sciendo

GEOLOGOS

Geologos 27, 1 (2021): 43–55
DOI: 10.2478/logos-2021-0004

Lacustrine deltas and subaqueous fans: almost the same, but different – a review

Beata Gruszka*, Tomasz Zieliński

Institute of Geology, Adam Mickiewicz University, Krygowskiego 12, PL-61-680 Poznań, Poland
* corresponding author, e-mail: bgruszka@amu.edu.pl

Abstract

Although deltas and subaqueous fans are both formed in the same near-shore zones of basins, the hydraulic conditions for their formation, development and sedimentary records are different. The present review discusses the results of previously published studies of fan deltas (Gilbert-type deltas) and subaqueous fans of lacustrine and glaciolacustrine environments. The depositional mechanisms of deltas and subaqueous fans, textural and structural features of the lithofacies associations and their typical lithofacies are presented. The characteristics of subaqueous fans, which are still relatively poorly understood and are often overlooked in sedimentological interpretations of lacustrine sedimentary successions, receive particular attention. The palaeoenvironmental and lithological differences between deltas and subaqueous fans are highlighted.

Key words: fan delta, Gilbert-type delta, ice-contact subaqueous fan, depositional mechanisms, sedimentology

1. Introduction

Recently, in this journal two studies have appeared in which the authors (Mleczak & Pisarska-Jamroży, 2019; Przepióra et al., 2019) analyzed the hydrological conditions and sediments in the transitional zone from river mouths to lake basins. The first-named study concerned a Pleistocene glaciolacustrine environment, while the second dealt with a modern lake. The described sediments show many similarities, because the depositional mechanisms were analogous. Nevertheless, the final palaeoenvironmental conclusions turned out to be different. In one of the studies the sediments were interpreted to be part of a fan delta, whereas the other study concluded to a subaqueous fan. These different conclusions are understandable, because both terms are often treated as synonymous and there is no clear, commonly accepted distinction between environmental conditions, depositional factors and sedimentary records of Gilbert-type deltas and subaqueous fans in lake settings. Our intention is to fill this gap and possibly spark a discussion on this issue.

In the present study we describe and compare the forms, processes and sediments in the transitional zone between river mouths and lakes under conditions of a large sediment supply. Thus, the main environments considered here are the marginal parts of glacial lakes and non-glacial lakes in mountain and upland settings, as well as lakes developed in active grabens.

While the large, common forms developing at the mouths of rivers in lakes and seas – deltas – have been studied extensively by numerous geologists for over a century, the subaqueous fans in lacustrine environments were 'discovered' only in the 1970s (Rust & Romanelli, 1975). These forms, hidden under water, have been investigated only marginally, because their occurrence is much less frequent and limited to only specific environmental conditions.

The aim of the present study is to review the results of the previous research of deltas and subaqueous fans, both modern and fossil. The ultimate objective is to determine which hydrological and depositional factors determine the differences in the sedimentological records of lacustrine deltas and subaqueous fans. Our findings may become the basis for more accurate palaeoenvironmental interpretations, which, in turn, may have repercussions on general palaeogeographical conclusions.

2. Review of processes and deposits of Gilbert-type deltas and subaqueous fans

2.1. Deltas

The Pleistocene deltas of the Bonneville glacial lake (USA – Utah, Idaho, Nevada) were studied by Gilbert (1890), who also introduced the concept of *fan delta*. For this reason, the terms *fan delta* and *Gilbert-type delta* have much in common. The term 'fan delta' emphasizes the presence of an upper alluvial fan. Each alluvial fan develops a significant decrease of the depositional surface slope (i.e. laterally decreasing flow velocity) over which a high concentration of sediment is transported. These conditions exist where rivers discharge into mountain and upland lakes or in glacial lakes.

One of the most commonly identified types of deltas is the Gilbert-type delta, which consists of three distinct zones (sedimentary subenvironments): subaerial alluvial fan (or delta plain), and two underwater parts: the delta front and the prodelta. The steep delta slope that originates in deep settings is characteristic of this delta type (Postma, 2003). The three mentioned deltaic subenvironments clearly differ in both textural and structural features of sediments. For this reason, three facies are distinguished: topset, foreset and bottomset facies (Fig. 1).

The topset facies is a record of alluvial fan or braid plain. The main factors in deposition are sheetflows and/or shallow flows in braided channels and sometimes massflows as well. Postma (1990) proposed that Gilbert-type deltas were formed from fluvial supply of two types. Type-A feeder system is a high-energy, steep (a few degrees) alluvial fan dominated by gravel-bed sheetflows. Type-B feeder system is the braid plain at a slightly lower slope (approx. 0.5°) with coarse bed-load channels. High-energy sheetflows deposit the massive gravels (Fig. 2A) (Ethridge & Wescott, 1984; Rohais et al., 2008). The braided channel facies

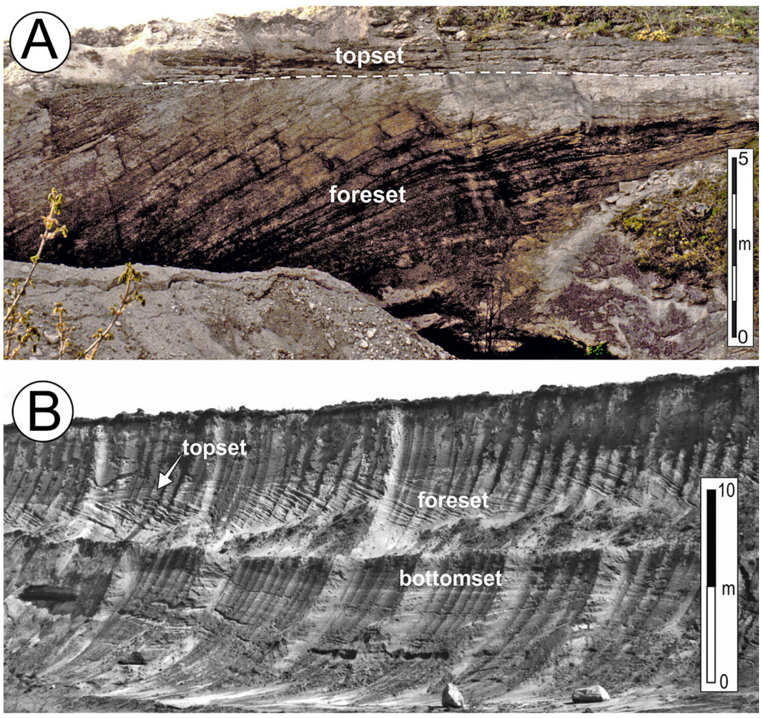

Fig. 1. Lithosomes with subfacies of Gilbert-type delta: A – Miocene marine calcarenites near Staszów (southern Poland); B – Pleistocene glaciolacustrine deposits in Bełchatów brown-coal mine (central Poland).

are represented by the beds derived from longitudinal bars (gravels and gravelly sands with horizontal stratification – Fig. 2D), transverse bars (sands and gravelly sands with planar cross-stratification – Fig. 2C), three-dimensional dunes (gravels and sands with trough cross-stratification – Fig. 2B), and scour pools (gravels and sands filling large troughs) (Ethridge & Wescott, 1984; Hwang & Chough, 1990; Longhitano, 2008). These beds are arranged in channel-like lithosomes up to 1.5 m thick, although occasionally they are thicker – up to 5 m (Lunkka & Gibbard, 1996; Lønne & Nemec, 2004; Ilgar & Nemec, 2005; Winsemann et al., 1918). Common features of all deposits of topset facies are erosive bases and fining-up grading of beds and bedsets (Dorsey et al., 1995; Gobo et al., 2015).

