Chapter 2
The Influence of Recent Deglaciation and Associated Sediment Flux on the Functioning of Polar Coastal Zone – Northern Petuniabukta, Svalbard

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Abstract The pristine coasts of Spitsbergen, major island of Svalbard Archipelago provide a superb opportunity to quantify how High Arctic coasts are responding to glacier retreat and associated intensified sediment flux to the fjord and shelf zones. This study focuses on the mechanisms controlling the recent coastal evolution (1990–2009) in Northern Petuniabukta, one of the most sheltered bays of central Spitsbergen, characterised by a semi-arid subpolar climate, limited wave action and rapid retreat rate of all surrounding glaciers. The formation of the coastal landforms here was to a large degree dependent of the rate of sediment excavation from alluvial fans and outwash plains that developed across a wide coast plain between the glacier valleys and the fjord. During last two decades most of the sediments transported from proglacial zones has been accumulated on outwash plains and after reworking supplied a prograding tidal flat system. Despite sheltered location and drier climate the rates of coastal evolution in Petuniabukta are comparable to those seen along the W and S coasts of Spitsbergen.

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2.1 Introduction

In contrast to mid- and low- latitude coasts, relatively little is known regarding the potential impacts of climate and sea-level change on the high latitude coastal margins (Overduin et al. 2014). Indeed, many of the existing intellectual paradigms regarding the functioning of polar coastal zone are now out-dated, based on descriptive geomorphology and a limited process-based understanding. Not only is the number of academic papers on high latitude coastal environments lower than from temperate and tropical regions, but also their qualitative nature seems to be insufficient to allow numerical modelling and more sophisticated data analyses (Byrne and Dionne 2002). Lantuit et al. (2010) indicated that only 1 % of Arctic coastlines have been investigated in sufficient detail to allow quantitative description of processes operating on them.

The most recent advances in high latitude coastal geomorphology is marked by significant discrepancy (Fig. 2.1a). Last decades have seen major development in Arctic coastal research due to projects of the Arctic Coastal Dynamics (ACD) Group (e.g. Rachold et al. 2005; Forbes 2011; Lantuit et al. 2012) and the reopening of Russian works to the wider scientific community, especially in the field of thermoabrasion (e.g. Aré 1988; Aré et al. 2008; Lukyanova et al. 2008; Streletskaya et al. 2009).

However, the major focus in these initiatives has been on understanding of the evolution of the ice-rich permafrost coastlines, particularly in N Alaska, NW

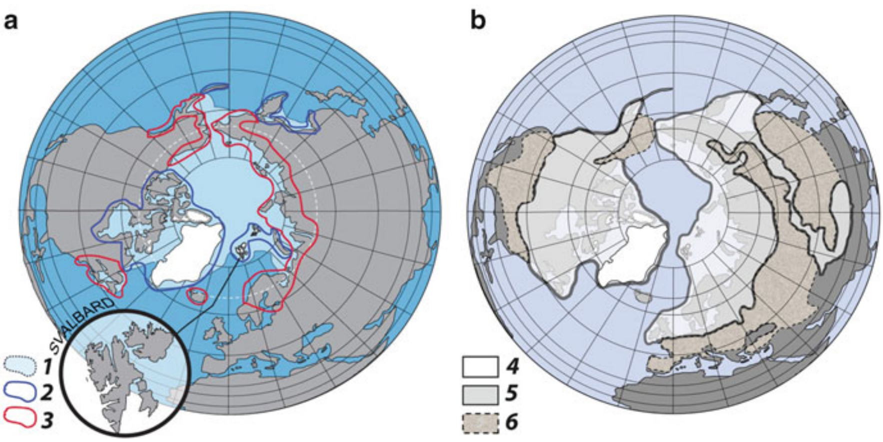


Fig. 2.1 (**a**) Simplified map of cold region coasts in the northern hemisphere (Modified after Byrne and Dionne 2002). *1* – Extent of winter sea ice cover; *2* – Zone of still relatively poorly studied cold region coasts where the mechanisms controlling coastal evolution remain unknown, *3* – Zone of relatively well-studied cold region coasts with running coastal erosion monitoring programmes, and number of high quality papers published in a last decade; (**b**) Map of palaeo – and modern paraglacial and paraperiglacial landsystems and landscapes in the northern hemisphere (Modified after Mercier 2008). *4* – Potential future paraglacial environments currently occupied by Greenland Ice Sheet and glaciers which duo to the climate warming may be exposed from ice in coming decades; *5* – Paraglacial environments during Holocene deglaciation; *6* – Paraglacial and periglacial environments during Holocene warming

Canada, and along the Siberian seas – regions characterised by some of the most rapid erosion rates in the world (Lantuit et al. 2012). In contrast, much less work has been done on the coastal environments of High Arctic archipelagos such as Svalbard, Franz Joseph Land, Canadian Arctic Archipelago or Greenland.

