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Morphology and surficial sediments of the Waldemar River confined outwash fan (Kaffiøyra, Svalbard)

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Abstract. The development and evolution of confined outwash fans in high Arctic regions depend on the rate of meltwater discharge, which is directly related to the glacier ablation rate, in turnassociated with climate conditions. Other factors controlling outwash fan morphology (e.g. depth and width of distributive channels) are processes of fluvial erosion, and the transport and deposition of sediments. These factors have not previously been considered together in relation to the evolution of the confined outwash fans which are commonly incised into the top of permafrost in the forefields of subpolar glaciers and in mountains in high Arctic regions. Morphology and surficial sediments of a confined outwash fan of the Waldemar River (NW Spitsbergen, Svalbard) were analysed on the basis of geomorphological and sedimentological studies. The results of our investigations show multiple relations between the depth and width of distributary channels, fan slope and textural features of glaciofluvial surficial sediments supplied into the fluvial system from the glacier and from lateral fluvial erosion of permafrost

Key words:
confined outwash fan,
fan slope,
permafrost,
Svalbard

Introduction

Valley-confined and tributary-junction fans are narrow and funnelled drainage fluvial systems with low numbers of channel branches (Nemec and Steel 1988; Silva et al. 1992; Viseras et al. 2003; Al-Farraj and Harvey 2005). Their development is related to the capacity of the basin to yield large volumes of sediments (Gómez-Villar et al. 2006). Confined outwash fans which develop in proglacial areas are fed by meltwaters flowing from glaciers and develop as a result of incision in the tundra surface and lateral erosion of channels. Thus, it is crucial to recognise the evolution of confined proglacial fans in high Arctic regions in order to be able to identify the processes and rate of arctic habitats' degradation under global climate warming (Rosgen 1996; Buffington et al. 2004).

The variation of fan morphology in relation to water discharge were discussed in many studies on alluvial fan development (Ferguson and Ashworth 1991; Parker et al. 1998a, b; Stock et al. 2007). Therefore, the main aim of our study is to recognise the spatial variations in the surficial sediments of a confined outwash fan developed in the high Arctic region in relation to the changes of fan surface morphology, which is directly related to the rate of channel lateral erosion and sediment motion thresholds (Solari and Parker 2000; Mueller and Pitlick 2005).

Geomorphological and geological settings

The Waldemar River outwash fan is located on the Kaffiøyra coastal plain on the western part of Oscar II Land (northwestern Spitsbergen, Svalbard, Fig. 1). This plain is 14 km long and up to 5 km wide (Sobota et al. 2016a). The Kaffiøyra region covers an area of about 310 km^2 and is composed of two geological formations (Dallmann et al. 1993; Hjelle 1993). The first consists of Late Proterozoic dolomites, pegmatites, quartzites, phyllites and marbles, and the second contains Palaeogene quartzites, dolomites, sandstones, siltstones and shales.

The Kaffiøyra's characteristic landforms are marine terraces which were elevated by the post-glacial rebound of 11.5–9.0 kyr BP (not calibrated ages; Niewiarowski et al. 1993). The terraces surfaces are composed of beach sands and gravels, which are covered in the eastern part by fluvioglacial deposits (in areas of outwash fans) and by glacial tills deposited before the Little Ice Age and redeposited due to solifluction (Forman 1989; Grześ et al. 2009; Jaworski and Chutkowski 2015).

Fig. 1. Location of the Waldemar River confined outwash fan on the Kaffiøyra coastal plain on the western part of Oscar II Land (northwestern Spitsbergen, Svalbard)

The fluvial systems of the Kaffiøyra plain comprise gravelly-bed braided rivers which drain individual glaciers (Sobota 2014). The analyzed Waldemar River confined outwash fan is a gravelly fan which is incised by up to 3 metres into the top of the permafrost and surfaces of marine terraces in the northern part of the Kaffiøyra plain (Figs 2 and 3). Moreover, the Waldemar River outwash fan is located in the western part of the glaciated catchment area of the Waldemar River, which is fed by meltwaters from the Waldemar Glacier (Nowak and Sobota 2015) (Figs 1 and 2).

