Post-Little Ice Age development of a High Arctic paraglacial beach complex

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ABSTRACT

We reconstruct the behaviour of a High Arctic gravel-dominated beach complex that has developed in central Spitsbergen, Svalbard, since the end of the Little Ice Age (LIA). The present coastal environment in northern Billefjorden (Petuniabukta) is characterised by limited wave action and ephemeral sediment delivery from non-glaciated, mainly snow-fed fans and talus slopes. Aerial photographic evidence and morpho-sedimentological observations of a beach-ridge plain and spit complex in northern Billefjorden reveal a dynamic coastal system. During the post-LIA period, a prominent coastal barrier at the mouth of the Ebbaelva migrated seaward several tens of metres and prograded northwards to form new spit systems, each >150 m in length. The post-LIA coastal evolution occurred in two main phases. In the first half of the 20th century, increased paraglacial sediment released by retreating land-based glaciers led to the development of a subaqueous spit-platform and the progradation of an ebb-tide delta into the mouth of Ebbaelva, diverting its mouth to the north-west. In the second half of the 20th century, the barrier prograded onto this platform, promoting development of three massive spits. Sedimentological data suggest that changes in beach-ridge composition that occurred during the 20th century are linked to episodic sediment delivery from an adjacent permafrost and snow-fed alluvial fan and delta system. Our work provides a basis for a new model of paraglacial barrier development that recognises the fundamental role of climate and sediment supply as two intimately connected processes that control coastal development in the High Arctic over decadal to centennial timescales.

KEY WORDS: *coastal evolution, beach-ridge plain, spit morphodynamics, paraglacial , High Arctic, Svalbard;*

Introduction

The coastal zone is a key interface where environmental changes impact directly on Arctic communities (Forbes *et al.,* 2011). Recent rapid warming of the Arctic atmosphere has intensified the operation of the geomorphic processes that control coastal evolution (Overduin *et al.,* 2014), causing increased degradation of permafrost (e.g. Wobus *et al.,* 2011), enhanced sediment supply from deglaciated catchments (e.g. Strzelecki *et al.,* 2015), and prolonged periods of open-water conditions and wave activity (e.g. Barnhart *et al.,* 2014). Since the AD 1950s there has also been an increase in the number and intensity of storms entering the Arctic (Zhang *et al.,* 2004), notably in summer months when coastlines lack protecting sea-ice cover. Despite the potential significance of these climate-driven processes, relatively little is known of the physical processes that control past, present and future polar coastal geomorphology and, according to Lantuit *et al.,* (2010), only about 1% of the Arctic coastlines have been investigated in sufficient detail to allow quantitative analysis of the processes operating on them.

The gravel-dominated barrier coastlines of the Svalbard Archipelago provide an excellent location to examine the processes that control High Arctic coastal change. Of special interest are the mechanisms by which polar coasts respond to enhanced landscape change following deglaciation associated with the abrupt climate warming observed since the end of the Little Ice Age (LIA), which is dated to c. 1900 AD on Svalbard (Szczuciński *et al.,* 2009).

According to Mercier (2000), paraglacial processes operating on Svalbard have already reduced glacial processes to a secondary role in controlling landscape change due to post-LIA atmospheric warming. This change is apparent in slope, valley floor and glacier foreland systems, where glacigenic landforms are being denuded by fluvial, aeolian or mass-wasting processes that are accelerated by permafrost degradation (e.g. Åkerman, 1980; Kida, 1986; Etzelmüller *et al.,* 2000; Lønne and Lyså, 2005; Lukas *et al.,* 2005; Mercier *et al.,* 2009; Owczarek *et al.*, 2014; Ewertowski and Tomczyk, 2015). However, the impact of these changes on the coastal zone is uncertain because there have been only a small number of studies of pre- and post-LIA coastal change.

Conventional models of paraglacial barrier coastal evolution have been developed from mid-latitude settings that were deglaciated following the Last Glacial Maximum. The dominant controls are considered in terms of sediment supply provided by coastal erosion, relative sea-level rise caused by forebulge collapse, and storm events (e.g. Orford *et al.,* 1991; Forbes and Syvitski, 1994; Orford *et al.*, 2002). In contrast, models of barrier development on High Arctic paraglacial settings are lacking and few detailed studies on polar barriers and beaches exist (Forbes and Taylor, 1994; St. Hilaire-Gravel *et al,*. 2012; Lindhorst and Schutter, 2014; St. Hilaire-Gravel *et al.,* 2015). For these paraglacial settings, we hypothesise that the importance of climate as a driver of present-day coastal change via its influence on coastal sediment supply is a critical factor in controlling coastal evolution.

Coastal change on Svalbard

Previous coastal studies on Svalbard have focused mainly on the relatively exposed, western coasts of Spitsbergen (Figure 1), such as in Bellsund and Kongsfjorden areas (e.g. Mercier and Laffly, 2005; Zagórski *et al.,* 2012). These areas are strongly influenced by warm and humid air masses brought by the West Spitsbergen Current, that leads to significant periods of open-water conditions and extensive wave fetch in summer months. In contrast, there has been little research on the morphodynamics of coastlines forming in inner-fjords settings (e.g. Billefjorden, Sassenfjorden) that are characterised by a polar desert climate, limited wave fetch and prolonged periods of sea ice (e.g. Strzelecki, 2011, Sessford *et al.,*2015). Another regional difference is that many deglaciated coasts of central Spitsbergen are controlled by sediment delivery from talus slopes and snow-fed mountain streams that form coarse-grained alluvial fan deltas (e.g. Lønne and Nemec, 2004). These fans are strongly influenced by ephemeral runoff that is linked to air temperature variations, and by high topographic relief that shortens the pathway from sediment source areas to the coast (e.g. Nemec and Steel, 1988; Colella and Prior, 1990; Harvey *et al.,* 2005). This mode of coastal sediment supply is very different to that in the glacier-dominated systems that are common on the west coast.

This paper aims to address the limited research to date on High Arctic coastal landform change through a detailed study of beach-ridge plain and spit system development following the end of the

LIA in central Spitsbergen. The aim is to quantify the rates of coastal change and identify the driving mechanisms responsible for coastal change.

STUDY SITE

The study area is located on the north-eastern coast of Petuniabukta (78°42' N; 16° 36' E) (Figure 1A), a small fjord-head bay, normally ice-bound between mid-November and mid-June. The bay consists of two basins: a deeper basin along the eastern coast (maximum depth about 60 m) and a western basin (maximum depth about 50 m) divided by a bedrock ridge that causes a shallowing in the central part of the bay (Figure 1C). Tidal flats occur in the northern part of the bay (Szczuciński and Zajączkowski, 2012) .

Annual precipitation is typically less than 200 mm, and the mean annual air temperature is about −6.5°C, with air temperatures above 0°C between June and mid-September (Rachlewicz, 2009). The active-layer thickness is in the range of 0.5-2.5 m (Gibas *et al.,* 2005). Snow cover is thin, reaching about 0.3 m on the ice-bounded fjord and 0.6-1.2 m in the valleys, although wind action produces 1-3 m deep snowdrifts at the base of cliffs. Winds are strongly influenced by the surrounding orography and the presence of a large ice-plateau to the northeast (Lomonosovfonna). The prevailing winds in Petuniabukta are from the S-SSE (along the fjord axis) and also the longest wave-fetch potential is from the south (about 6 km). A secondary wind direction is from the northeast, driven by katabatic winds coming from outlet glacier valleys that drain the ice field and giving the wave fetch of about 3 km. The tidal range is about 1.5 m.

