; Miall, 1996). Successions of terminoglacial fans usually reflect an upward transition from the proximal into the middle environment, with the distal deposits on top. Each of these units is thinner and finer grained than the underlying material. Cycles are rare, because these fans form and develop very rapidly in response to a melting and retreating ice front. It could therefore also be stated that the lithosomes of these subaerial terminoglacial fans represent seventh-order units in the stratigraphic architecture scheme developed by Miall (1996).

Small-scale cycles form successions ranging from decimetres to some metres thick, and display a fining-upward character. They owe their origin to the short-term evolution of bed and channel forms controlled by changing hydrological conditions (the macroform cycle of Godin, 1991). They consist commonly only of a channel facies and represent waning floods (cf. Fraser, 1993; Zaleha, 1997). Under glaciofluvial conditions, such cycles may be governed by a diurnal hydrological rhythm (Olsen & Andreasen, 1995). This simple type of cyclicity is, as a rule, well developed in terminoglacial fans.

Slope

An interesting difference from most other types of fans is that those formed under terminoglacial conditions have a relatively gentle slope, even in their proximal

mal parts. Nemeč & Postma (1993) mention a slope of up to 10–12° for mountainous ‘wet’ fans, whereas the slope of terminoglacial fans rarely exceeds 2–5°; the latter value is, surprisingly, consistent with that of the type II alluvial fans of Blair & McPherson (1994b), i.e., with that of semi-arid fans formed by coexisting sheetflows, hyperconcentrated streams and debris flows.

Water supply, channel characteristics and depositional processes

The water supply in the terminoglacial zone is highly irregular. Periods in which there is hardly any supply (e.g., during winters) alternate with periods in which there are large supplies, sometimes of a catastrophic nature (e.g., when an ice barrier damming off a glacial lake breaks through) (see Mokhtari Fard, 1998). A similar (though less pronounced) irregularity in water supply is found only in arid environments, where sudden outbursts of rain may occur. Nemeč & Postma (1993) took the consequences of changes in water supply into account in their subdivision of alluvial fans into three genetic types, dominated by debris flows, stream flows and sieve lobes. This distinction is not suitable for terminoglacial fans, because debris flows and streams coexist on such fans: debris flows dominate the proximal subenvironment, whereas streamflows do so in the middle subenvironment. Sieve-lobe-dominated fans are absent in the terminoglacial zone because truly coarse open-work beds are atypical of this environment and because, moreover, the groundwater table tends to be close to the sedimentary surface.

Several authors (among others Brierley et al., 1993) state that the size of bars in the braided channels on fans increases in a distal direction. We found the opposite, probably as a result of decreasing channel depth. The latter finding (the channels eventually become so shallow that unchannelized flows take over) is consistent with descriptions by Davis (1938), Friend (1978) and Heward (1978a). McGowen & Groat (1971) state that sandy transverse bars are characteristic of distal alluvial fans, but there are hardly any indications for such bars under terminoglacial conditions: the streams in the distal subenvironment are so shallow that, if channelized flow occurs, the stage of upper plane-bed conditions is reached, so that bars do not develop. In fact, transverse (foreset) sand bars are fairly typical of these braided channels, but only on the middle terminoglacial fan (see facies *M-1* in Zieliński & Van Loon, 1998). We ascribe this to the strong aggradational character of channel flows on this part of the fan.

Processes and deposits in the proximal subenvironment

The important role of debris flows in the proximal subenvironment contrasts with the models proposed for fans by Miall (1970), Gloppen & Steel (1981) and Kochel & Johnson (1984). On the other hand, Brierley et al. (1993) mention 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.

Processes and deposits in the middle subenvironment

In the middle subenvironment, many authors (e.g., Amajor, 1986) interpret abundant deposits as being a result of grain flow. We did not recognise any of such sediments, however, possibly because the mass flows of till material are too cohesive owing to the high percentage of silt and clay; grain flows can develop only in material 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.