The fluvial system of the Waldemar River consists of braided-distributary channels which migrate on the fan surface and are active only during the summer seasons (Fig. 3). The meltwater discharge (0.5–1.4 m^{3}s^{-1}) is variable in relation to the ablation rate of the Waldemar Glacier (Sobota 2005; Sobota 2013).

Methods

The morphology of the fan surface and distributive channel (slope S, bankfull channels depth D_b and bankfull width W_b), and the spatial distribution of sediments on the Waldemar River fan surface were analyzed in its proximal, middle and distal zones at 153 measurement points (Figs 2, 5 and 6). The bankfull flow was defined as the difference between the highest channel banks and the lowest point along the channel cross section (e.g. Fig. 4E). The slope of the fan surface (S) was as-

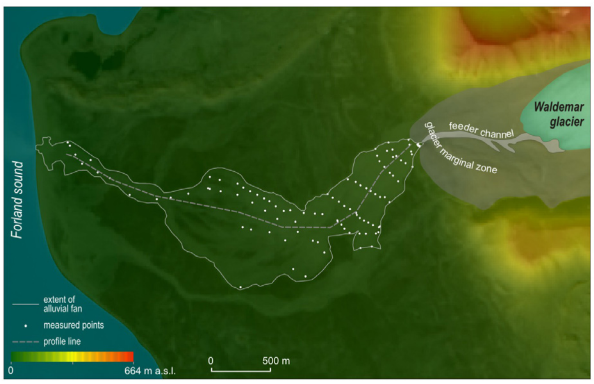

Fig. 2. Extent of the Waldemar River confined outwash fan and location of measured points on 20-m Digital Elevation Model (DEM) received from Norwegian Polar Institute (https://data.npolar.no/dataset/dce53a47-c726-4845-85c3-a65b46fe2fea)

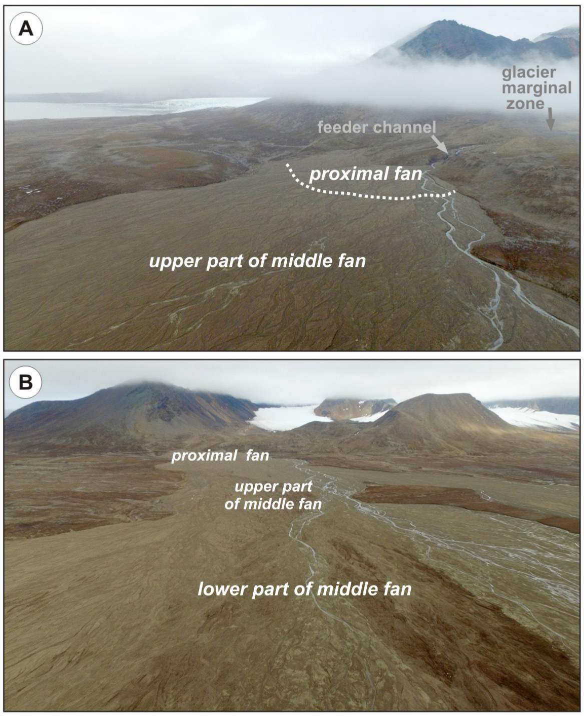

Fig. 3. Braided-distributary channels of the Waldemar River confined outwash fan: A – proximal zone and upper part of mid-fan incised in Kaffiøyra plain; B – middle part of outwash confined fan characterised by changeable fan width

sessed using a 20-m Digital Elevation Model (DEM) (https://data.npolar.no/dataset/dce53a47-c726-4845-85c3-a65b46fe2fea).