One of the characteristic features distinguishing High Arctic coastal environments from those along Siberian, Chuckchi and Beaufort Seas is the influence of former and recent glacial systems on the coastal morphology, sediment supply and long-term evolution.

This strong effect of glacial legacy in the form of relatively high relief (steep-walled fjords), abundance of coarse glacigenic sediments in the coastal zone delivered from erosion of relict and modern glacial landforms, rapid sea-level changes driven by glacio-isostatic rebound inscribes vast sections of High Arctic coasts into the paraglacial coastal environments (Fig. 2.1b).

2.1.1 Paraglacial Coastal Environments

According to Forbes and Syvitski (1994) paraglacial coastal environments are '*those on or adjacent to formerly ice-covered terrain, where glacially excavated landforms or glacigenic sediments have a recognizable influence on the character and evolution of the coast and nearshore deposits*'. It is noteworthy that the major developments in our understanding of paraglacial coastal system were achieved along coasts of Ireland, NE United States and Atlantic Canada (Forbes and Taylor 1987; Carter et al. 1989; Orford et al. 1991; Shaw et al. 1990; Forbes et al. 1995; Orford et al. 2002). These are coasts that develop by the reworking of inherited sources of glacigenic sediments, thus transforming relict glacial landforms into active coastal landforms until their full destruction. The mid-latitude paraglacial coasts have already adjusted to non-glacial conditions and their evolution is controlled mainly by trend in relative sea-level change and the energy of the surrounding body of water. In the High Arctic coastal zone development is much strongly linked with climate-driven processes including ongoing deglaciation and sediment fluxes from still actively accumulated glacial and periglacial landforms e.g. moraine belts, outwash plains, talus slopes, alluvial fans (e.g. Lønne and Nemec 2004).

Mid-latitude paraglacial coasts which were often formed by submergence of lowlands are commonly characterised by gentle slopes and shallow nearshore zone, whereas the High Arctic coasts are dominated by high relief fjord topography. This is an important factor controlling the wave climate and the accommodation space for sediments delivered to the coastal zone. For instance the barriers formed by ocean waves that approach gentle slopes tend to be wider and thinner than along the coasts with steep slopes where their thickness and height increases (St-Hilaire-Gravel et al. 2010).

The climate amelioration that followed the last major glaciation ended also the operation of periglacial processes on glacigenic sediments in mid-latitudes and led to the complete melt out of permafrost, which is still an important '*sediment binder*' in the high latitudes. The Arctic beach morphology is also strongly influenced by sea ice processes, which are very limited if not absent along present-day mid-latitude paraglacial coasts.

Another significant factor controlling the sediment availability along paraglacial coasts is the presence of vegetation cover. The majority of glacial landforms in mid-latitudes are covered by vegetation, whereas freshly exposed moraines, drumlins, or eskers as well as Arctic coastal landforms (deltas, spits, barrier islands) are barren and more vulnerable to washout, wind action or mass wasting.

In fact, vast sections of mid-latitude paraglacial coasts are already in the 'post-paraglacial period' and their evolution is no longer controlled by glacial history (i.e. Hein et al. 2012).

Despite several differences between the functioning of paraglacial coastal zone in the mid-latitudes and polar regions the latter did not received much attention. Until recently the major advances in understanding of the mechanisms controlling High Arctic paraglacial coastal systems has been made in Svalbard Archipelago (e.g. Mercier and Laffly 2005; Zagórski et al. 2013).