The topset facies passes downwards into the foreset facies. This is a sedimentary record of the slope (front) of the delta. The slopes of the delta fronts are high angled (from 15° to 35°; see Fig. 3), because the grains are accumulated at the angle of repose; slightly smaller for sand, larger for gravel (Hwang & Chough, 1990; Adams & Schlanger, 2000; Hanáček et al., 2018; Krzyszkowski et al., 2019). Deposition on the delta slope is gravitational; transported grains can be dispersed (debris fall), in high concentration (debris flow) or in the turbidity current. Gilbert-type deltas are formed under conditions of high sediment supply, and each larger sediment delivery causes the grains to move down a steep slope (Longhitano, 2008). The debris fall (grain fall) mechanism most often affects coarse grains – gravels (Fig. 4). They fall loosely downwards, producing characteristic layers with the coarsest grains and the greatest thickness in the lower parts of the foresets – the so-called toesets (Nemec, 1990; White, 1992; Slomka & Hartman, 2019). Under conditions of higher concentration of grains, transport takes place as a debris flow. Debris flows often arise as a result of slides, which are recorded in the upper parts of foresets as spoon-shaped niches filled with massive sediment (Chough & Hwang, 1997; Krzyszkowski et al., 2019). These massflows are of a cohesionless nature – they are the true grain flows or cohensionless debris flows *sensu* Nemec & Steel (1984). In this way, gravelly, gravelly-sandy or sandy layers with a massive structure and coarsening-up grading are formed (Doktor, 1983; Sohn et al., 1997; Falk & Dorsey, 1998; Winsemann et al., 2007) (Fig. 5). The frequency of lithofacies derived from gravity flows is high and usually amounts to 40–50% of the foreset facies (Nemec et al., 1999). The massflow deposition is also recorded in synsedimentary deformations, including intraformational crumpling and deformed soft-sediment clasts (Doktor, 1983; White, 1992; Pisarska-Jamroży & Weckwerth, 2013). Cohesionless debris flows move at high velocities. Mulder et al. (1997) determined that on slopes steeper than 10° (and this condition prevails on the fronts of Gilbert-type deltas) mass flows become supercritical. Very often the travelling massflow is diluted with ambient water, and evolves

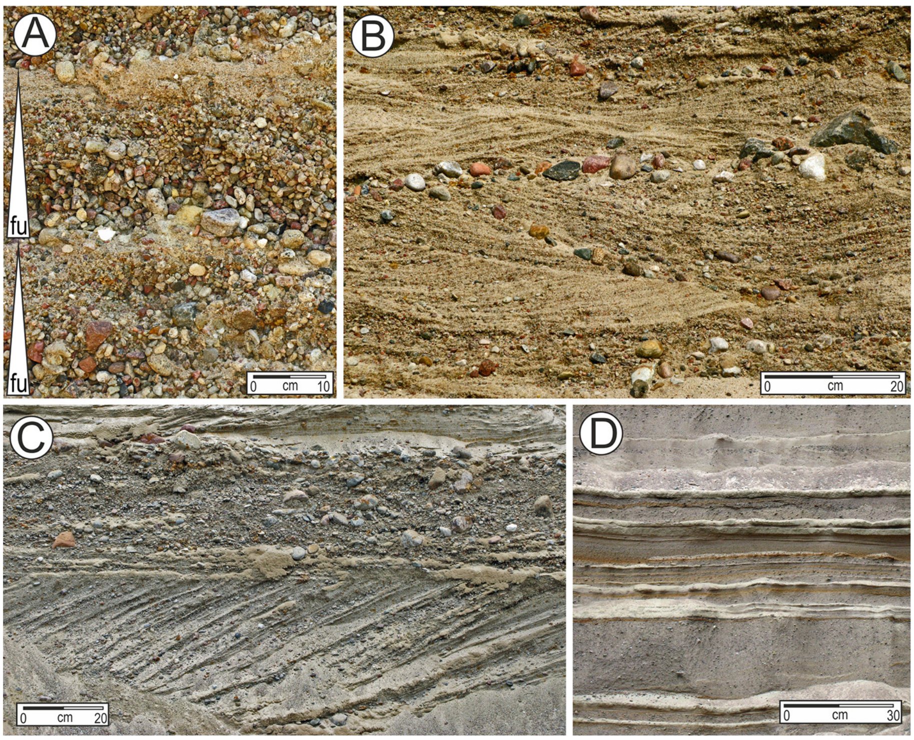

Fig. 2. Typical topset lithofacies (Pleistocene, Bełchatów, central Poland): A – Massive gravels of sheetflow origin, fining-up tendency (fu) is marked; B – Gravelly sand with trough cross-stratification derived from three-dimensional dunes; C – Gravelly sand with tabular cross-stratification derived from transverse bar, massive sandy gravel of diffuse gravel sheet above; D – Two thick beds of massive and poorly stratified gravelly sands derived from longitudinal bars.

into a turbidity current (Falk & Dorsey, 1998), called *surge currents* referred to be *linked debrite-turbidite deposit* (Haughton et al., 2003). Massive and/or deformed, argillaceous bed with mud clasts and chips (debrite) overlain by sand-to-silt graded bed (turbidite) is a typical succession of this deposit.

Turbidity currents are also generated by failure of the delta slopes (Zeng et al., 1991; Hilbe & Anselmetti, 2014) or the mouth bars located on the delta crest (Syvitsky et al., 1988). These are most often *hyperconcentrated density flows* (Mulder & Alexander, 2001). Transport in such currents occurs in two 'layers'. In the lower 'layer', the grains are so highly concentrated that the transporting medium shows the characteristics of a massflow (grain flow). Sediment concentration in the upper 'layer' is reduced and the grains are carried by turbulence (i.e. true turbidity current). The deposits of these two 'layers' form a *bipartite deposit*, where the coarser member with reverse grading is overlain by a finer one with normal grading (Lowe, 1982; Falk & Dorsey, 1998; Sohn et al., 1999). The succession usually starts with an erosive surface and the structure of both members is massive (Mulder & Alexander, 2001). It should be emphasized that surge currents are short-term phenomena (lasting up to several hours), while they are characterized by high dynamics. They travel along the delta slope at velocities of 0.5–4 m/s (Syvitski & Hein, 1991; Mulder et

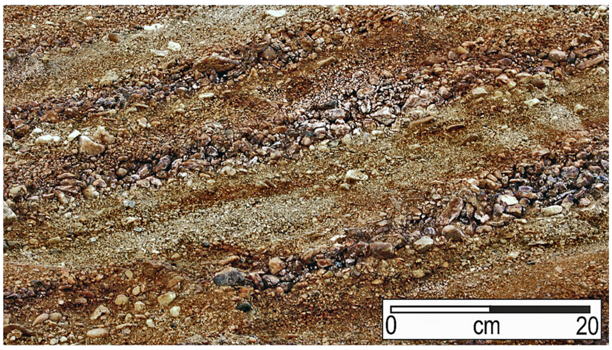

Fig. 4. Gravelly foresets deposited from coarse-grained subaqueous avalanches – the grain falls. Świdnica area, Sudetes Mts foreland, southern Poland.

al., 2003). The slower currents usually act as sheetflows, and high-energy currents are concentrated in erosive channels – *chutes*. Density flows accelerate with the distance along the delta front; for this reason, most channels are formed in the toeset zone (Lønne, 1993; Breda et al., 2007; Gobo et al., 2014). It is assumed that most of the currents on steep delta slopes are characterized by such a high energy that they become supercritical (Nemec, 1990; Mulder et al., 1997: Lang et al., 2017). When they reach a critical stage, the hydraulic jump occurs with violent turbulence and the flow erodes a trough. This is filled with massive sediment or with characteristic backset cross-stratification, which is the evidence of