Analysis of the grain-size distribution of the fan surface sediments (e.g. median particle grain diameter d_{50} and sediments storing σ; Graham et al., 2005) was assessed using Digital Gravelometer software on the basis of photographs of surface sediments (carried out at the 153 measurement points) taken perpendicular to the fan surface from a height of 1.5 m (Mao and Surian 2010; Reid et al. 2010). This software is commonly used in sedimentological studies (e.g. Mao et al. 2008; Mao and Surian 2010) because calculation errors are typically less than 0.05 phi (Graham et al. 2005). To minimise calculation errors, 3 photographs of surface sediments were taken at each of the measured points and one of them (with the best quality related to the sharpness and contrast) was selected for further analysis using the Digital Gravelometer. The analysed sediments were classified texturally according to the Udden–Wentworth scale (Wentworth 1922). The statistical parameters of the grain-size distribution were analysed on the basis of geometric (modified) graphical measures. The spatial distribution of these parameters was determined based on the ordinary kriging method using ArcGIS 9.3 software. Ordinary kriging is the most widely used spatial estimation method, in which the error variance is minimised because (unlike with simple kriging) the method does not assume knowledge of the mean or covariance. For this reason, ordinary kriging represents the most common kriging method in practice and its aim is to predict the value of the random variable at an unsampled point of a geographical region as well (Wackernagel 1995; Yamamoto 2005; Webster and Oliver 2007).

Physical processes controlling water flow and the rate of sediment transport in rivers and alluvial fans are influenced by the geometry of the channel cross section and the roughness of riverbed. This roughness depends on the bed material size in the case of a gravel-bed river, and thus the dimensionless index D_b/d_{50} indicates the interference of sediment particles in the flow in the channel (Buffington and Montgomery 1999; Vollmer and Kleinhans 2007; Stock et al. 2007; Kumar 2011).

Morphology of the confined outwash fan

The Waldemar River fan surface is concave-up and declines from the fanhead at an altitude of 68 m a.s.l. to 0.7 m a.s.l., and its average surface gradient is 0.016 (Table 1, Fig. 2). This confined fan is radial in the proximal zone and is narrow in the middle and distal zones. The distributary channels predominantly have plane beds with transverse ribs and clast dams in the proximal zone, whereas low-relief longitudinal and alternate gravelly bars occur in the middle and distal zones (Fig. 4 B, E). The depth of fan incision into the marine terraces varies from 3 m at the proximal and middle fan zones down to 0.4 m at its distal fan (Fig. 4). The overbank areas were transformed seasonally by sheetfloods during the high ablation rate of the Waldemar Glacier.

The morphology variation of the confined outwash fan was identified in the three morphological zones (proximal, middle and distal) which were described in terms of fan surface slope and distributary channel widths and depths (Figs 5 and 6). The surface slope of the fan proximal zone varies in the