The geology of the study area comprises a mosaic of Precambrian, Devonian and Carboniferous-Permian outcrops that are disturbed by the Billefjorden Fault (Dallmann *et al.,* 2004). The dominant geomorphological processes operating in the surrounding valley systems and along the mountain slopes are the fluvial reworking and mass wasting of glacial and periglacial deposits associated with paraglacial landscape rejuvenation following deglaciation and LIA glacier advance (Strzelecki 2009; Rachlewicz, 2010; Evans *et al.,* 2012; Ewertowski, 2014; Pleskot, 2015). In the last century, all glaciers in the area experienced mass loss and rapid frontal retreat, at rates up to 15 m yr^{-1} for land-terminating glaciers and 35 m yr^{-1} for the marine-terminating Nordenskiöldbreen (Rachlewicz *et al.,* 2007; Małecki *et al.,* 2013; Małecki, 2013).

The steep valley slopes of Ebbadalen support extensive alluvial fans. One of the largest fan systems is formed by Dynamiskbekken (Figure 2A), which receives sediments and water from melting snow-patches and thawing of the active layer in the Wordiekammen massif (Szpikowski *et al.,* 2014). Mixed fine gravel-sand sediments in the swash zone between Dynamiskbekken delta and Ebbaelva mouth result from longshore transport of sediment eroded from the large uplifted palaeospit system located at the eastern shore of Petuniabukta (Figure 2B). Finer sediments eroded from this paleospit mix with coarse sediments delivered in the summer months by Dynamiskbekken (Figure 2C). Longshore drift transports sediments towards the Ebbaelva mouth where they are deposited in a gravel-dominated beach complex, which is a key focus of this study (Figure 2F).

The modern Ebbaelva barrier has an active storm ridge crest to the south of the mouth of the Ebbaelva at about 0.25 m to 0.75 m above present mean sea level, and is part of a larger spit system separated by shallow lagoons that are inundated during high tides. The active beach typically comprises finer, often sandy sediments in the lower parts with a distinct break in beach slope that separates sandy from gravelly parts higher up (Figure 2E). This suggests a classification of the modern beach within the "composite gravel beach type" (Jennings and Schulmeister, 2002). The beach resembles the fair-weather Arctic beaches described by Mason (2010), with small changes in morphology caused by overtopping and occasional overwashing. The morphological effects of ice-push, ice pile-up and ice melting on the beach are ephemeral and destroyed in the first few days of open-water conditions each year.

The Billefjorden relative sea-level (RSL) history is characterised by a fall from the local marine limit (40-45 m a.s.l.) during the early Holocene to reach present sea level by *ca.* 3 ka cal BP, after which RSL likely fell below present before rising to the current level (Long *et al.,* 2012). A narrow gravel-dominated barrier (6 to 15 m wide) is typical of much of the Petuniabukta coast but, in the mouth of the Ebbaelva, it has developed into an 80 to 100 m wide beach-ridge plain (Figure 2A) with five finger-like spits (numbered I-V). In the widest section of the beach-ridge plain are 24 narrow (<1 m) and low (<0.5 m) beach-ridges, which are separated from the uplifted late Holocene marine terrace (1.24 m a.s.l.) by a low cliff. We use the term "Ebba Spit-Complex" (ESC) as a descriptive term for this landform.

DATA AND METHODS

Fieldwork was conducted over five summer seasons between 2008 and 2012 and during additional short visits in 2013 and 2014. The topography of the ESC and the modern barrier was surveyed using a real time kinematic (RTK) differential GPS (horizontal and vertical precision= ± 0.02 m). Each summer the modern barrier was surveyed to quantify changes in shoreface profile. A RTK-dGPS survey across the ESC was conducted in the widest part with the best preserved beach-ridges (Figure 3A). Elevations refer to height above present mean sea level in metres. An EagleFish Elite 480 sonar was used to map seabed morphology, with particular attention paid to the nearshore zone.

Aerial photogrammetry

We compare aerial images taken by the Norwegian Polar Institute (NPI) in 1936, 1961, 1990 and 2009 to determine post-LIA ESC evolution. The basis for comparison was an orthophotomap created from digital aerial images taken in 2009, calibrated using ground control points measured with DGPS during the 2010 summer fieldwork. Images from 1961 and 1990 were imported to ArcGIS 9 software, overlaid on the 2009 orthophotomap and georectified using a third order polynomial transformation with a total RMSE error of < 0.5 m. Shorelines of 1961, 1990 and 2009 were delimited using the middle of the first, fully emerged ridge visible on any image. This procedure sought to minimise the error stemming from different phases of tidal cycle captured on individual photographs. Changes in shoreline position that are < 2.5 m are not considered further because it is not possible to distinguish if the visible coastal landforms comprise ephemeral gravel berms or storm ridges, which are currently separated by about 2 m. Unfortunately, the image from 1936 could not be used in quantitative analysis executed in ArcGIS software, because of its low resolution and angle of photography (it is an oblique image). However, we establish an approximate outline of the contemporary ESC based on the configuration of visible coastal landforms and other orientation points, such as wooden huts built on uplifted marine terraces (Figure 5).

Beach sedimentology

We use the sedimentological characteristics of the ESC beach-ridges to help reconstruct past coastal conditions. Beach crests were photographed using a Nikon D80 Digital single-lens reflex camera from a fixed height of 1.5 m (Figure 4). Digital images were processed in Wolman_Jack software, which calculates grain-size distribution based on b-axis measurements. Fifty pebbles were randomly collected from each ridge crest for *a-b-c* axes measurements using a vernier calliper to determine their form (blades, discs, spheres, rods) using Zingg's classification (Zingg, 1935). The shape of pebbles composing the beach-ridge may yield information on environmental conditions in which they were deposited (e.g. Carr *et al.,* 1970; Howard, 1992; Sutherland and Lee, 1994; Pyökäri, 1999). In general, disc-shaped clasts are typical for beach gravels and are transported further up a beachface than are rods and spheres, which tend to accumulate downslope (e.g. Bluck 1967; Anthony 2008). The blades, which in this study are also found in the upper part of the beach profile, are considered to be freshly formed and associated with brief remodelling in fluvial transport (Howard 1992). According to Howard (1992), the abundance of blades is an indicator of sediment maturity, with the greatest number of blades in fluvial systems, fewer occurrences in the coastal zone and the fewest in the subtidal environment. Arctic beach characteristics (form and regime) are strongly influenced by the length of the open-water period and the presence of ice on the beach, in the beach (permafrost) and offshore sea-ice conditions (e.g. McCann and Owens 1969; St. Hilaire-Gravel *et al.* 2010). We therefore hypothesise that the dominant form of clasts found in the 24 ridges should, apart from the provenance, provide an indirect measure of intensity of wave action. Information on the movement, depositional processes and provenance of finer coastal sediments can be obtained from studies of their magnetic properties (e.g. Lario *et al.,* 2001; Rotman *et al.*, 2008; Cioppa *et al.,* 2010; Gawali *et al.,* 2010). To this end, we analysed the size distribution and magnetic susceptibility (MS) of fine sediments from 24 beach-ridge swales from the ESC. Samples (about 0.5 kg) were dried and sieved in a fume cupboard using a 2 mm sieve installed on a vibratory sieve shaker. Later each sample of fine sediments (<2 mm) was divided in a riffle-box and about 12 g of sample was ball-milled in a Fritsch pulverisette. After ball-milling, the homogenous powder was packed in 10 cc pots and analysed in a Bartington Instruments Ltd MS2B Dual Frequency Sensor, which measures susceptibility at low and high frequency (470 and 4700 Hz respectively). The average of five measurements is expressed as mass specific values in 10^{-6} m^3 kg^{-1}.