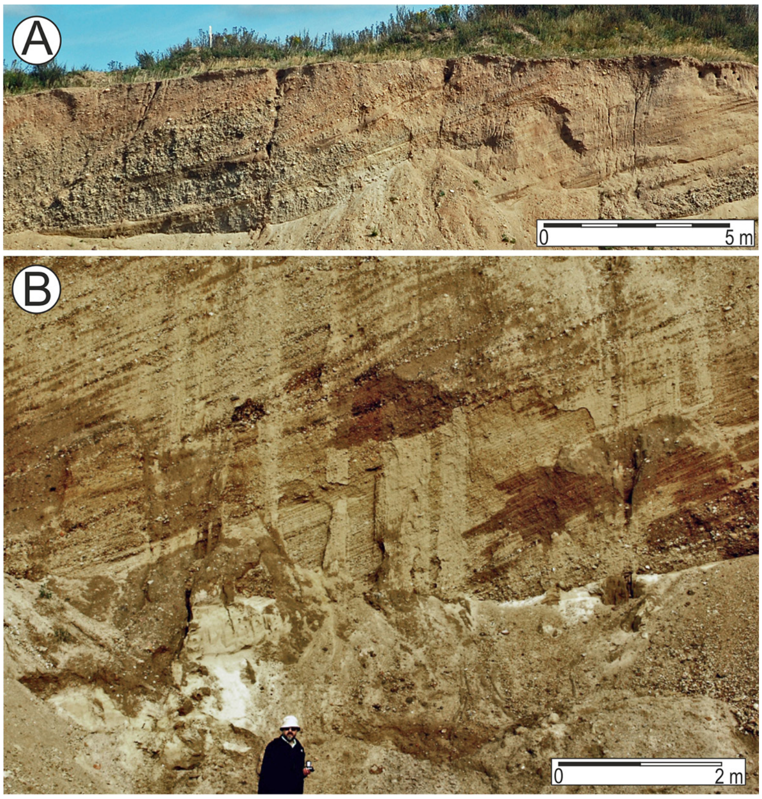

Fig. 3. Foresets of the Pleistocene glaciolacustrine Gilbert-type deltas. Both sites are located in the foreland of Sudetes Mts (southern Poland). Advancing ice sheet dammed deep lakes in foremountain valleys outflowing towards the glacier. A – Variable dip and grain-size of foresets prove that delta progradation took place in successive phases (photo P. Migoń).

antidune deposition (Borhold & Prior, 1990; Massari, 1996; Winsemann et al., 1918) (Fig. 6).

Lower and further away from the delta front the subenvironment with the lowest energy occurs: the prodelta with bottomset facies. Due to the vicinity of a steep slope, this zone is reached by massflows, which, together with turbidity currents, are the main depositional drivers in the proximal part of a prodelta (Eriksson, 1991). Turbidity currents are characterized by high power and high sediment concentration. Therefore, most often gravelly turbidites are intercalated with sandy turbidites (Røe, 1995; Winsemann et al., 2018). It is even assumed that supercritical currents depositing the sediment in the antidune bed configuration reach the prodelta as well (Leszczyński & Nemec, 2015). The beds of prodeltaic debrites and turbidites usually have a massive structure. Although the prodelta is the lowest-energy subenvironment of the delta, erosive surfaces are still common in its successions as records of the channels that reach this zone from the lower part of the delta slope (Stingl, 1994; Leszczyński & Nemec, 2015). The distal prodelta is a distinctly low-energy subenvironment. Deposition occurs simultaneously from traction and suspension. Weak currents deposit fine sand, usually silty sand. Two-dimensional ripples are formed, which are most often climbing-type bedforms (Fig. 7). All of the above-mentioned sedimentary facies exist as intercalations between thin-bedded silts, which derived from fine suspension fallout in periods of water stagnation, when the prodelta was not reached by the currents and massflows from the delta slope.

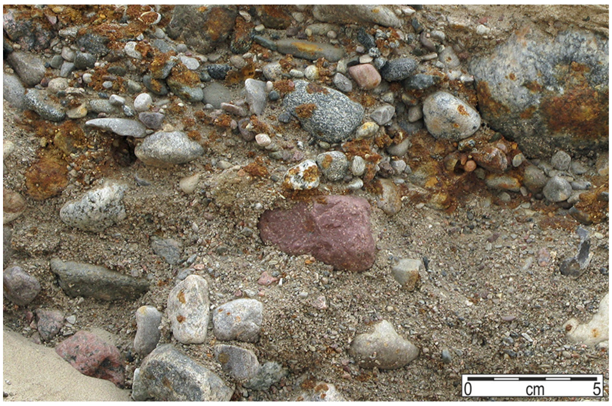

Fig. 5. Coarse-grained debrite layer in foreset subfacies derived from cohesionless debris flow – the grain flow.

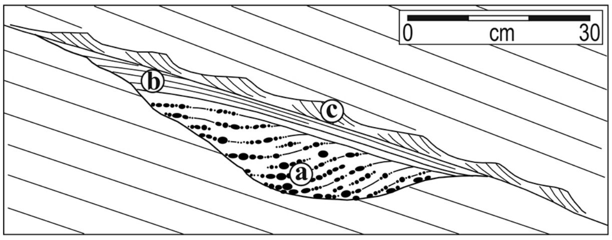

Fig. 6. The scour eroded by hydraulic jump on delta slope (based on Massari, 1996). a – Gravelly sand with backset cross-stratification (supercritical deposition), b – Horizontally stratified sand (upper plane bed), c – Horizon of ripples (lower flow regime).

2.2. Subaqueous fans

Subaqueous fans are formed in shallow lakes. Such bathymetric conditions were typical of the Pleistocene proglacial lakes fed by meltwater rivers. The maximum depths of these lakes were rarely exceeded 10 m. The lengths of subaqueous fans usually do not exceed 200 m (Paterson & Cheel, 1997). At most times small lakes are hydrologically open (i.e. with river outflow), and characterized by limited accommodation space, which is an important factor in the formation of subaqueous fans. In shallow open lakes, the flow velocity gradient between the river inflow and the basin is relatively small. This means that in shallow water there are usually long-lived currents above the subaqueous fan. For this reason, sediment deposition occurs from traction currents (Gruszka, 2001, 2007).

The subaqueous fan surfaces are characterized by relatively low slopes. They range from 3° to 15°,

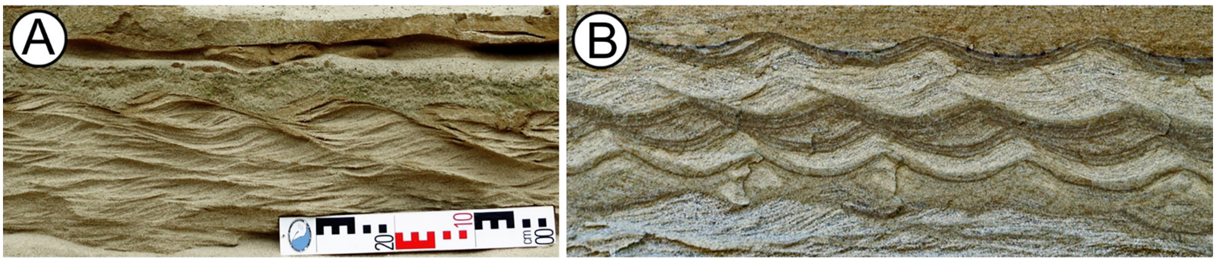

Fig. 7. Bottomset facies of distal prodelta (Bełchatów, central Poland). Fine-grained sands derived from climbing ripples. A-type climbing cross-lamination (A) was formed from some faster current than B-type lamination (B). A-type structure records the predomination of traction over suspension transport, and B-type structure proves deposition purely from suspension. On both photos the rippled bed is overlain by silty layer.

most often 4–10° (Hornung et al., 2007; Winsemann et al., 2009; Woźniak et al., 2018) (Fig. 8). As a rule, there is no apparent slope break; the longitudinal profile of the subaqueous fan is almost uniform (Gilbert & Crookshanks, 2009).

Due to the lack of a steep slope, only two subenvironments can be distinguished in the subaqueous fan: (1) a proximal mouth-bar zone, which passes into (2) the distal zone that corresponds to the prodelta.