In the middle part of polar fans, Catto (1993) found abundant silt and diamict beds in the inter-channel areas. They were formed by gelifluction flows of the permafrost active layer. Such redeposition does not occur on terminoglacial fans. They are probably too short-lived and have a too high aggradation ratio, so that the results of slowly acting creep by gelifluction are easily destroyed by faster processes affecting the sedimentary surface. Periglacial phenomena can develop only in the uppermost parts of terminoglacial successions, but are rare even there.

Processes and deposits in the distal subenvironment

Friend (1978) states that the distal subenvironment of fans is characterised by a system of numerous distributary channels, which is in contrast with our observations that this subenvironment is dominated by unchannelized flows. Our observations with respect to deposition in shallow, ephemeral ponds is consistent with Friend’s observations. Our findings are also largely 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 Fahnestock (1963), who state that a single, broad channel dominates in this subenvironment too; these studies, however, concern sandurs (flat, wide braidplains, commonly with a great extent) rather than true glacial fans (much steeper, with a small extent).

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 in other environments than under terminoglacial conditions. 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.

The dominance of unchanneled currents 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) and Kessel & Lowe (1987) consider to be characteristic, require large rivers that can develop a sinuous course on large alluvial plains (if the flow is continuous, not intermittent).

Granulometry

The granulometric characteristics of fans formed under terminoglacial conditions are atypical if compared with those of classical alluvial fans. Whereas fans are usually derived from material that has undergone at least some fluvial sorting (cf. Kochel & Johnson, 1984), the parent material of terminoglacial fans consists of morainic material, i.e. unsorted tills. A relatively wide range of grain sizes is therefore available, with a high content of particles smaller than sand. The abundance of fine-grained debris-flow deposits (flowtills) on the proximal fan is in contrast with the situation on non-glacial fans. Several authors (among them Beaty, 1963; Amajor, 1986; Brierley et al., 1993; Blair & McPherson, 1994a) note that the debris-flow deposits on such fans are coarse diamicts, frequently containing boulders; they are interpreted as deposits from cohesionless debris flows.