RESULTS

Post-Little Ice Age spit evolution of the Ebba Spit-Complex: GIS and photogrammetry

During the time interval AD 1936-2009 the ESC prograded and developed three new spits: III, IV and V (Figure 5). We assume that spits I and II, adjacent to uplifted marine terraces, were formed after the end of the LIA, but a lack of imagery covering the first decades of the 20^{th} century precludes quantitative description of the rate of change and time of accumulation.

Analysis of aerial photographs from 1961, 1990 and 2009 enables identification of the following major coastal changes:

a) The orientation of beach-ridges in ESC is characterised by strong irregularity (Figure 3A), typical for drift-aligned gravel beaches (e.g. Carter,1988). The main axes of beach-ridges and spit V formed during last 20 years and are oriented almost exactly north-south. Spits IV and III together with associated beach ridges accumulated almost in parallel, towards NNW However, the second branch of spit IV diverged from the 1990s tip of the spit in an even more westward orientation. Apart from first five beach-ridges accumulated along the cliff in the NNW direction, most of older beach-ridges (pre-1936) and spits I and II were oriented in a north-eastern direction similar to several Late Holocene beach-ridges visible on a surface of uplifted marine terrace.

b) Between 1961 and 1990 the ESC along transect A - B on Figure 3A prograded 28 m (about 1 m yr^{-1}) seaward. Between 1990 and 2009 the rate of progradation dropped to 0.4 m yr^{-1} and the beach-ridge plain widened by about 8 m.

c) The ESC doubled in area between 1961 and 1990, expanding from 14,320 to 24,100 m^2 (Figure 5). In the next 19 years the area of ESC expanded to 29,840 m^2 in 2009. The increase in ESC extent is related to the development of three new spits which grew out from the widest part of the beach-ridge plain during the last 70 years. The spit III developed between 1930s and 1960s. In 1961 spit was 140 m long and covered 2848 m^2 (Table 1). In the following 29 years this spit extended about 1.9 m yr^{-1} northward and was 196 m long in 1990. During this period the spit area grew by 615 m^2. Between 1990 and 2009 the spit III migration towards the mouth of the Ebbaelva ceased and a loss of 449 m^2 was observed due to erosion.

d) The formation of spit IV must have begun before 1961 (Figure 5) as the beginning of the landform was already jutting out of the beach-ridge plain in 1961 and covered 611 m^2. The northward growth of the spit between 1961 and 1990 amounted to 149 m (5.1 m yr^{-1}). Between 1990 and 2009 the spit extended northward about 20 m and migration into the mouth of Ebbaelva stopped. However, the expansion of the spit continued as the tip started to branch. The new tip of the spit prograded about 70 m north-west from the end of the 1990s spit. Figure 5 shows that spits frequently shifted across the spit platform.

e) In comparison with the extension of spits III and IV, the formation of the most recent spit (V) was faster (about 5.5 m yr^{-1}). The length of the spit V increased from 67 m in 1990 to 172 m in 2009 and expanded in area by 3138 m^2. The further extension of the youngest spit was probably impeded once the barrier reached the westward branch of spit IV. This led also to the closure of a lagoon between the two spits. As observed during the fieldwork seasons carried out between 2010 and 2014, the gap between spit V and the west tip of spit IV has continued to decrease and in future years the continued westward progradation of the spit is expected.

Post-Little Ice Age spit evolution of the Ebba Spit-Complex: morpho-sedimentological change

DGPS topographic survey indicates that the mean slope of the pre-1961 beach-ridge plain was about 10‰ (Figure 3B), increasing slightly during the next 30 years to 11‰ (from 1961 to 1990) and then 16‰ for the section that formed between 1990 and 2009. The 13 beach-ridges that formed before 1961 were also wider (mean width between ridges is 2.8 m) and have gentler slopes than that of the younger ridges. The mean height of beach-ridge crests was approximately 60 cm a.s.l. The eight ridges formed between 1961 and 1990 are more closely spaced. These ridges are narrower (mean width 2.2 m) and have steeper beach-faces than those formed in the first half of the 20th century. By 1990 the height of the crest of beach-ridges above sea level had decreased to about 30 cm a.s.l (from 48 cm a.s.l. which is typical for the 1961 and 1990 period), and in the last 20 years the distance between consecutive storm ridges has increased. Overall, therefore, beach-ridge crest heights have gradually decreased through the 20th century, while the spacing between ridges has become more variable. The spacing between ridges decreased from 1961 to 1990 and increased again after 1990.

In terms of clast morphology (Figure 3C), the surface of the beach-ridges is dominated by blade-shaped pebbles (18 ridges: I-VI, VIII, IX, XII, XIV-XVII, XXII-XXIV). Discs dominate in a few ridges formed around the 1960s (VII, X, XI) and three ridges that accumulated at the beginning of the 1990s (XIX-XXI). There is no strong correlation between clast form and size. Mean b-axis size range between 17.8 mm for ridges deposited before 1961, through to 17.6 mm for clasts in ridges formed between 1961 and 1990, and 19.2 mm on the surface of beach-rides deposited in last two decades (ridges XXI-XIII). Of the 24 beach-ridges studied, only the 2009 storm ridge was composed of granule-size clasts, which were approximately half the size of the clasts in the remaining three ridges deposited between 1990 and 2009 (Table 2). A trend to finer sediment sizes is also recorded in the five spits that project from the beach-ridge plain (Table 3). The middle of the beach-face of spit I adjacent to the uplifted marine terrace is mostly composed of gravel. The b-axis from clasts forming the spit crest is 21.1 mm. In spits II and III the gravel content remains above 40% and the mean length of b-axis of clasts in the crest was 17.9 mm and 17.2 mm respectively. A significant decrease in the gravel content occurred between 1990 and 2009, causing the mosaic of poorly sorted sediments in spits IV (1990) and V (2009) to be sand-dominated (63-72%). However, the mean size of clast b-axis remained above 17 mm in the crest of spit IV and increased to 22.4 mm in the youngest spit. The samples from the surface of spit V were taken shortly after a storm event on the 15th of August 2010, which had thrown larger clasts onto the beach-ridge surface.

The sedimentological analysis of the fine sediment comprising the matrix that fills the spaces between pebbles in beach-ridge swales (Table 2) reveals substantial changes in magnetic susceptibility (mass specific MS values in 10^{-6} m^3 kg^{-1}) whenever the sand incorporated into the beach-ridge coarsens (see swales X, XI, XV, XXIV and modern swash).