Mouth bars – large-scale dunes (microdeltas) – are typical of the proximal zone in low accommodation settings (Yperen et al., 2020). Well-developed mouth bars are generally formed where the inflow feeding the lake is strongly channelized. This is most often the case in a glaciolacustrine environment, where the water and sediment supply come from a glacier crevasse or tunnel (Rust & Romanelli, 1975; Lang et al., 2017), although fossil mouth bars have also been found within deposits of non-glacigenic settings (Zavala et al., 2006; Jerrett et al., 2016). Mouth bars have progradational fronts inclined at 10–15° (Mortimer et al., 2005). Their depositional record is represented by sandy or sandy-gravelly foresets with tangential or sigmoidal shape (Fig. 9). In their proximal parts (i.e., in the zone of the highest flow velocity), trough-shaped erosive depressions are formed (Fig. 10). Gravels with up-current dipping laminae fill these scours (Lang et al., 2020). This backset stratification results from a hydraulic jump, i.e. a sudden transition from supercritical to subcritical flow. Mouth bars can be poorly developed; occasionally, they are not formed at all. In the case of a very shallow basin, the deposition in the proximal zone is dominated by sheetflows. Massive or horizontally stratified beds are common here (Dasgupta, 2002; Gruszka & Terpiłowski, 2014; Lang et al., 2020). In the proximal zone of subaque-

Fig. 9. Succession of sandy microdelta (Kornica, Łuków Plain, eastern Poland). Sigmoidal shape of layers proves the intensive current in river-mouth zone of shallow glacial lake.

Fig. 8. Deposits of subaequous fans. Low-angle stratification proves the gentle slope of fan. A – Light laminae are sandy and darker ones are sandy-silty (Ujście site in northern Poland, photo by M. Mleczak); B – Sands form light layers, and organic sandy silts form dark ones; scale bars are 1.5 m long (Suchedniów site in central Poland, photo from Przepióra et al., 2019).

ous fans, stationary antidunes (Lang et al., 2017), which are bedforms typical of transitional conditions between the lower and upper flow regime, are also present. Their lithofacies consist of gravel or sand with sinusoidal stratification (Lang et al., 2020). In this proximal zone, shallow chutes are often incised, filled with sand or gravelly sand with a massive structure or trough cross-stratification (Rust & Romanelli, 1975; Hornung et al., 2007). The transition of proximal deposits into the 'prodelta' (distal fan) facies is gradual.

The distal subaqueous fan is a zone of sand and silt accumulation. Deposition occurs most often from underflows, which are low-density turbidity currents (Mulder & Alexander, 2001). As a result, sandy and silty, fining-up successions are formed by the waning nature of turbidity current. They may contain three intervals of the Bouma sequence: T_{bce} (horizontally stratified sand → sand with ripple cross-lamination, frequently with climbing ripple structures → silt with massive structure or horizontal lamination) or T_{bde} (horizontally stratified sand → sandy silt with horizontal lamination → massive silt) (Mastalerz, 1995; Paterson & Cheel, 1997). Two-member sequences are also common, i.e. rhythmites: T_{bc} (horizontally stratified sand → ripple-cross laminated sand), T_{be} (horizontally stratified sand → silt), and even very fine-grained rhythm T_{de} (silty sand → silt) (Knudsen & Marren, 2002; Winsemann et al., 2007). The thickness of the turbidite successions is usually up to a few centimetres (Pharo & Carmack, 1979; Liverman, 1991). Underflows with a low concentration of suspended load are sometimes regarded as traction currents. In the case of tractionites, the deposition of fine-grained sand and silty sand occurs in the configuration of ripples (often climbing ones) or small-scale (< 15 cm in height) dunes. As a result, sand layers with cross-lamination and/or cross-stratification alternate with numerous silt layers (Fielding & Webb, 1996; Woźniak et al., 2018; Lang et al., 2020). While the turbidites are most frequently characterized by a fining-up texture, tractionites often do not show this feature.

Turbidity currents in subaqueous fans are generated by river floods. For this reason, they are quite long-term phenomena and can run up to weeks (Mulder & Syvistski, 1995; Zavala et al., 2006). During this time, their physical parameters (velocity and sediment concentration) undergo only slight changes. Therefore, they are treated as quasi-steady flows. Suspension concentration is most often limited to the area of the river inflow. This determines the low velocity of the turbidity currents moving over the subaqueous fans. The maximum velocity does not exceed 2.5 m/s (Yu et al, 2006), and most often it is several dozen cm/s (Chikita, 1992; Mulder et al., 2003). Deposition occurs both from traction and from suspension. All of these features of turbidity currents controlled by river inflow became the basis for distinguishing a separate category of underflows – *the hyperpycnal turbidity currents*, and their deposits were given the genetic name of *hyperpycnites* (Alexander & Mulder, 2002; Mulder et al., 2003).

What are lithological features indicative of the classical hyperpycnite? Unlike the Bouma sequence, the succession is pensymmetrically graded (the coarsest grain-size level in the middle part of the bed): silt → sand → silt or fine sand → medium sand

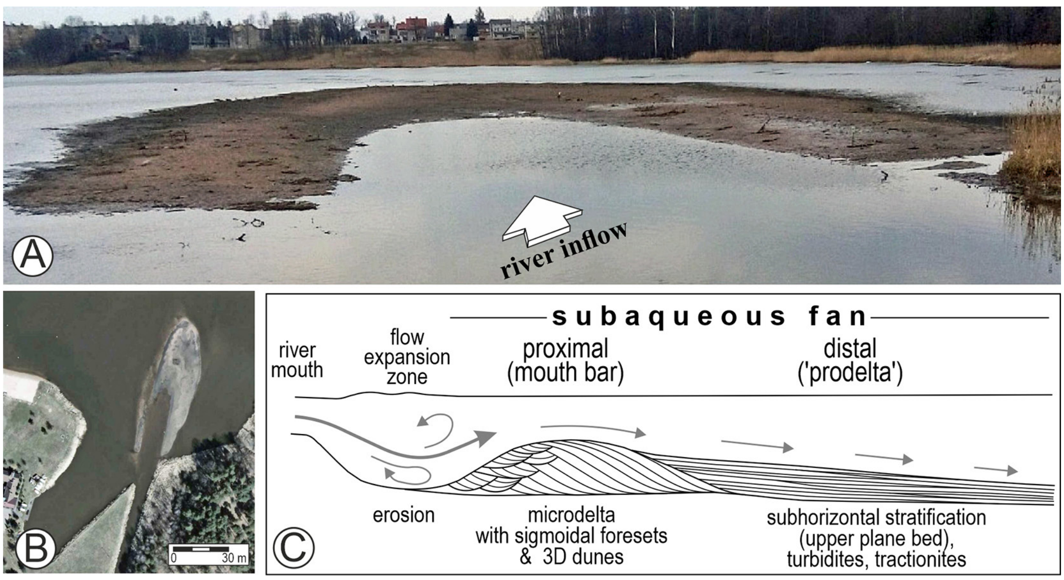

Fig. 10. Subaqueous fans: A, B – real photos; C – theoretical model. Both photos by Przepióra et al. (2019). Model draft partly based on Lang et al. (2017).

→ fine sand . The lower, coarsening-up part of the succession is a record of the increasing river flood. The silt is usually laminated while the sand can have a massive structure, horizontal lamination or ripple cross-lamination. The upper part of the succession may start from a discrete erosive surface that results from the flood crest. Despite erosion, the hyperpycnites are, in horizontal plan, non-channelised lobate-shaped depositional bodies (Cao et al., 2018). Minor floods do not result in erosive surfaces; in such cases, the transition between both parts of the succession is gradational. Declining energy of the waning flood is recorded in the fining-up trend of the upper member: sand with low-angle cross-stratification → sand with horizontal stratification → sand with climbing ripples or massive/laminated silt (Mulder et al., 2001; Zavala et al., 2006). Obviously, this is a model succession that occurs relatively rarely. The lower member, associated with the rising phase of the flood, may not be preserved due to erosion. In this case, the hyperpycnite becomes a normally graded bed (Carvalho & Vesely, 2017) and is practically indistinguishable from the Bouma-type turbidite. Hyperpycnites are relatively well recognized in the lake environment, when the flood-generated flow enters low density water, whereas their presence in the sea is still under debate (Shanmugan, 2018, 2019; Van Loon et al., 2019; Zavala, 2020).