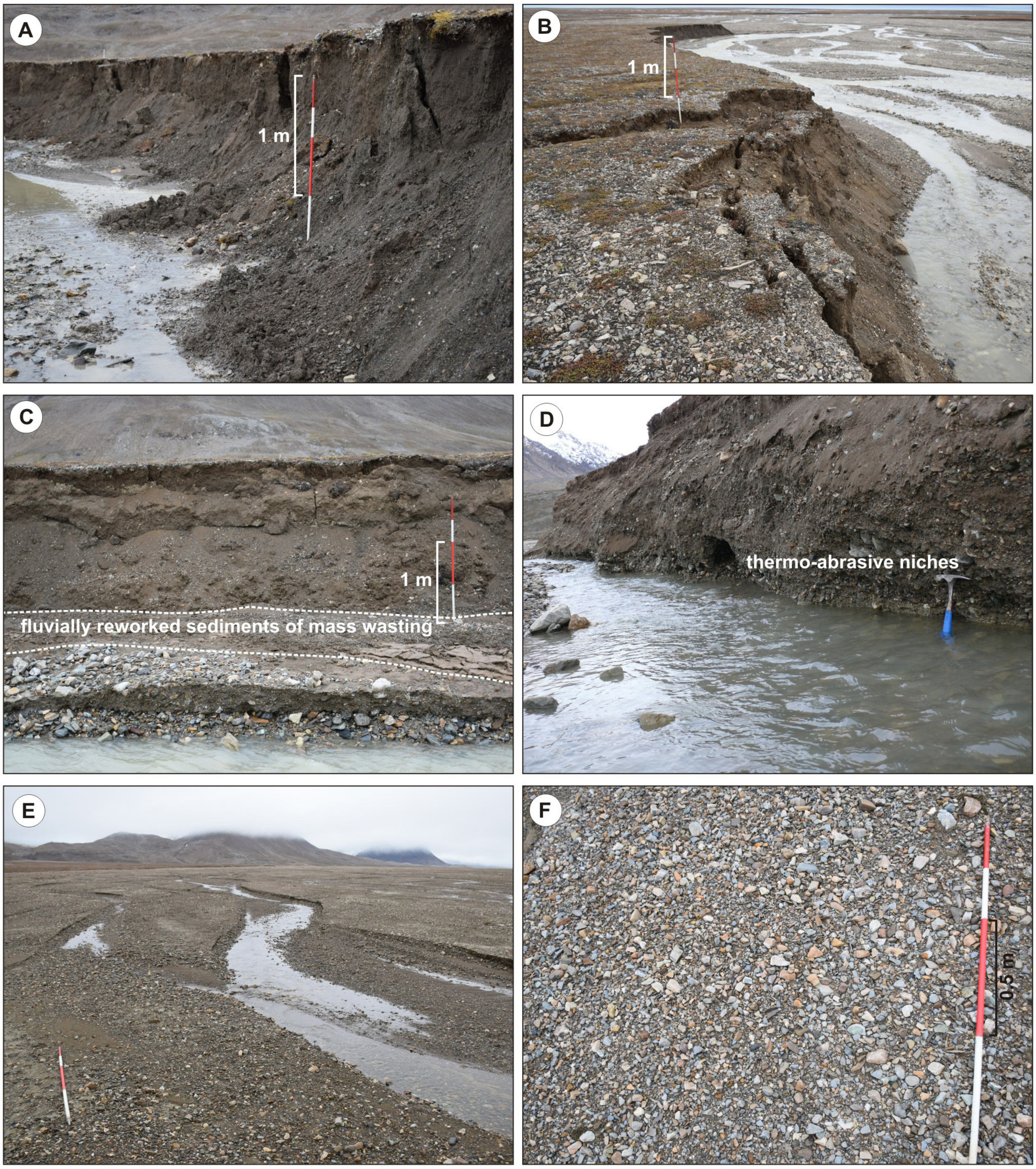

Fig. 4. Landforms of river bank erosion, morphology and surficial sediments of the confined outwash fan of the Waldemar River: A, B – mass movements due to river bank erosion of permafrost upper layer and massive inputs of unconsolidated sediments into the channel bed; C – sediments of mass movements deposited at the base of slope and reworked by meltwaters in overbank area: D – river bank erosion with thermo-abrasive niches developed as a result of the thawing zone's progradation within the frozen river bank; E – morphology of middle zone outwash fan; F – surficial sediments of confined fan of the Waldemar River at mid-fan area

range 0.005–0.157 (Table 2, Fig. 5), but a significant decline in the fan slope from 0.052 to 0.023 was identified 350 m from the fan head and was considered as the border between the proximal and middle zones. Only one active and laterally migrated channel developed in the proximal zone, and thus the morphology of the fan surface is dominated by many inactive channels (Fig. 3). These channels have the highest values of bankfull depth (up to 1.0 m) of the entire alluvial fan (Table 2). Channel widths in the proximal fan zone vary between 3 and 6 m (Table 2, Fig. 6).