DISCUSSION

The focus of this study is a sheltered High Arctic bay, where sediments are supplied by non-glaciated, mainly snow-fed streams, from longshore drift and from debris flows on talus slopes. The study period (from 1936 to 2009) coincides with a particular phase of climatic change on Svalbard marked by two episodes of atmospheric warming that coincide with positive North Atlantic Oscillation (NAO) phases. The first phase took place between 1900 and the 1930s and the second, which started in the mid-1970s, saw an accelerated temperature rise in the 1990s that has persisted until the present (Figure 3D). As a result of the 20^{th} century air temperature increase, glaciers on Svalbard have retreated rapidly with an associated release of glacigenic sediment (Etienne *et al.,* 2008). Conversely, the occurrence of a negative NAO phase during the cooler 1960s coincided with an increase in precipitation, which culminated around 1960. The latter is significant because geomorphic activity in High Arctic settings is controlled mainly by the impact of precipitation on solifluction, frost weathering and active-layer development (Humlum, 2002). The growth of fragile tundra vegetation, which may stabilize polar slope systems, also depends on the rate and type of precipitation. It is therefore noteworthy that during the 1950 and 1970 period several catastrophic slush avalanches and debris flows were documented in central Spitsbergen that transported a significant amount of coarse sediments and which were related to extreme meteorological and hydrological events, e.g. major rainfalls or spring snowmelts (Czeppe, 1966; Jahn, 1976; Larsson, 1982; André, 1990). We hypothesise that a combination of these processes significantly accelerated sediment delivery to the coastal zone during and shortly after these events.

Åkerman's (1984) analysis of debris-flow occurrence in central Spitsbergen talus slopes also linked their development with 'wet conditions' related to enhanced precipitation. His study on the spatial distribution of debris flows suggests that, in the inner part of the island, their formation is much more common on east- and north-facing slopes and/or in narrow valleys than in other types. This model helps to explain the large accumulation of debris flows on the slopes of Dynamiskbekken valley (located on the northern slope of Wordiekammen), which supplies the fan system with coarse clastic sediments (Figure 1B). It is likely that occasional slush avalanches and debris flows occurred in Dynamiskbekken valley during the last century. Indeed, field observations show several old fan-like debris covers and boulder tongues overlying the tundra surface in the middle part of the valley that resemble talus and block debris covers described after a massive slush avalanche in Steinvikdalen (Czeppe, 1966; Jahn, 1967).

From the above, it is clear that many of the spits and the ESC evolution in Petuniabukta developed during a period of high sediment availability that began after the LIA in both coastal and terrestrial environments. An important question to address is what effect did these conditions have on the coastal morphodynamics in Petuniabukta?

Since the end of LIA, the ESC in Petuniabukta has significantly expanded, with the formation of three spits (III-V), which each extended alongshore about 200 m. These landforms are larger than spit I and II, which formed before 1936, and their axes are also tilted towards the NW (Table 1). One likely explanation for this process is the shallowing of the nearshore zone in NE Petuniabukta that was related to increased post-LIA sediment accumulation. Support for this hypothesis can be found in Szczuciński *et al.,'s* (2009) analysis of LIA and post-LIA sea-bed sediment accumulation rates (SAR) in Petuniabukta. Their research highlighted that SAR in the fjord rapidly increased since the end of the LIA, reaching probably the highest rates in the last two millennia, and that sedimentation from suspension takes place mostly within the first 100 m of the mouth of the Ebbaelva and main tidal flat channels. From these observations we hypothesise that the increased accumulation of fine sediments in the Ebbaelva mouth and progradation of the tidal flat created favourable conditions for the development of the submarine platform that, in turn, facilitated the growth of subaerial spits in the mouth of Ebbaelva and the concurrent seaward migration of the barriers. The progressive rotation of the axes of spits III-V towards the NW may also be explained by this phenomenon.

The relationship between subaerial coarse clastic barrier development and subaqueous platform accretion is well-documented by Shaw and Forbes (1992) in Newfoundland. Their study suggests that during the Holocene the prerequisite for beach-ridge formation was the prior development of large, fine sediment submarine platforms. The coastal margin topography and relative sea-level changes were clearly also important as a longer-term parameter that controls water depth and accommodation space, but sediment availability in the nearshore zone was crucial for paraglacial barrier coast development. Comparable conditions are known from the Dungeness foreland in southern England (Long *et al.,* 2006). A similar process, but at a decadal time-scale, has operated in the mouth of the Ebbaelva since the end of the LIA to provide the platform for subsequent ESC development.

Once established, the ESC experienced two periods of development as indicated by differences in the size and orientation between the pre-1961 spits (I and II) and post-1961 spits (III-V). We hypothesise that the first phase occurred during the first half of the 20th century when post-LIA glacial retreat delivered large volumes of sediment to the coast, forming the ESC and growth of the Ebbaelva ebb-tide delta. At the same time, coarse sediment delivered from the Dynamiskbekken fan to the coast initiated the seaward migration of the ESC and the development of two gravel-dominated spits. However, due either to the lack of accommodation space or to insufficient sediment supply, these spits could not expand into the mouth of the Ebbaelva. The second phase coincided with a period of increased debris-flow activity (as seen elsewhere in Svalbard – see above) triggered by an increase in precipitation associated with the negative NAO phase (from the 1950s to the1970s). We hypothesise that sediment delivery from terrestrial sources (e.g. fan, talus slopes, catastrophic debris flows) dominated the spit and ESC evolution during this phase.

Sedimentological characteristics of the barrier beaches provide further insight into the processes controlling coastal change during the post-LIA period. The spits that formed before 1961 (i.e., the landward part of the spit complex) are composed mainly of gravel. These have wider beach ridges with gentler beach-face slopes relative to the subsequent ridges. A dominance of blade-shaped clasts in the pre-1961 beach-ridges may suggest the steady delivery of freshly formed clasts from the fan (Figure 3C). At the end of this period, however, there were changes either in wave activity/sea-ice conditions, or in the source of sediment supply, since the beach-ridges became dominated by disc-shaped clasts (Figure 3C). The large accumulation of discs in the beach-ridges could reflect increased clast modification by waves or reactivation of relict channels in the fan system that extended the fluvial reshaping of clasts before reaching the coast. An alternative hypothesis is that slush avalanches during this interval may have supplied the beach-ridges with disc-shaped pebbles that were eroded from abandoned channels and debris flows. The sudden drop in magnetic susceptibility noted in sediments from the final stage of the pre-1961 period (swales X-XI) also implies a change in sediment source (Table 2).

The composition and size of spit III suggest that sediment sources have changed during the period of study, with a switch to abundant, albeit finer sediment delivery. This shift coincides with a significant cooling of climate on Svalbard that occurred during the 1960s. The reduction in height of the beach-ridges formed between the 1960s and 1980s (Figure 3B) may also be an expression of more severe sea-ice conditions during this period. However, it is also possible that increased precipitation at the same time as temperature cooling caused increased snow accumulation in the Dynamiskbekken valley. Therefore, although the discharge season was shortened, snow-melt floods could likely still deliver significant amounts of sediment to the coast. We suggest that snowy conditions at this time were favourable for slush avalanches and other nivation processes that reactivated and rejuvenated debris tongues, as described from the nival cirque on Ariekammen slopes during the snowy year of 1958 (Jahn, 1967).

The prominence of fine sediments in spit III could reflect the washing out of fines from the fan by rainfall events. However, the further fining of spit deposits observed in spits IV and V, which formed during a period of warming on Svalbard, requires a slightly different explanation. This change in spit sediment composition from gravel-dominated to sand-dominated may reflect the shallowing of the nearshore zone associated with tidal flat progradation and Ebbaelva ebb-tide delta formation (see above). An increase in the supply of finer sediments together with less severe sea-ice conditions coincided with the expansion of the ESC which, between 1990 and 2009, migrated seaward over 40 m. An increase in the supply of sandy deposits for the development of spits IV and V is also an outcome of the increasing significance of sediment delivery through alongshore transport from the erosion of the palaeo-spit, as fan-fed sediment supply diminished. Field observations of Dynamiskbekken fan sediment delivery to the coast from 2005 to 2010 suggests that in recent years the supply of coarse sediments has reduced to that delivered by extreme spring snow-melt discharge events only. Reports on the Dynamiskbekken sediment supply from the late 1980s indicate that the stream was able to flow across the whole fan and discharge directly to the bay (Kostrzewski *et al.,* 1989), suggesting that the drop in sediment delivery probably began in the 1990s and intensified in first decade of the 21st century.