3. Discussion: Differences between the Gilbert-type delta and the subaqueous fan in a lacustrine and glaciolacustrine succession

Gilbert-type deltas are the forms that accumulate on the margins of deep basins that exist for long periods. The accommodation space of such basins is large. Subaqueous fans, in contrast, are formed in shallow, open (i.e. with river outflow), most often ephemeral lakes. They are typical of minor accommodation space conditions. The classical Gilbert-type delta is formed when the rising water level of the basin (i.e. increasing accommodation space) and the sediment supply are in balance. Such conditions usually do not occur in shallow lakes, where subaqueous fans are formed. On the contrary, shallow, ephemeral lakes are most often drained and then their accommodation space decreases. For the reasons mentioned above, deltas are controlled by simultaneous progradation and aggradation, while in the case of subaqueous fans, progradation is dominant. The shallow-water nature of the subaqueous fans and the deep-water nature of the deltas underlie the hypothesis that during the development (i.e. deepening) of the basin, there is an evolution of sedimentary environments consisting in the initial formation of a subaqueous fan, which then transforms into the Gilbert-type delta or, in some cases, into deltas superimposed on each other (Nemec et al., 1999; Plink-Björklund & Ronnert, 1999; Hanáček et al., 2018). In case of high aggradation rate of Gilbert-type delta, it may turn into shoal-water prograding delta (Gobo et al, 2014).

The fan delta (Gilbert-type delta) consists of three subenvironments that clearly differ in morphology, bathymetry and hydrodynamic conditions. These are the subaerial fan, delta slope (delta front), and prodelta. The boundaries between these zones are sharp and clear. In the subaqueous fan, at most two subenvironments are distinguished: mouth bar or shoal with sheetfloods and distal 'prodelta'. The morphological transition from the proximal to the distal zone is gradual. Therefore, the variability of bathymetric and hydrodynamic conditions is less pronounced along the fan. The front of the delta is steep (15–35°) as it slopes at the stability angle of sediment (angle of gravitational deposition of sand or gravel). On the low slope of a subaqueous fan (5–10°) the gravitational movement of the sediment does not occur (Table 1).

The existence of a steep delta front determines the specificity of transport and deposition in the foreset and even bottomset zone. The loose grains on the fast-prograding delta front undergo frequent sliding and/or rolling. Thus, debris flows, grain falls and high-density turbidity currents are generated, which often reach the prodelta. Hydrodynamics is controlled differently on the subaqueous fan – only by the river discharge. Therefore, in the middle zone of the subaqueous fan (i.e. the spatially analogous zone to the delta front), the sediment transport mechanisms are quite different, being dominated by low-density turbidity currents and traction currents with an even lower sediment concentration. On the slope of the delta the surge currents (i.e. derived from subaqueous slumps) are characterized by high sediment concentration, which makes them high-energy (velocities reaches 4 m/s), but short-lived. It is different on the subaqueous fan. The concentration of suspended load depends only on the turbidity of the inflowing river waters, and therefore it is distinctly lower. Therefore, these hyperpycnal flows (i.e. underflows) operate at lower velocities ($v < 2$ m/s), but last longer depending on the duration of the river flood. Sometimes the sediment concentration and flow velocity are so low that the grains are transported by traction – as a bedload.

Table 1. Main differences between Gilbert-type delta and subaqueous fan formed in lacustrine setting.

Gilbert-type delta	Subaqueous fan
Morphology and lacustrine environment	
Deep lake (large accommodation space)	Shallow lake (minor accommodation space)
Large depositional form	Small depositional form
Steep slope (15–35°) of delta front	Gentle slope (5–10°, almost uniform over the entire fan surface)
Synchronous progradation and aggradation	Nearly only progradation
Hydrodynamics	
High concentration of sediment being transported	Moderate concentration of sediment being transported
Currents induced mainly by gravity flows on steep delta slope	Currents induced mainly by river discharge
Short-lasting surge currents	Long-lasting, nearly steady hyperpycnal flows
High-energy currents prevail ($1 < v < 4$ m/s)	Low/moderate-energy currents prevail
Deposition and deposits	
Most often: debris flows, grain falls, high-density turbidity currents	Most often: low-density turbidity currents, traction currents
3 sedimentary subenvironments: subaerial fan, delta front, prodelta	2 (or 1) sedimentary subenvironments: mouth bar (or shoal with sheetflows), 'prodelta'
Gravels in subaerial fan, gravels and sands in delta front, sands and silts in prodelta	Sands, gravelly sands in mouth bar, sand, sand with silt in 'prodelta'
Thick coarsening-upward cycles	Thin lithosomes without upward grading
Predominantly beds of 10–20 cm thick	Predominantly thin (≤ 10 cm) beds, ~ 1 cm sandy-silty rhythmites are frequent
Large lateral variability of lithology	Lateral variability of lithology noticeable on short distances

The differences in the morphology of deltas and subaqueous fans, their sedimentary subenvironments, hydrodynamics and depositional processes mean that these forms have different sedimentary records (Table 1). Deltas are large-scale lithosomes whose considerable thickness is a function of lake depth. The long-lived existence of lakes, in turn, determines the great lengths of deltaic lithosomes. The situation is different in the case of the sediments of subaqueous fans. These shallow-lake forms are recorded in sedimentary bodies of a small thickness. Moreover, the progradational nature of subaqueous fans determines that the lengths of the lithosomes are many times greater than their thickness (sheet-like shape of fan-derived successions).

Deltas, formed at the mouths of larger rivers, are most often represented by higher energy (coarser-grained) deposits compared to subaqueous fans. Moreover, the gravitational redeposition of the material on the steep slopes of deltas leads to a broader extent of coarse-grained lithofacies in a distal direction (towards the central zone of the lake) in relation to the lithosomes of the subaqueous fans. Therefore, gravel beds occasionally constitute a significant lithological component even in the prodelta facies. Due to high frequency of underwater debrites, bipartite deposits (debrite-to-turbidite successions) and high-density turbidites, the beds of deltas are thicker than those in subaqueous fans, which often (especially in the outer part) consist of low-density turbidites and tractionites.

Migration of the topset, foreset and bottomset facies is controlled by simultaneous progradation and aggradation of the delta. This process leads to the formation of large-scale cycles with distinct coarsening-upward grading. It is different with the subaqueous fan. The presence of only two facies (proximal and distal), their poor grain-size differentiation, and minor aggradation ratio preclude the formation of distinct cycles.

The clearest lithological differences between the lithosomes of deltas and subaqueous fans are observed in their middle zones, i.e. in the sediments of the steep delta front and the slightly inclined fan. In other sections, the delta and fan lithosomes differ less clearly. The proximal facies of the Gilbert-type delta are composed of subaerial alluvial fan deposits. Sometimes gravelly, gravelly-sandy or sandy infills of shallow braided channels may be similar to scour-and-fill structures derived from hydraulic jumps or sheetflows acting in proximal shoal of the subaqueous fan. In such a case, the only distinguishing feature of delta and subaqueous fan may be the texture. The proximal facies of the subaqueous fan are usually more finely grained than analogous facies in the delta. Mouth bars may also be present in the proximal zones of both forms. The distal facies of the delta and the subaqueous fan are often similar too (the prodelta facies). Both are dominated by sandy-silty heterolithic sediments developed as thin rhythmites. As mentioned above, only the presence of gravelly-sandy beds within the fine-grained prodelta succession proves that the massflows take place on the adjacent steep slope, i.e. is evidence of the delta environment, not of a subaqueous fan.