The width of the middle zone of the Waldemar River outwash fan increases from 360 to 950 m as the slope declines from 0.054 to 0.004 (Figs 2 and 5). The substantial decrease in slope is noted at 1,700 m from the fan head and thus this place was determined as the border between the mid- and distal fan zones (Fig. 5). The mid-fan channel bankfull widths in the middle zone fluctuate between 1 and 8 m, and bankfull channel depth varies in the range 0.05–0.4 m (Table 2, Fig. 6).

The surface morphology of the distal zone of the Waldemar River confined fan is characterised by a slope which decreases from 0.047 to 0.00004 at the distance of 2.2 km (Table 2, Fig. 5). The width of this zone decreases abruptly to 90 m downfan (at the distance of 1,800 m from fanhead) (Fig. 2). Distributary channels have widths in the range 0.8–8.0 m and depth 0.05–0.5 m (Table 2, Fig. 6).

Surface sediments

Grain-size analysis at the 153 measured points on the surface of the Waldemar River outwash fan enabled us to asses fluctuations in spatial grain-size distribution of the fan surficial sediments. These sediments of the fan proximal zone consist of pebbles (38.37–79.18%), cobbles (19.72–58.48%), boulders (11.91–16.48%) and granules (0.91–4.27%) with admixture of sands (0.08–0.55%) (Table 2, Fig. 6). Due to this, the proximal zone of the Waldemar River confined fan is dominated by pebbles, cobbles and boulders, in contrast to the middle and distal zones where the contents of these fractions are lower (Table 2, Fig. 6). This difference in grain-size composition of surficial sediments causes the increase in d_{50} values for sediments in the proximal zone (Tables 1 and 2, Fig. 7). These deposits are poorly and very poorly sorted (σ in the range of 2.20–4.43 mm).

The analysis of the spatial variation of the surficial sediments in the middle zone of the Waldemar River fan indicates a continuing decrease in the contents of cobbles, granules and sands and an increase in pebbles (Fig. 6). Thus, the surface sediments in this fan zone are dominated by pebbles (43.07–97.72%) with admixture of cobbles (0.01–53.64%) and with low content of granules and sands (median values 2.43% and 0.3%, respectively) (Table 2, Fig. 6). All these sediments are moderately and poorly sorted (σ in range 1.94–3.33). The sorting index decreases downfan as do values of d_{50} (Table 2, Fig. 7).

Surface sediments in the distal fan zone consist of pebbles (57.85–94.87% and cobbles (2.75–40.5%) with admixture of granules and sands (Table 2, Fig. 6). These deposits are moderately and poorly sorted, with d_{50} values in the range 20.34–48.99 mm (Table 2, Fig. 7).

Table 1. Morphology and surface sediments of the Waldemar River alluvial fan

	Min	Max	Median	SD
S	0.00004	0.157	0.016	0.012
W_b [m]	0.80	8.00	4.00	1.60
D_b [m]	0.05	1.00	0.15	0.15
Sands [%]	0.08	0.78	0.29	0.14
Granules [%]	0.91	4.27	2.36	0.72
Pebbles [%]	38.37	97.62	73.90	14.00
Cobbles [%]	0.01	58.48	23.54	13.23
Boulders [%]	11.91	16.48	12.88	2.41
d_{50} [mm]	17.71	76.84	36.05	12.86
σ [mm]	1.94	4.43	2.55	0.39
D_b/d_{50}	1.45	22.41	4.53	3.82