One of the other factors that modified the delivery of fine sediments to the coast is the blocking of Dynamiskbekken coastal outlets by longshore drift (Figure 3D). In the last five years the majority of fan channels were blocked by a prominent storm ridge that led to the formation of several deep hollows (several metres wide and up to 0.5 m deep) that became filled with muddy and sandy sediments in the back of the barrier (Figure 2D). As noted by Zenkovich (1967) the topography of beach-ridge plains depends on the interaction of wave activity, the rate of sea-level change and the rate of sediment supply. Therefore the difference in the grain-size characteristics of spits III-V (48% of gravel in spit III, 36% of gravel in spit IV and 27% of gravel in spit V) explains also the change in ESC topography that divides beach-ridges formed in 1961-1990 from those that formed between 1990 and 2009 (Table 3, Figure 3B). We hypothesise that production of wider ridges resulted from increased open-water conditions in the Isfjorden-Billefjorden system, such that although locally sea-ice conditions in Petuniabukta remained severe, the fetch of the larger waves entering the bay from a S-SE direction resulted in an increase in longshore sediment transport. This change could explain the finer-grained nature of the sediments (and reduced MS) that accumulated in beach-ridge swales deposited between 1990 and 2009 (Table 2). Present-day deposits characterised by such a low MS (<10) occur in the barrier coast located at the entrance to Petuniabukta, and so their entrainment into the most recent beach-ridges and spit system must relate to enhanced longshore sediment transport.

Lastly, it is possible that during the last decade the processes discussed previously may also explain the general decrease in clast size seen in the modern beach-ridge (ridge XXIV on Figure 4). Following the cessation of coarse sediment supply by the blocking of Dynamiskbekken fan channels (Figure 2D), the barrier lost its local source of coarser clasts. Thus the modern barrier and spit are composed of sediments that during longshore transport experience significant sorting, as is typical for coarse-grained, drift-aligned beaches (Orford *et al.,* 1991).

CONCLUSIONS

The study leads to the following conclusions:

1.) Since the end of the LIA, the Ebba Spit-Complex has experienced significant seaward progradation and lateral extension through the formation of three new spits.

2.) Compared to the 1961-1990 period the seaward progradation rates between 1990 and 2009 slowed (from 1 m yr^{-1} to 0.4 m yr^{-1}). Beach-ridges from the colder decades of the 20^{th} century (1960-1980s) were generally more closely spaced and narrower than those of the pre-1960s and those formed in the last 20 years. The height of beach-ridge crest has been gradually decreasing through the 20^{th} century, from 0.6 m (1900-1961), 0.48 m (from 1961 to 1990) to 0.3 m (from 1990 to 2009) above MTL.

3.) The post-LIA development of the Ebba spits and beach-ridge plain was largely controlled by the formation of a submarine platform that was dependent on sediment supply to the coast from deglacierising catchments. The uneven delivery of debris from the fan system depended mainly on changes in precipitation, which influenced slope stability and ephemeral stream flow, and the duration of open-water conditions.

4.) The future evolution of the Ebba Spit-Complex will depend on the ability of the landform to adjust to the increasingly delayed delivery of paraglacial sediment from glacier outwash plains and valleys that are increasing in size and storage capacity as a result of glacier retreat up-valley. This, together with factors such as intensified precipitation related to increase in storminess that is predicted in the coming decades, will destabilize permafrost that binds sediments in talus and fan systems. This will potentially lead to the further reactivation of slope processes and the accelerated delivery of coarse clastic sediment to the coast. Increased sediment delivery to the coast will provide potentially favourable conditions for extension of depositional landforms. The relationship between RSL change and gravel-dominated barrier evolution in Petuniabukta may also experience significant change as the post-LIA rebound of the land may reduce RSL rise; indeed this process may already be underway.

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Spit	1961		1990		2009		Rate of spit growth [m yr^{-1}]	
	length [m]	area [sq m]	length [m]	area [sq m]	length [m]	area [sq m]	1961-1990	1990-2009
Spit III	140	2848	196	3463	196	3014	1.9	0
Spit IV	52	611	201	3321	250	3693	5.1	2.6
Spit V	x	x	67	980	172	4118	x	5.5

Table 1 Post-LIA changes (length/area) of three spits formed in the mouth of Ebbaelva. x – landform did not exist in this period, no rate calculated.

BEACH RIDGE	Sediment type in swale	Mean φ	Sorting	Skewness	Kurtosis	Magnetic Susceptibility 10^{-6} m^3 kg^{-1}	*Mean clast size in beach-ridge crests [mm]*
PRE-1961 BEACHES							
I	Very Coarse Silty Very Fine Sand	4.0	1.8	0.4	1.4	21.8	*14.1*
II	Very Coarse Silty Very Fine Sand	3.9	1.7	0.4	1.5	25.7	*17.3*
III	Very Coarse Silty Very Fine Sand	3.7	2.1	0.3	1.6	21.4	*14.2*
IV	Very Coarse Silty Very Fine Sand	3.6	2.1	0.3	1.7	19.5	*13.8*
V	Very Coarse Silty Very Fine Sand	4.0	1.8	0.4	1.5	23.7	*16.5*
VI	Very Coarse Silty Very Fine Sand	3.8	2.3	0.2	1.6	18.6	*31.4*
VII	Very Coarse Silty Very Fine Sand	4.0	1.7	0.3	1.5	25.5	*24.7*
VIII	Very Coarse Silty Very Fine Sand	3.8	1.7	0.4	1.5	21.2	*15.2*
IX	Very Coarse Silty Very Fine Sand	3.7	1.9	0.2	1.6	24.4	*15.3*
X	Poorly Sorted Very Coarse Sand	0.1	1.4	0.7	2.5	6.8	*15.9*
XI	Poorly Sorted Coarse Sand	0.4	1.2	0.3	1.7	4.9	*18.1*
XII	Very Coarse Silty Very Fine Sand	3.4	2.0	0.1	1.6	20.1	*17.5*
1961-1990 BEACHES							
XIII	Very Coarse Silty Very Fine Sand	3.5	1.9	0.2	1.7	23.8	*17.3*
XIV	Very Coarse Silty Fine Sand	3.4	1.7	0.2	1.7	23.0	*15.2*
XV	Poorly Sorted Very Coarse Sand	-0.01	1.2	0.5	1.9	5.7	*17.8*
XVI	Very Coarse Silty Very Fine Sand	3.4	1.8	0.2	1.4	30.5	*18.6*
XVII	Very Coarse Silty Very Fine Sand	3.4	1.8	0.2	1.6	27.3	*14.9*
XVIII	Very Coarse Silty Fine Sand	3.6	1.8	0.3	1.3	29.4	*19.8*
XIX	Very Coarse Silty Very Fine Sand	3.7	2.4	0.1	1.5	26.0	*17.4*
XX	Very Fine Sandy Very Coarse Silt	5.0	2.7	0.3	1.1	22.0	*19.5*
POST-1990 BEACHES							
XXI	Very Coarse Silty Very Coarse Sand	1.9	2.7	0.6	0.9	16.5	*18*
XXII	Very Fine Sandy Very Coarse Silt	4.9	2.3	0.4	1.1	16.0	*19.6*
XXIII	Coarse Silt	7.0	2.4	0.2	1.0	12.0	*20*
XXIV	Poorly Sorted Very Coarse Sand	0.6	1.7	0.6	1.7	7.5	*8.6*
swash zone	Moderately Sorted Very Coarse Sand	-0.3	0.7	0.5	1.5	1.5	-

Table 2 Characteristics of fine sediments collected from beach-ridge swales including logarithmic Folk and Ward (1957) graphical measures and corresponding magnetic susceptibility. Last column (*italics*) to the right

summarises the results of mean clast size (in mm) analysis carried out in Wolman_Jack software on clasts observed on the surface of the beach-ridge crests.