Glaciolacustrine fans (so-called *ice-contact underwater fans*), accumulated at the mouths of glacier tunnels, differ from the presented scheme on the origin and lithology of the non-glacigenic subaqueous fans. The difference in their formation is that they are fed with very high-energy meltwater flows transporting all fractions (from clay to boulders) in high concentration (Back et al., 1998). For this reason, the proximal parts of these fans contain more coarsely grained clusters or oversized clasts (Russell & Arnott, 2003; Hornung et al., 2007; Winsemann et al., 2009). Another distinctive feature is the presence of gravelly diamictons derived from cohesive debris flows (Lønne, 1995), which are not found in fluvially-induced subaqueous fans. The flows at the mouths of subglacial tunnels are heavily hyperconcentrated flows most often (Paterson & Cheel, 1997; Russell & Knudsen, 1999; Ravier et al., 2014). These hydraulic conditions determine the specific lithology of the ice-contact underwater fans: very poor sorting (diamictic texture), large thickness of beds, massive structure. It should be emphasized that most often subglacial inflows are very fast. Therefore, sedimentation in the proximal parts of the fans usually occurs from supercritical flows (Russell & Arnott, 2003). Antidunes with hydraulic jumps are often formed there, which are recorded with sandy-gravelly backsets in the sedimentary succession (Hornung et al., 2007; Lang et al., 2017). Other high-energy bedforms are also laid down, such as chute-and-pool structures, cyclic steps and humpback dunes (for details see Lang et al., 2020). Even in the distal parts of these fans, the flows are so fast that antidunes can form.

4. Conclusions

Deltas (more precisely: fan deltas or Gilbert-type deltas) are formed at the margins of seas and deep lakes, while subaqueous fans develop in shallow lakes most often. The former ones are accumulated as a result of simultaneous progradation and aggradation, while the fans are dominated by progradation.

Fan-delta successions are built of three distinct facies: topset, foreset and bottomset. The topset facies is deposited subaerially, mainly in the braided channels and/or sheetflows. Foreset deposits are the most important facies for the fan delta. On an underwater, steep slope, the gravitational movement of grains (deposition of debrites) occurs, often combined with density flows (deposition of turbidites). In spite of being the lowest-energy zone of the delta, the prodelta often consists (especially in the proximal part) of turbidites and debrites. In contrast, its outer part is a zone of a characteristic sand and silt deposition from traction currents and suspension settling.

The depositional environment of subaqueous fan is divided into two zones: proximal and distal. They are not separated by a distinct slope (as in deltas) and therefore both facies pass gradationally into each other. Mouth bars (large dunes or microdeltas) are characteristic of the proximal zone. They are often accumulated behind large scours eroded by an intense vortex (hydraulic jump). In other cases, the proximal zone is dominated by the deposition from sheetflows (conditions of supercritical-to-subcritical transition). The distal part of the fan is dominated by turbidity currents (origin of Bouma successions) or low-density traction currents.

Differences between fan deltas and subaqueous fans are as follows. In the sedimentary record, deltas build large-scale, thick sedimentary bodies, while fans form broad lenses of limited thickness. The same relationship applies to low-rank depositional units, i.e. beds, sets and cosets. Lithosomes of deltas are dominated by gravity-transport deposits, i.e., large-scale foresets derived from cohesionless debris flows. On subaqueous fans this deposition is limited to lee faces of low mouth bars only. There are no deposits related to subaerial channels (topset facies in fan deltas) in the successions of subaqueous fans. Generally, deltas are built of coarser sediments than fans. The sedimentological identification of fan deltas is relatively easy, because subsequent facies differ significantly in their lithological features, both texturally and structurally. On subaqueous fan, the hydraulic conditions are more uniform, and they change gradually with the direction of flow. Therefore, the lithological contrast between the proximal and distal facies is smaller and the identification of fossil fans is more difficult.

Glacigenic subaqueous fans (ice-contact subaqueous fans) clearly differ from the fans of non-glacial lakes. The sediments supplied from the glacier are coarse-grained, poorly sorted, their concentration is higher, and the flows are an extremely high-energy nature. Therefore, sedimentary successions of ice-contact fans often contain debrite beds and numerous structures that resulted from rapid supercritical flows.

Acknowledgements

The authors like to thank two anonymous reviewers for their constructive comments and useful remarks, which improved the final manuscript.

References

Adams, E.W. & Schlanger, W., 2000. Basic types of submarine slope curvature. *Journal of Sedimentary Research* 70, 814–828.

Alexander, J. & Mulder, T., 2002. Experimental quasi-steady density currents. *Marine Geology* 186, 195–210.

Back, S., de Batist, M., Kirillov, P., Strecker, M.R. & Vanhauwaert, P., 1998. The Frolikha Fan: a large Pleistocene glaciolacustrine outwash fan in N Lake Baikal, Siberia. *Journal of Sedimentary Research* 68, 841–849.

Bornhold, B.D. & Prior, D.B., 1990. Morphology and sedimentary processes on the subaqueous Noeick River delta, British Columbia, Canada. *International Association of Sedimentologists Special Publication* 10, 169–181.

Breda, A., Mellere, D. & Massari, F., 2007. Facies and processes in a Gilbert-delta-filled incised valley (Pliocene of Ventimiglia, NW Italy). *Sedimentary Geology* 200, 31–55.

Cao, Y., Wang, Y., Gluyas, J.G., Liu, H., Liu, H. & Song, M., 2018. Depositional model for lacustrine nearshore subaqueous fans in a rift basin: The Eocene Shahejie Formation, Dongying Sag, Bohai Bay Basin, China. *Sedimentology* 65, 2117–2148.

Carvalho, A.H. & Vesely, F.F., 2017. Facies relationships recorded in a Late Paleozoic fluvio-deltaic system (Parana, Brazil): Insights into the timing and triggers of subaqueous gravity flows. *Sedimentary Geology* 352, 45–62.

Chikita, K., 1992. Dynamic processes of sedimentation by river-induced turbidity currents. II. Application of a two-dimensional, advective diffusion model. *Transactions of Japan Geomorphological Union* 13, 1–18.

Chough, S.K. & Hwang, I.G., 1997. The Duksung fan delta, SE Korea: growth of delta lobes on a Gilbert-type topset in response to relative sea-level rise. *Journal of Sedimentary Research* 67, 725–739.

Dasgupta, P., 2002. Architecture and facies pattern of a sublacustrine fan, Jharia Basin, India. *Sedimentary Geology* 148, 373–387.

Doktor, M., 1983. Sedimentation of the Miocene gravel deposits in the Carpathian Foredeep. *Studia Geologica Polonica* 78, 107 pp. (in Polish with English summary)

Dorsey, R.J., Umhoefer, P.J. & Renne, P.R., 1995. Rapid subsidence and stacked Gilbert-type fan deltas, Pliocene Loreto basin, Baja California Sur, Mexico. *Sedimentary Geology* 98, 181–204.

Eriksson, P.G., 1991. A note on coarse-grained gravity-flow deposits within Proterozoic lacustrine sedimentary rocks, Transvaal Sequence, S Africa. *Journal of African Earth Sciences* 12, 549–553.

Ethridge, F.G. & Wescott, W.A., 1984. Tectonic setting, recognition and hydrocarbon reservoir potential of fan delta deposits. *Memoir Canadian Society of Petroleum Geologists* 10, 217–235.

Falk, P.A. & Dorsey, R.J., 1998. Rapid development of gravelly high-density turbidity currents in marine Gilbert-type fan deltas, Loreto Basin, Baja California Sur, Mexico. *Sedimentology* 45, 331–349.

Fielding, C.R. & Webb, J.A., 1996. Facies and cyclicity of the Late Permian Bainmedart Coal Measures in the N Prince Charles Mts, MacRobertson Land, Antarctica. *Sedimentology* 43, 295–322.

Gilbert, G.K., 1890. Lake Bonneville. *U.S. Geological Survey Monitor* 1, 438 pp.

Gilbert, R. & Crookshanks, S., 2009. Sediment waves in a modern high-energy glacilacustrine environment. *Sedimentology* 56, 645–659.