The difference between our model and that of

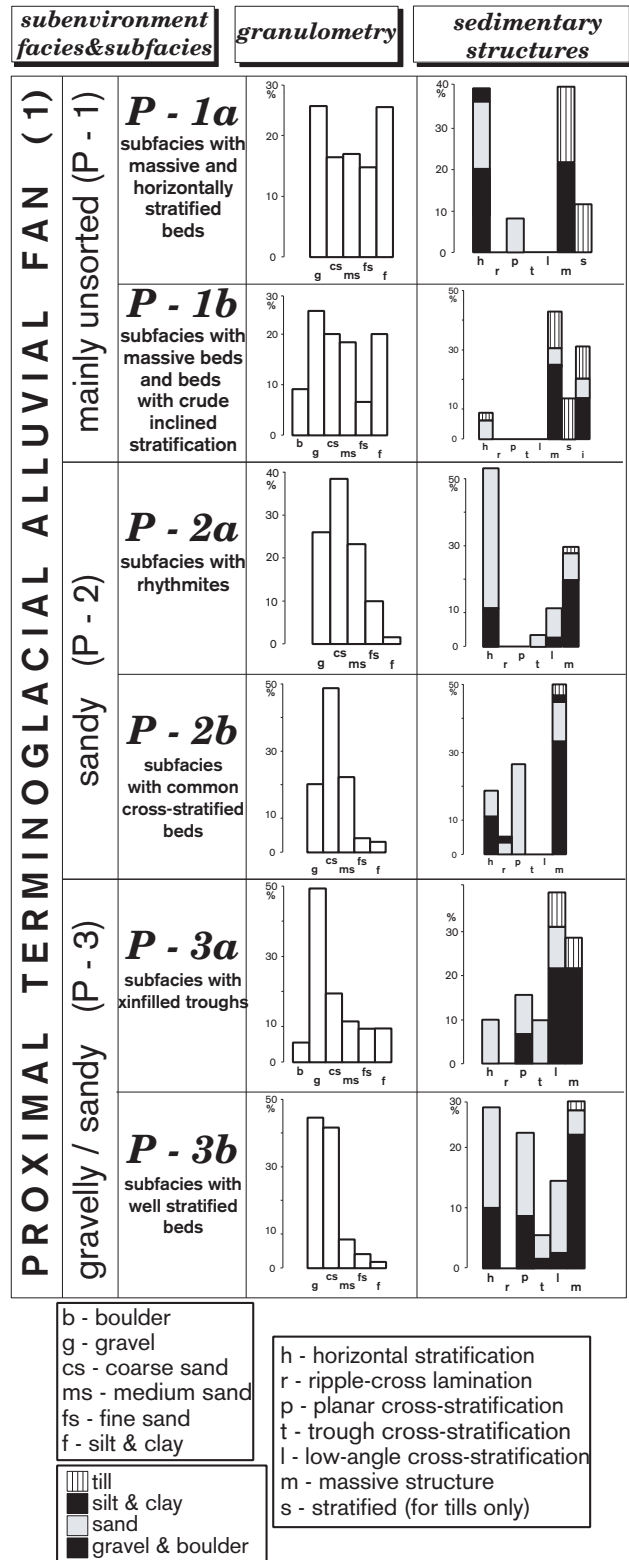


Fig. 10. Average grain size and sedimentary structures in the three subenvironments of the terminoglacial fans under study.

Kochel & Johnson (1984) for humid-glacial fans may be due to the fact that Kochel and Johnson took large sandurs as the basis for their conclusions. Sandurs may, however, be considered to be large alluvial plains (braidplains) rather than true alluvial fans; we want to

Table 1. Comparison of the most typical (average) characteristics of the main types of fan.

	terminoglacial fan	'wet' (humid) fan	'debris-flow'(semi-arid) fan	megafan (including large sandurs)
length	small (up to 1-2 km)	small (up to 1-2 km)	small (up to several km)	large (tens of km long)
slope	segmented, moderate	segmented, steep or moderate	clearly segmented, steep	uniform, gentle
thickness	up to few tens of metres	up to few tens of metres	tens of metres	tens to hundreds of metres
source of sediment & water	glacial crevasses and slopes	mountain valley	mountain valley or bedrock slope	mountain valley system (or large glacial conduits)
subenvironments	proximal, middle and distal (see this contribution)	proximal (gravel-bed stream facies, sand-bed stream facies), and distal (sheetflood or floodplain) facies	proximal (debris-flow facies) and distal (sabkha facies)	proximal (gravel-bed channel facies), middle (sand-bed braided or anastomosed channel facies), and distal (meandering channel and floodplain facies)
vertical facies transitions	regular (from base to top: proximal-to-middle-to-distal facies succession), commonly capped by flowtill	commonly regular (from base to top: proximal-to-distal facies succession)	without regular facies transitions	regular (from base to top: proximal-to-distal facies succession)
grain size	distally fining trend (from diamicts to fines), relative lack of fines in middle fan, slight (due to local variation in supply) fining upwards tendency	upwards & distally fining trend (from gravel to sand or silty sand)	generally coarse-grained, no to slight distally fining trend (from coarse diamict to sandy mud)	slowly distally fining trend over long distances (from gravel to fines), no distinct vertical trend
erosional contacts	in middle part only	present	rare	present
diamict presence	abundant in proximal part	rare (in proximal part only)	abundant in entire fan	commonly absent
bed thickness	medium (decreasing distally)	medium (decreasing distally and upwards)	large	medium/large
typical lithofacies	Gmm, Gm, Sh, Sl	Gm, Sh, St, Sp, Sm	Gmm, Gms	all fluvial lithofacies present
dominant depositional agents	cohesive debris flows, sheetflows, braided streams	braided streams, sheetflows	cohesive and cohesionless debris flows, hyperconcentrated flows	braided and meandering channels with floodplains
fluvial discharge	commonly large, unsteady, cyclical	large, unsteady	torrential	large, ephemeral or perennial
recurrence interval	days to months	tens to hundreds of years	from few to tens of years	annual (seasonal)
aggradation ratio	50-100 cm / year	approx. 0.1 cm / year	2-5 cm / year	approx. 1 cm / year

emphasize explicitly that this results in a number of differences between these two types of deposits (cf. Blair & McPherson, 1994a).