Spit:	% Gravel	% Sand	% Mud	Mean φ	Sorting	Skewness	Kurtosis
Spit I	62.6	36.2	1.2	-1.35	1.6	0.31	0.84
Spit II	42.1	54.8	3	-0.53	2.06	-0.06	0.78
Spit III	48.9	50.5	0.5	-1.12	1.35	-0.13	0.86
Spit IV	36.5	63.1	0.4	-0.23	1.40	0.01	0.23
Spit V	27.4	72.5	0.1	-0.01	1.73	-0.17	0.90

Table 3 Sedimentological characteristics of surface sediments composing the beachfaces of spits I-V in the Ebbaelva mouth. For location of spits see Figure 3.

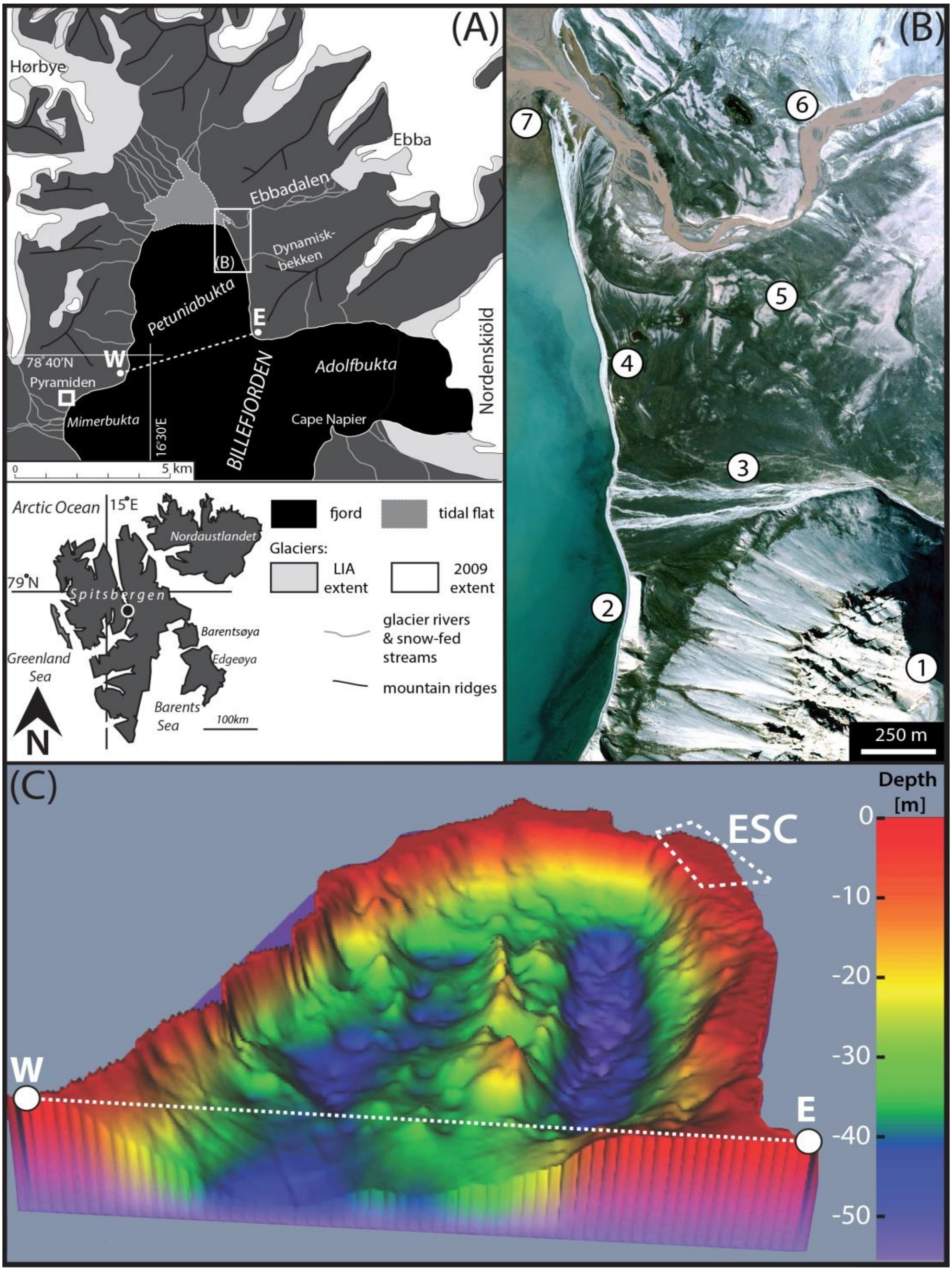

Figure 1 (A) Location of the study area: Petuniabukta, Northern Billefjorden, central part of Spitsbergen. The extent of present-day and LIA glaciers modified after Rachlewicz *et al.* (2007) and Małecki (2013). (B) Sources of non-glacial sediment supply: site 1 – Wordiekammen massif with extensive talus slopes, site 2 – uplifted palaeospit, site 3 – The Dynamiskbekken alluvial fan and delta, site 4 – low unconsolidated cliff eroded in raised marine terrace, site 5 – flights of raised beaches, site 6 – Ebbaelva incising into raised beaches, site 7 – Ebba Spit-Complex with five spits, separated by shallow lagoons. (C) Petuniabukta seabed topography obtained from basic EagleFish Elite 480 sonar soundings in 2009.