Gobo, K., Ghinassi, M. & Nemec, W., 2014. Reciprocal changes in foreset to bottomset facies in a Gilbert-type delta: Response to short-term changes in base level. *Journal of Sedimentary Research* 84, 1079–1095.

Gobo, K., Ghinassi, M. & Nemec, W., 2015. Gilbert-type deltas recording short-term base-level changes: Delta-brink morphodynamics and related foreset facies. *Sedimentology* 62, 1923–1949.

Gruszka, B., 2001. Climatic versus tectonic factors in the formation of the glaciolacustrine succession (Belchatow outcrop, central Poland). *Global and Planetary Change* 28, 53–71.

Gruszka, B., 2007. The Pleistocene glaciolacustrine sediments in the Belchatow mine (central Poland): Endogenic and exogenic controls. *Sedimentary Geology* 193, 149–166.

Gruszka, B. & Terpiłowski, S., 2014. Sedimentary record of the Younger Saalian ice margin stagnation in E Poland: development of a regular pattern of glaciolacustrine kames. *Geografiska Annaler* A, 97, 279–298.

Hanáček, M., Nyvlt, D., Skacelova, Z., Nehyba, S., Prochazkova, B. & Engel, Z., 2018. Sedimentary evidence for an ice-sheet dammed lake in a mountain valley of the Eastern Sudetes, Czechia. *Acta Geologica Polonica* 68, 107–134.

Haughton, P.D.W., Barker, S.P. & McCaffrey, W.D., 2003. 'Linked' debrites in sand-rich turbidite systems – origin and significance. *Sedimentology* 50, 459–482.

Hilbe, M. & Anselmetti, F.S., 2014. Signatures of slope failures and river-delta collapses in a perialpine lake (Lake Lucerne, Switzerland). *Sedimentology* 61, 1883–1907.

Hornung, J.J., Asprion, U. & Winsemann, J., 2007. Jet-efflux deposits of a subaqueous ice-contact fan, glacial Lake Rinteln, NW Germany. *Sedimentary Geology* 193, 167–192.

Hwang, I.G. & Chough, S.K., 1990. The Miocene Chunbuk Fmormation, SE Korea: marine Gilbert-type fan-delta system. *International Association of Sedimentologists Special Publication* 10, 235–254.

Ilgar, A. & Nemec, W., 2005. Early Miocene lacustrine deposits and sequence stratigraphy of the Ermenek Basin, Central Taurides, Turkey. *Sedimentary Geology* 173, 233–275.

Jerrett, R.M., Bennie, L.I., Flint, S.S. & Greb, S.F., 2016. Extrinsic and intrinsic controls on mouth bar and mouth bar complex architecture: Examples from the Pennsylvanian (Upper Carboniferous) of the central Appalachian Basin, Kentucky, USA. *Geological Society of America Bulletin* 128, 1696–1716.

Knudsen, O. & Marren, P.M., 2002. Sedimentation in a volcanically dammed valley, Bruarjökull, NE Iceland. *Quaternary Science Reviews* 21, 1677–1692.

Krzyszkowski, D., Krzywicka, A., Wachecka-Kotkowska, L. & Sroka, W., 2019. The Middle Pleistocene glaciolacustrine environment of an ice-dammed mountain valley, Sudeten Mts, Poland. *Boreas* 48, 966–987.

Lang, J., Le Heron, D.P., Van Den Berg, J.H. & Winsemann, J., 2020. Bedforms and sedimentary structures related to supercritical flows in glacigenic settings. *Sedimentology* doi: 10.1111/sed.12776

Lang, J., Sievers, J., Loewer, M., Igel, J. & Winsemann, J., 2017. 3D architecture of cyclic-step and antidune deposits in glacigenic subaqueous fan and fan-delta settings: Intergrating outcrop and ground-penetrating radar data. *Sedimentary Geology* 362, 83–100.

Leszczyński, S. & Nemec, W., 2015. Dynamic stratigraphy of composite peripheral unconformity in a foredeep basin. *Sedimentology* 62, 645–680.

Liverman, D.G.E., 1991. Sedimentology and history of a Late Wisconsinan glacial lake, Grande Prairie, Alberta, Canada. *Boreas* 20, 241–257.

Longhitano, S.G., 2008. Sedimentary facies and sequence stratigraphy of coarse-grained Gilbert-type deltas within the Pliocene thrust-top Potenza Basin (S Apennines, Italy). *Sedimentary Geology* 210, 87–110.

Lowe, D.R., 1982. Sediment-gravity flows. II. Depositional models with special reference to the deposits of high-density turbidity currents. *Journal of Sedimentary Petrology* 52, 279–297.

Lønne, I., 1993. Physical signatures of ice advance in a Younger Dryas ice-contact delta, Troms, N Norway: implication for glacier-terminus history. *Boreas* 22, 59–70.

Lønne, I., 1995. Sedimentary facies and depositional architecture of ice-contact glaciomarine systems. *Sedimentary Geology* 98, 13–43.

Lønne, I. & Nemec, W., 2004. High-arctic fan delta recording deglaciation and environment disequilibrium. *Sedimentology* 51, 553–589.

Lunkka, J.P. & Gibbard, P., 1996. Ice-marginal sedimentation and its implications for ice-lobe deglaciation patterns in the Baltic region: Pohjankangas, W Finland. *Journal of Quaternary Sciences* 11, 377–388.

Massari, F., 1996. Upper-flow-regime stratification types on steep-face, coarse-grained, Gilbert-type progradational wedges (Plesistocene, S Italy). *Journal of Sedimentary Research* 66, 364–375.

Mastalerz, K., 1995. Deposits of high-density turbidity currents on fan-delta slopes: an example from the upper Visean Szczawno Fm., Intrasudetic Basin, Poland. *Sedimentary Geology* 98, 121–146.

Mleczak, M. & Pisarska-Jamroży, M., 2019. Miocene quartz sands redeposited on subaqueous and alluvial fans during the Saalian: Interpretation of the depositional scenario at Ujście, western Poland. *Geologos* 25, 125–137.

Mortimer, E., Gupta, S. & Cowie, P., 2005. Clinoform nucleation and growth in coarse-grained deltas, Loreto Basin, Baja California Sur, Mexico: a response to episodic accelerations in fault displacement. *Basin Research* 17, 337–359.

Mulder, T. & Alexander, J., 2001. The physical character of subaqueous sedimentary density flows and their deposits. *Sedimentology* 48, 269–299.

Mulder, T. & Syvitski, J.P.M., 1995. Turbidity currents generated at river mouths during exceptional discharges to the world oceans. *Journal of Geology* 103, 285–299.

Mulder, T., Savoye, B. & Syvitski, J.P.M., 1997. Numerical modelling of a mid-sized gravity flow: the 1979 Nice turbidity current (dynamics, processes, sediment budget and seafloor impact). *Sedimentology* 44, 305–326.

Mulder, T., Migeon, S., Savoye, B. & Faugeres, J.C., 2001. Inversely graded turbidite sequences in the Deep Mediterranean: a record of deposits from flood-generated turbidity currents? *Geo-Marine Letters* 21, 86–93.

Mulder, T., Syvitski, J.P.M., Migeon, S., Faugeres, J.C. & Savoye, B., 2003. Marine hyperpycnal flows: initiation, behavior and related deposits. A review. *Marine & Petroleum Geology* 20, 816–882.

Nemec, W., 1990. Deltas – remarks on terminology and classification. *International Association of Sedimentologists Special Publication* 10, 3–12.

Nemec, W. & Steel, R.J. 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass–flow deposits. [In:] E.H.Koster and R.J. Steel (Eds). Sedimentology of Gravels and Conglomerates. *Canadian Society of Petroleum Geologists Memoir* 10,1–31.

Nemec, W., Lønne, I. & Blikra, L.H., 1999. The Kregnes moraine in Gauldalen, west-central Norway: anatomy of a Younger Dryas delta in a palaeofjord basin. *Boreas* 28, 454–476.