Table 2. Morphology and surface sediments of alluvial fan zones

	Proximal fan		Middle fan		Distal fan	
	Min	Max	Min	Max	Min	Max
S	0.005	0.157	0.004	0.054	0.00004	0.047
W^b [m]	3.00	6.00	1.00	8.00	0.80	8.00
D_b [m]	0.20	1.00	0.05	0.40	0.05	0.50
Sands [%]	0.08	0.55	0.11	0.78	0.09	0.45
Granules [%]	0.91	4.27	1.15	4.08	1.10	3.35
Pebbles [%]	38.37	79.18	43.07	97.62	57.85	94.87
Cobbles [%]	19.72	58.48	0.01	53.64	2.75	40.50
Boulders [%]	11.91	16.48	14.20	3.23	12.88	12.88
d_{50} [mm]	27.88	76.56	48.83	12.85	17.71	76.84
d_{95} [mm]	95.78	282.25	167.75	49.06	43.30	261.42
D_b/d_{50}	3.23	22.41	9.06	4.09	1.45	11.29

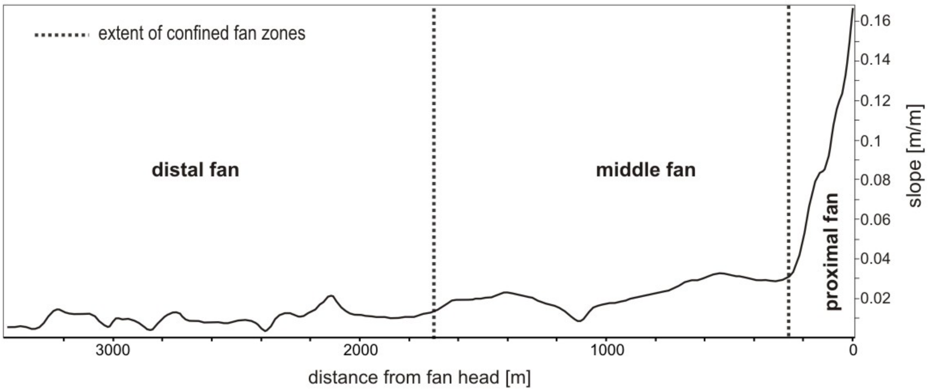

Fig. 5. Downfan slope changes and extents of fan zones

Relationships between confined outwash fan morphology and its surficial sediments' spatial distribution

The relationships between morphology and lithological features of confined outwash fan surficial sediments are associated with the evolution of outwash fan morphology and sedimentary processes which take place under conditions in which permafrost exists in high Arctic regions. Understanding these relationships is crucial for determining outwash fan evolution and processes of sediments transportation and deposition (Parker et al. 1998a, b; Stock et al. 2007; Litwin Miller et al. 2014). In the case of the Waldemar River confined outwash fan,