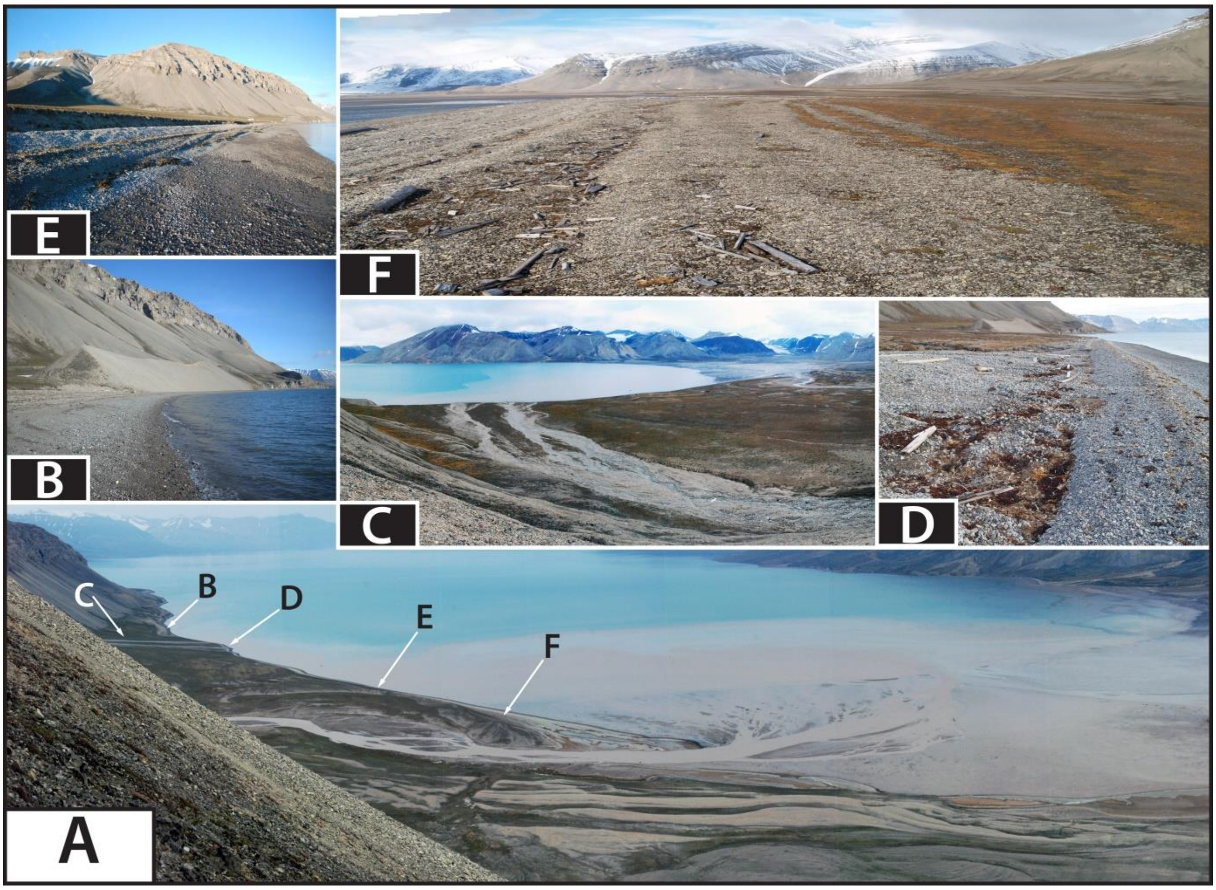

Figure 2 (A) – Panoramic view of north-eastern coast of Petuniabukta with major main landforms responsible for sediment delivery to the Ebba Spit-Complex: (B) Uplifted palaeo-spit system, (C) Dynamiskbekken delta; (D) – Dynamiskbekken delta channel blocked by modern storm ridge; (E) modern beachface in a longshore corridor along the low unconsolidated cliff between Dynamiskbekken delta and ESC; (F) Beach-ridge plain in Ebba Spit-Complex.

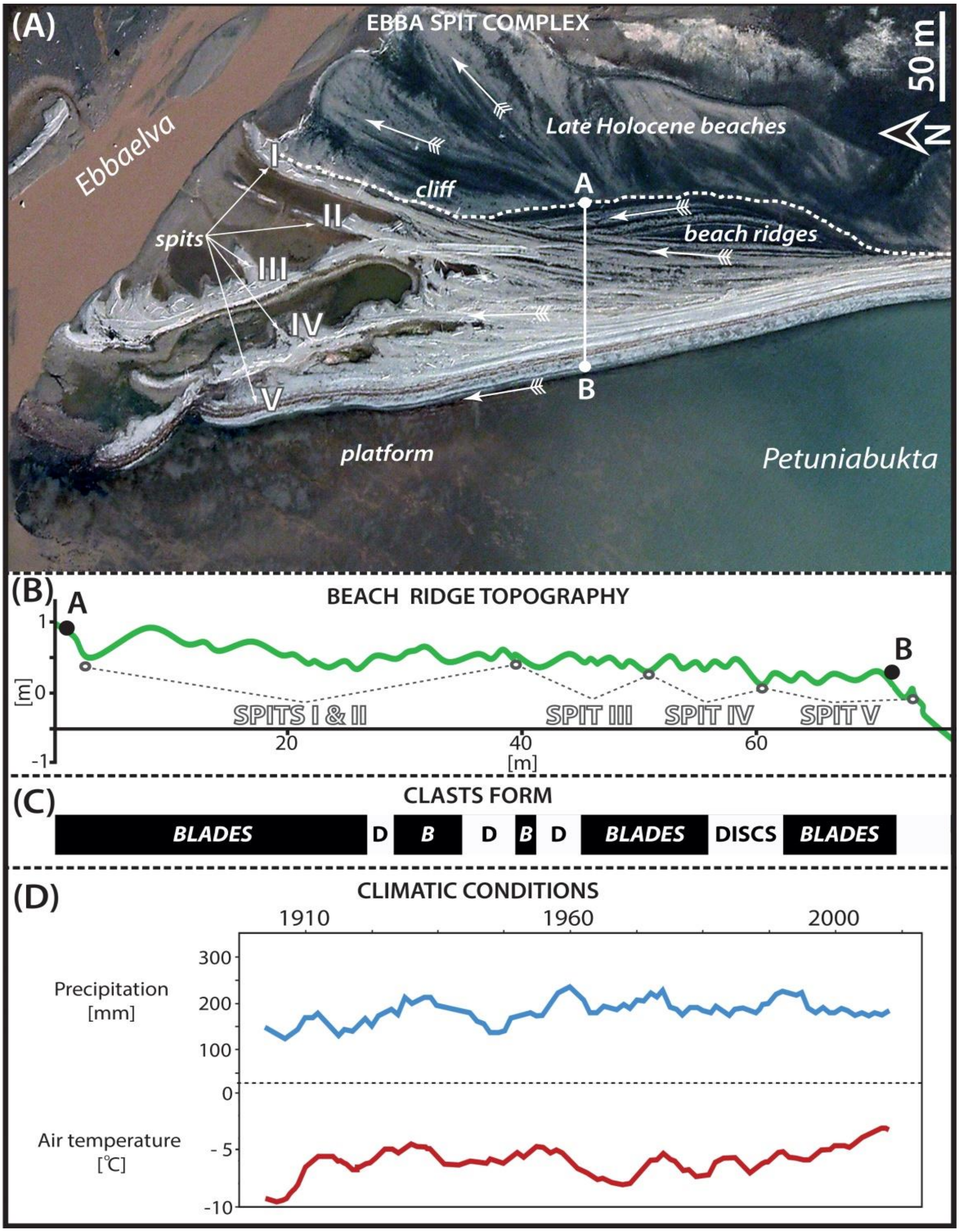

Figure 3 (A) Orthophotomap of barrier coast and Ebba Spit-Complex in north-eastern Petuniabukta based on NPI aerial images taken in summer 2009. Five spits (I-V) are marked; white arrows indicate the dominant orientation of beach-ridges; white dashed line shows the location of small cliff separating last preserved Late Holocene marine terrace from ESC (B) Ebba Spit-Complex topography along A-B transect based on RTK-dGPS survey (summer 2009); (C) Classification of clast form composing beach-ridge crests based on Zingg (1935); (D) Climatic conditions in Svalbard after the termination of LIA: precipitation and air temperature record since 1912 based on a 5-year running mean of monthly meteorological series homogenised by the Norwegian Meteorological Institute. Modified after: www.climate4you.com website by Prof. Ole Humlum.