Another remarkable feature is that fans, as a rule, show a gradually decreasing grain size in distal directions. In terminoglacial fans, however, a relative lack of fine-grained material is found in the middle subenvironment (Fig. 10). The presence of more fines in the proximal than in the middle subenvironment must be attributed to the much more frequent occurrence in the former of till-derived (and therefore commonly diamictic) mass-flow deposits.

Conclusions

The study shows that fans that form under subaerial terminoglacial conditions, with marginal moraines as parent material, are different from most other types of fans (see Blair & McPherson, 1994a). The major characteristics of fans from different environments are compared in Table 1. In spite of the many important differences, the subaerial terminoglacial fans have many properties in common with fans from

other environments – for instance, the distinct differentiation into a proximal, a middle and a distal subenvironment. A compilation of the most important elements determining the character of subaerial terminoglacial fans is presented in Figure 11.

A specific characteristic of terminoglacial conditions is the irregular – and sometimes huge – supply of water. In combination with the water-saturated character of the unsorted source material (diamicts constituting 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. 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. Terminoglacial fans appear to form an intermediate category. The frequent mass flows 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

	PROXIMAL FAN	MIDDLE FAN	DISTAL FAN
lithology and sedimentary characteristics	dominance of coarse sand and gravel, frequent diamicts, thick beds, gravel in sheets and channels, sands mainly in sheets, diamicts in lobes, lenses and troughs, most beds massive or with crude horizontal stratification, load casts and normal faults common	dominance of sand, frequent as vertical sequences, sometimes fining upwards, medium to thick beds, flat or slightly erosive contacts, mainly sheets or wide lenses, sometimes as channel fill, mainly horizontal or low-angle stratification, less frequently massive structure or high-angle cross-stratification	dominance of fine sand and silt, most often as rhythmites, thin to medium beds, rarely erosive contacts, mainly sheet-like beds, abundant horizontal and ripple lamination
fan morphology	slope steep (> 0.05), irregular surface due to gravity-flow lobes, deep, narrow channels (<i>width/depth</i> ratio = $5+10$), wide, smooth surfaces of gravel and/or sand	moderate slope ($0.01+0.05$), wide, shallow (< 1 m) braided sand-bed channels, wide, smooth sand surfaces between and around the channels	slight slope ($<< 0.01$), very shallow, wide braided sand-bed channels within almost plane area with local lows without drainage (ephemeral ponds)
main depositional processes	sediment gravity flows coming from the ice slope forming lobes and sheets, reworking of previously deposited material by sheetfloods and by channelized currents, deposition in channels (longitudinal bars, gravel sheets)	deposition in braided channels (mainly as transverse foreset bars, plane beds, dunes; less commonly as gravel sheets), vertical accretion from high-energy sheetfloods (upper plane-bed conditions), infrequent settling of fine particles from suspension in abandoned channels	vertical accretion from low-energy sheetfloods, frequent settling of fine particles from suspension in ephemeral ponds and abandoned channels, low-energy deposition in braided channels (current ripples)