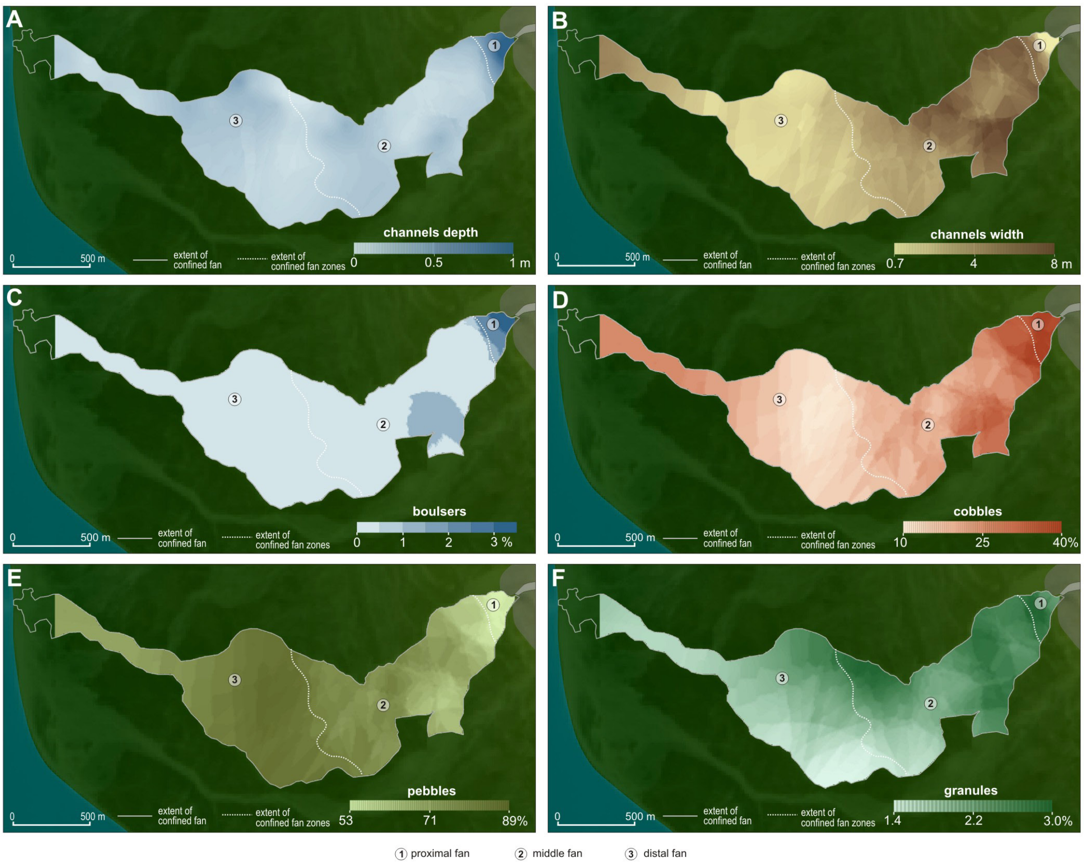

Fig. 6. Morphology of the distributive channels and lithological characteristics of confined fan surface: A – spatial variation of bankfull channel depths; B – spatial variation of bankfull channel widths; C – changes in the spatial distribution of boulders, D – cobbles; E – pebbles; F – granules in surficial sediments of the Waldemar River confined fan

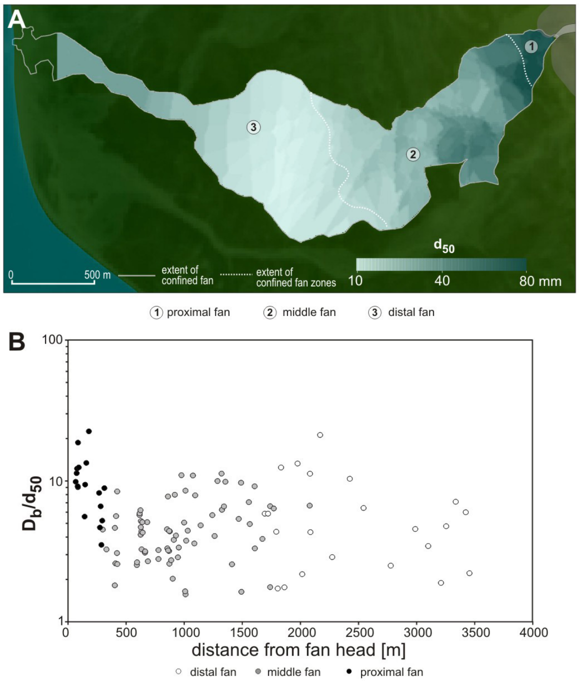

Fig. 7. Grain size-distribution characterised by spatial and downfan changes in median grain diameter (A) and downfan changes of D_b/d_{50} index (B)

the rate of river bank erosion (related to the distributary channels' lateral incision into the permafrost) influences the lateral confined fan expansion (Sobota et al. 2018). Such erosion includes thermal and mechanical erosion, which are responsible for the development of niches which generate gravitational instability in the river banks and initiate gravity flows of the sediments which comprised the upper part of the permafrost layer (Walker et al. 1987; Weckwerth and Pisarska-Jamroży 2015). These processes caused massive inputs of unconsolidated sediments into the distributary channels of the confined outwash fan (Fig. 4). Similar processes can influence the results of luminescence dating of alluvial deposits due to poor quartz-grain bleaching (Weckwerth et al. 2011, 2013).