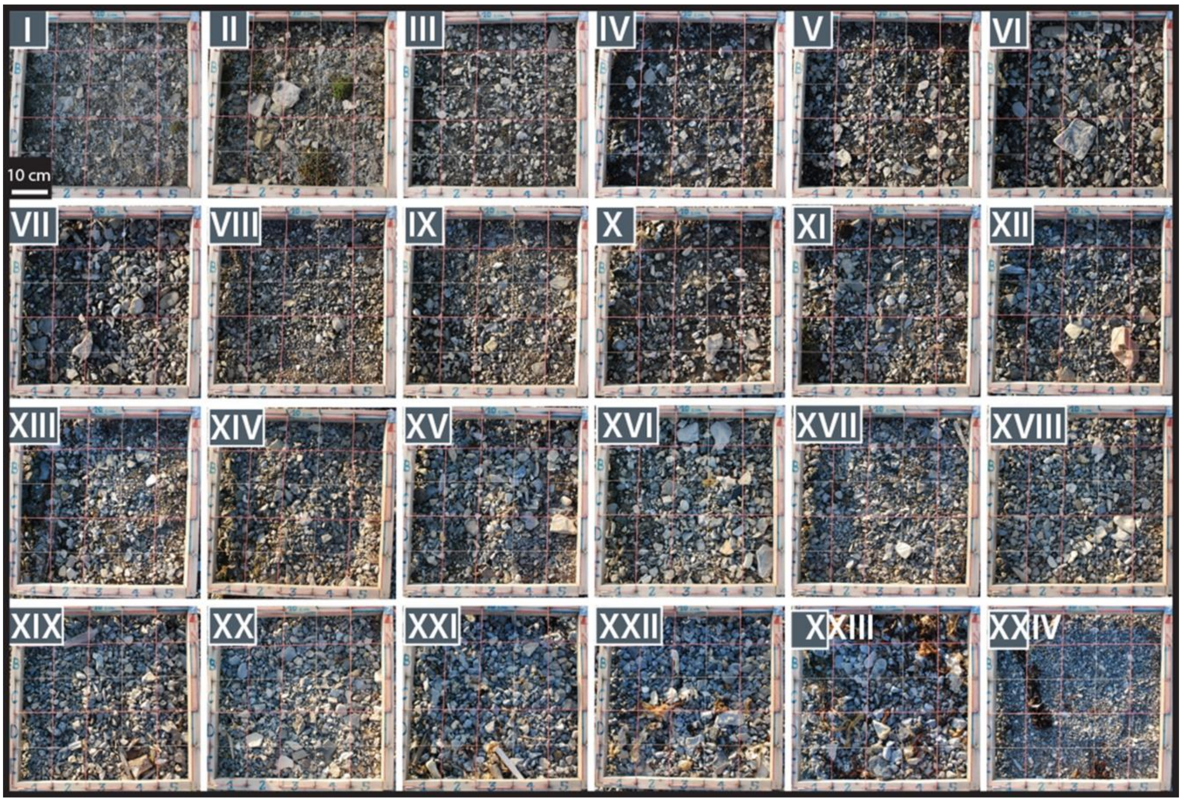

Figure 4 Representative images of 24 beach-ridges surfaces (I-XXIV) photographed in summer 2009 used for clast size distribution analysis in Wolman_Jack software.

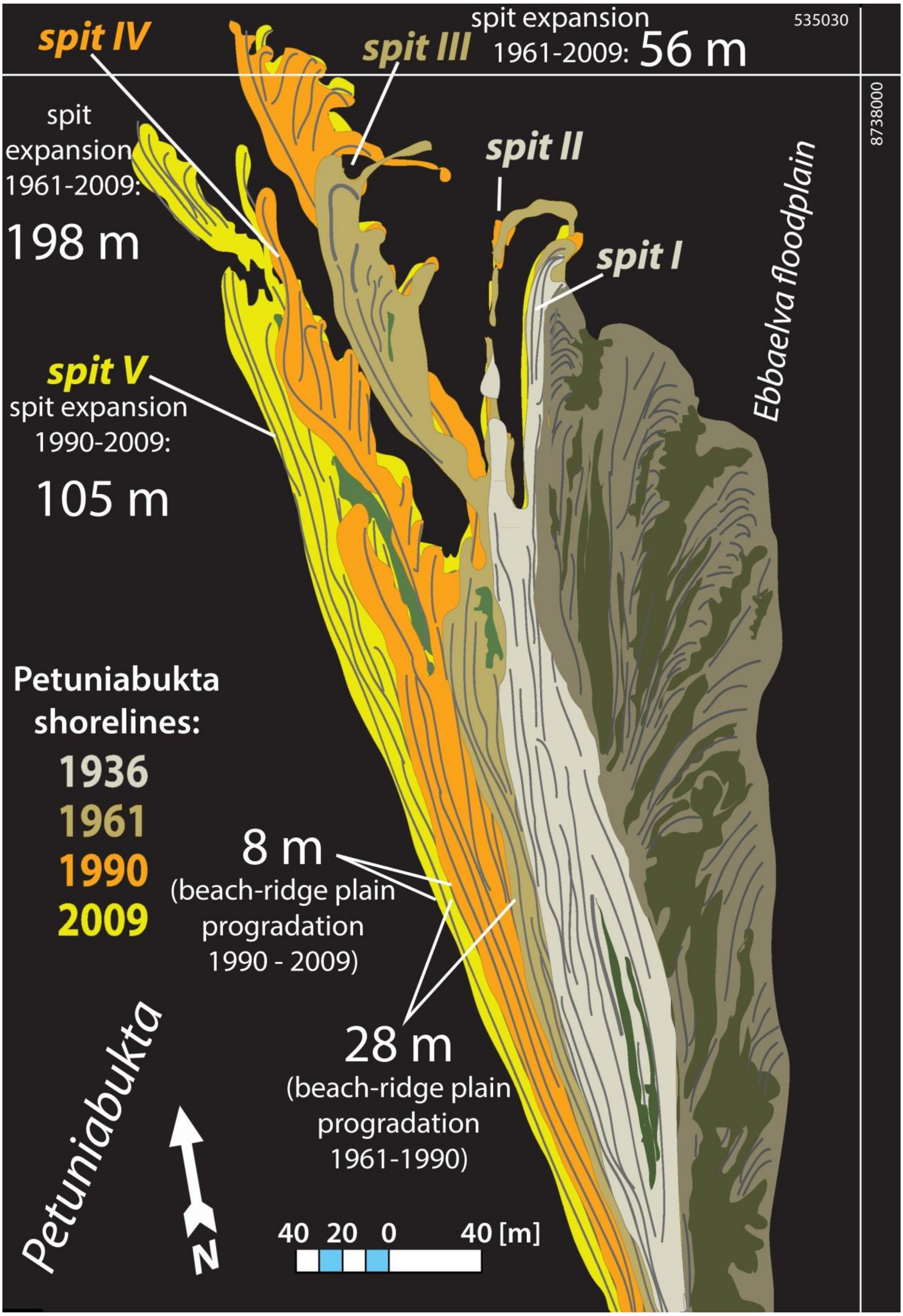

Figure 5 The post-LIA changes of Ebba Spit-Complex based on digital photogrammetric analysis of images taken by Norwegian Polar Institute in years 1961-2009. The location of the 1936 shoreline and Ebba Spit-Complex extent is approximate and based on visual interpretation of an oblique photograph.