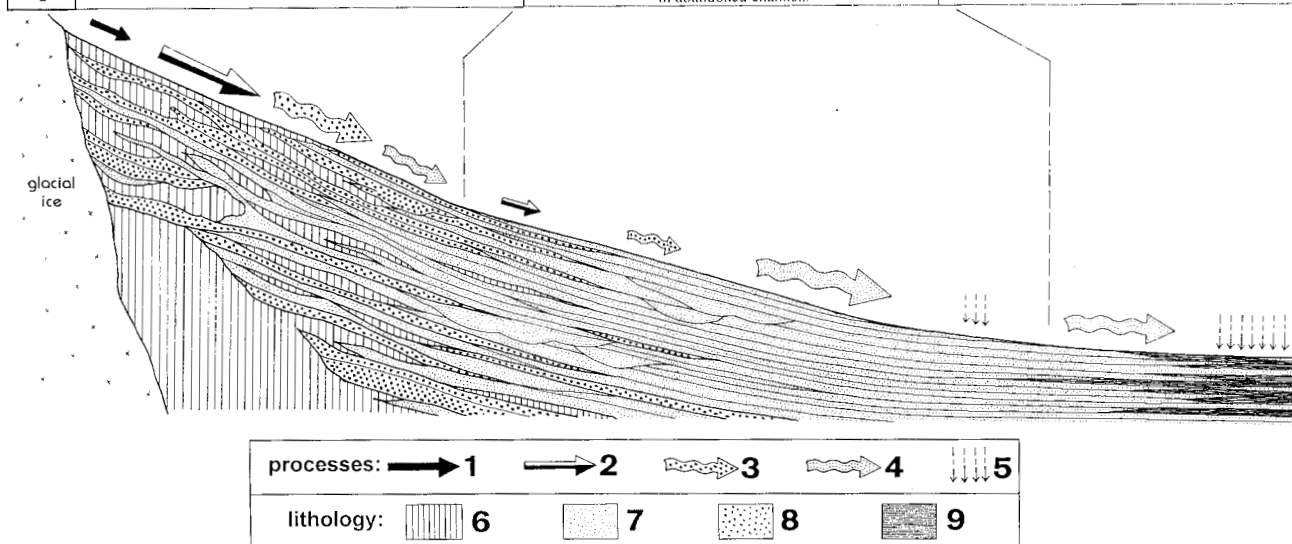


Fig. 11. Compilation of the most important elements determining the characteristics of terminoglacial fans.

1 = mass flow; 2 = fluvial reworking of mass-flow deposits; 3 = gravel-laden currents; 4 = sand-laden currents; 5 = settling from suspension; 6 = till; 7 = sand; 8 = gravel; 9 = silt. Size of arrows indicates relative importance.

of the reworked mass-flow deposits is usually still traceable, indicating that reworking is only slight in most cases.

The middle subenvironment is dominated not by mass-flow processes but by sedimentation from numerous shallow braided streams and from unchanneled flows. This holds also for the distal subenvironment, but settling of fines in ephemeral ponds also plays a significant part here.

One explanation for the diverging character of the terminoglacial fans is that they tend to stop forming at a stage when they have not had a change to develop completely, because the ice front shifts to and fro. This 'immature' character may be deduced from the following sedimentological observations:

- the fans are rarely over a kilometre long; this might indicate that they stop their development during (or even before) the second phase distinguished by Blair & McPherson (1994b), whereas the third (final) phase of fan development is the one during which the front of the fan progrades significantly;
- relatively few erosional surfaces are present in terminoglacial fans, whereas erosional channels (particularly in the proximal part) are typical of the last phase of fan development (Hooke, 1967; Blair, 1987; Blair & McPherson, 1994b);
- the proximal part shows so little erosion activity that only a relatively small amount of particles deposited originally on the proximal fan later reach the middle and distal parts, where aggradation is consequently restricted.

It thus appears that terminoglacial fans never reach a mature stage, but – as a rule – show still juvenile characteristics even at the end of their development. This is in contrast to all other types of fan, which as a rule continue to develop, reaching a mature and even a senile phase. It can thus be concluded that subaerial terminoglacial fans represent a type that 'fossilize' somewhere in the middle of the normal fan evolution.

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