The rate of sediments transport and deposition is directly related to the slope variations, and the three zones of the analyzed confined fan were thus distinguished in terms of slope changes, which are fundamental for controlling sedimentary processes. These zones have the variable geometry of a braided-distributary channel (e.g. channel depth and width) and fluctuations in sediments grain-size spatial distribution (Fig. 6 and 7). In the case of the analysed confined outwash fan, which developed in the high Arctic region, the slope decreases downfan as the relative roughness of water flow increases (a decrease in D_b/d_{50} index) in the fan proximal zone and the upper reach of the middle fan zone (Table 2, Fig. 7B). Then, the D_b/d_{50} index increases in the rest of the mid-fan as a result of d_{50} reduction and in response to the channel deepening (Fig. 7). In the distal fan zone, changeable values of relative roughness (D_b/d_{50} index) were observed despite the d_{50} increasing. Moreover, channel depths do not change significantly in the distal fan (Fig. 6) as is expected for alluvial fans (Field 2001; Stock et al. 2007).

The spatial distribution of surficial sediments in the area of Waldemar River confined fan indicate that boulder and cobble contents decrease as the slope decreases in the proximal zone and as the percentage of pebbles decreases in the distal fan. The increased percentage of coarse fractions in surficial sediments in the middle and distal fan zones is typical for the confined outwash fan of the Waldemar River and is caused by the inputs of sediments and the concentration of coarse particles in a slow-moving traction carpet (Reid et al. 1985; Iseya and Ikeda 1987) as a result of massive inputs of unconsolidated sediments into the distributary channels from permafrost erosion. This process caused a reduction in sediment mobility due to a decrease in near-bed flow velocity and turbulent fluctuations (Mueller et al. 2005; Vollmer and Kleinhans 2007; Lamb et al. 2008). Thus, size-selective mobility favours finer sediments, which resulted in channel bed armouring (Parker 1990; Paola et al. 1992; Ferguson 2003; Stock et al. 2007; Lamb et al. 2008). These processes decrease fine fraction contents, and increase the percentage of coarse particles in surficial sediments, because energy flow is insufficient to transport these particles, which would result from the channel gradient in middle and distal fan zones. For this reason, High-Arctic confined outwash fans incised into the active permafrost layer have a limited possibility of bifurcation but an increased rate of sediment input into the distributary channels. These processes resulted in the size-selective entrainment of sediments and transport of the fine fraction to the coastal lagoon which encloses the Waldemar River fan from the west. A similar process of confined fan distal segment progradation was reported by Nemec and Steel (1988).

Conclusions

On the basis of the above analyses, the following conclusions can be drawn:

1. The morphology and bed structure of distributive channels in outwash confined fans developed in high Arctic region are closely related to changes in fan slope, fan width and the rate of lateral fluvial erosion of permafrost, on which sediment supply depends.

2. The hydraulic gradient, depth and width of distributary channels affected the rates of sediment transport. This process is related to the fan width because fan narrowing causes an increase in energy flow and, thus, similar transport capacity could be observed in the mid- and distal-fan zones.

3. The increasing of energy flow due to fan narrowing allows the transport of coarser grains than in the case of unconfined fans of similar slope. These coarser particles were supplied and deposited in the middle and distal fan zones due to lateral permafrost erosion (mechanical and thermal).

4. Confined fan lateral expansion due to increasing of meltwater discharge (caused by climate warming in high Arctic regions) results in a reduction in the area of tundra and degradation of the upper part of permafrost. Thus, the recognition of processes of confined outwash fan evolution is crucial for determination of the dynamics of transformations in high Arctic regions and can be considered as an indicator of polar environment changes resulting from climate fluctuations.

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