Paterson, J.T. & Cheel, R.J., 1997. The depositional history of the Bloomington Complex, an ice-contact deposit in the Oak Ridges Moraine, S Ontario, Canada. *Quaternary Science Reviews* 16, 705–719.

Pharo, C.H. & Carmack, E.C., 1979. Sedimentation processes in a short residence-time intermontane lake, Kamloops Lake, British Columbia. *Sedimentology* 26, 523–541.

Pisarska-Jamroży, M. & Weckwerth, P., 2013. Soft-sediment deformation structures in a Pleistocene glaciolacustrine delta and their implications for the recognition of subenvironments in delta deposits. *Sedimentology* 60, 637–665.

Plink-Björklund, P. & Ronnert, L., 1999. Depositional processes and internal architecture of Late Weichselian

ice-margin submarine fan and delta settings, Swedish west coast. *Sedimentology* 46, 215–234.
Postma, G., 1990. Depositional architecture and facies of river and fan deltas: a synthesis. *International Association of Sedimentologists Special Publication* 10, 13–27.
Przepióra, P., Kalicki, T., Aksamit, M., Biesaga, P., Frączek, M., Grzeszczyk, P., Malęga, E., Chrabąszcz, M., Kłusakiewicz, E. & Kusztal, P., 2019. Secular and catastrophic processes reflected in sediments of the Suchedniów water reservoir, Holy Cross Mountains (Poland). *Geologos* 25, 139–152.
Ravier, E., Buoncristiani, J.-F., Clerc, S., Guiraud, M., Menzies, J. & Portier, E., 2014. Sedimentological and deformational criteria for discriminating subglaciofluvial deposits from subaqueous ice-contact fan deposits: A Pleistocene example (Ireland). *Sedimentology* 61, 1382–1410.
Rohais, S., Eschard, R. & Guillocheau, F., 2008. Depositional model and stratigraphic architecture of rift climax Gilbert-type fan deltas (Gulf of Corinth, Greece). *Sedimentary Geology* 210, 132–145.
Røe, S.L., 1995. Stacked fluviodeltaic cycles in the Upper Proterozoic Godkeila Member, Varanger Peninsula, N Norway. *Norsk Geologisk Tidsskrift* 75, 229–242.
Russell, H.A.J. & Arnott, R.W.C., 2003. Hydraulic jump and hyperconcentrated-flow deposits of a glacigenic subqueous fan: Oak Ridges Moraine, S Ontario, Canada. *Journal of Sedimentary Research* 73, 887–905.
Russell, A.J. & Knudsen, O., 1999. Controls on the sedimentology of the November 1996 jökulhlaup deposits, Skeidararsandur, Iceland. *International Association of Sedimentologists Special Publication* 28, 315–329.
Rust, B.R. & Romanelli, R., 1975. Late Quaternary subaqueous deposits near Ottawa, Canada. *Society of Economic Paleontologists and Mineralogists Special Publication* 23, 238–248.
Shanmugam, G., 2018. The hyperpycnite problem. *Journal of Palaeogeograph*y 7, 6, https://doi.org/10.1186/s42501-018-0001-7
Shanmugam, G., 2019. Reply to discussions by Zavala (2019) and by Van Loon, Hüeneke, and Mulder (2019) on Shanmugam, G. (2018, Journal of Palaeogeography, 7 (3): 197–238): 'the hyperpycnite problem'. *Journal of Palaeogeography* 8, 31, https://doi.org/10.1186/s42501-019-0047-1
Slomka, J.M. & Hartman, G.M.D., 2019. Sedimentary architecture of a glaciolacustrine braidplain delta: proxy evidence of a pre-Middle Wisconsinan glaciation (Grimshaw gravels, Interior Plains, Canada). *Boreas* 48, 215–235.
Sohn, Y.K., Kim, B.C., Hwang, I.B., Bahk, J.J., Choe, M.Y. & Chough, S.K., 1997. Characteristics and depositional processes of large-scale gravelly Gilbert-type foresets in the Miocene Doumsan fan delta, Pohang Basin, SE Korea. *Journal of Sedimentary Research* 67, 130–141.
Sohn, Y.K., Rhee, C.W. & Kim, B.C., 1999. Debris flow and hyperconcentrated flood-flow deposits in an alluvial fan, northwestern part of the Cretaceous Yongdong Basin, Central Korea. *The Journal of Geology* 107, 111–132.
Stingl, K., 1994. Depositional environment and sedimentary of the basinal sediments in the Eibiswalder Bucht (Radl Fm. and Lower Eibiswald Beds), Miocene W Styrian Basin, Austria. *Geologische Rundschau* 83, 811–821.
Syvitski, J.P.M. & Hein, F.J., 1991. Sedimentology of an Arctic Basin: Hirbilung Fjord, Baffin Island, Northwest Territories. *Geological Survey of Canada Paper* 91–11, 61 pp.
Syvitski, J.P.M., Smith, J.N., Calabrese, E.A. & Boudreau, B.P., 1988. Basin sedimentation and the growth of prograding deltas. *Journal of Geophysical Research* 93, C6, 6895–6908.
Van Loon, A.J., Hüneke, H. & Mulder, T., 2019. The hyperpycnite problem: comment. *Journal of Palaeogeography* 8, 1. https://doi.org/10.1186/s42501-019-0034-6
White, J.D.L., 1992. Pliocene subaqueous fans and Gilbert-type deltas in maar crater lakes, Hopi Buttes, Navajo Nation (Arizona), USA. *Sedimentology* 39, 931–946.
Winsemann, J., Asprion, U., Meyer, T. & Schramm, C., 2007. Facies characteristics of Middle Pleistocene (Saalian) ice-margin subaqueous fan and delta deposits, glacial Lake Leine, NW Germany. *Sedimentary Geology* 193, 105–129.
Winsemann, J., Lang, J., Polom, U., Loewer, M., Igel, J., Pollok, L. & Brandes, C., 2018. Ice-marginal forced deltas in glacial lake basins: geomorphology, facies variability and large-scale depositional architecture. *Boreas* 47, 973–1002.
Winsemann, J., Hornung, J.J., Meinsen, J., Asprion, U., Polom, U., Brandes, C., Baussman, M. & Weber, C., 2009. Anatomy of subaqueous ice-contact fan and delta complex, Middle Pleistocene, NW Germany. *Sedimentology* 56, 1041–1076.
Woźniak, P.P., Pisarska-Jamroży, M. & Elwirski, Ł., 2018. Orientation of gravels and soft-sediment clasts in subaqueous debrites – implications for palaeodirection reconstruction: case study from Puck Bay, N Poland. *Bulletin of Geological Society of Finland* 90, 1–14.
Yperen, A.E., Poyatos-Moré, M., Holbrook, J.M. & Midtkandal, I., 2020. Internal mouth-bar variability and preservation of subordinate coastal processes in low-accommodation proximal deltaic settings (Cretaceous Dakota Group, New Mexico, USA). *The Depositional Reco*rd 6, 431–458.
Yu, B., A. Cantelli, J. Marr, C. Pirmez, C. O'Byrne & G. Parker, 2006. Experiments on Self-Channelized Subaqueous Fans Emplaced by Turbidity Currents and Dilute Mudflows. Journal of Sedimentary Research 76(6), 889–902.
Zavala, C., 2020. Hyperpycnal (over density) flows and deposits. *Journal of Palaeogeography* 9, 17, https://doi.org/10.1186/s42501-020-00065-x
Zavala, C., Ponce, J.J., Arcuri, M., Drittanti, D., Freije, H. & Asensio, M., 2006. Ancient lacustrine hyperpycnites: a depositional model from a case study in the Rosayo Fm. (Cretaceous) of west-central Argentina. *Journal of Sedimentary Research* 76, 41–59.
Zeng, J., Lowe, D.R., Prior, D.B., Wiseman, W.J. & Bornhold, B.D., 1991. Flow properties of turbidity currents in Bute Inlet, B.C. *Sedimentology* 38, 975–996.

Manuscript submitted: 15 January 2021
Revision accepted: 25 March 2021