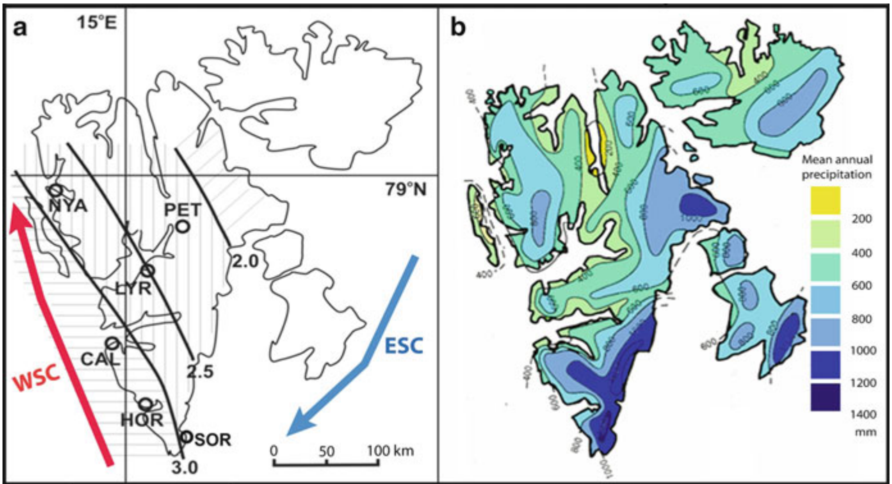
2.1.2 Svalbard Paraglacial Coasts

During the twentieth century large areas of Svalbard have experienced significant shift from glacial-dominated into the non-glacial dominated environments (Mercier 2000). This process is associated with the rapid retreat of glaciers since the termination of the Little Ice Age (LIA), which on Svalbard occurred around AD 1900 (Szczuciński et al. 2009).

The post-LIA glacier retreat exposed vast proglacial and valley systems filled with unstable glacigenic sediments prone to paraglacial transformation (e.g. Lukas et al. 2005; Lønne and Lyså 2005; Etienne et al. 2008; Rachlewicz 2009; Irvine-Fynn et al. 2011; Evans et al. 2012). In addition, the warming of climate and occurrence of extreme precipitation events observed in the last century, destabilised and reactivated sediment delivery to the coast from numerous periglacial landforms including debris flows, slush avalanche lobes and solifluction tongues (Jahn 1967; Åkerman 1984; André 1990; Mercier et al. 2009). Those processes have influenced the evolution of Svalbard coastal zone by providing huge amounts of unconsolidated sediments, which have been used to accumulate new coastal landforms such as spits, tombolos, lagoons, barriers, deltas and tidal flats (e.g. Moign and Guilcher 1967; Klemsdal 1986; Héquette and Ruz 1990; Kowalska and Sroka 2008). For instance on Brøggerhalvøya Mercier and Laffly (2005) have documented *ca*. 90 m of coastal progradation between 1966 and 1995 and linked it with a period of accelerated glaciofluvial sediment delivery from extending proglacial zone of Midre and Austre Lovénbreen. The strong link between glaciofluvial sediment input and coastal evolution has been also observed in Calypsostranda by Zagórski (2011). His study suggests that during 1936–2007 the shift in direction of sediment delivery from the retreating Renardbreen resulted in the cessation of sandur seaward progradation and, in consequence of expanded open water conditions, over

100 m coastal erosion. In Recherchefjorden post-LIA deglaciation led to the transformation of Renardbreen from a marine-terminated into a land-terminated glacier type and resulted the formation of entirely new coastlines composed of unstable glacigenic sediments prone to abrupt modification by marine processes (e.g. Zagórski et al. 2012b). In southern Spitsbergen (Sørkappland) Ziaja et al. (2009) found an evidence of even more dramatic coastal change in the form of ca. 200–460 m shoreline retreat between 1936 and 2005 which led to the destruction of Davislaguna lake.

It is important to notice that the most of previous studies describing the adjustment of coastal zone to deglaciation were located in western and southern parts of Spitsbergen, directly influenced by West Spitsbergen Current (Fig. 2.2) and



c Year	Location	Mean air temperatures in July-August 2005-2006 [°C]								
		1-10.7	11-20.7	21-31.7	**11-31.7**	1-10.8	11-20.8	21-31.8	**1-31.8**	**11.7 - 31.8**
2005	**PYR**	-	5.7	7.1	**6.4**	6.1	6.1	6.5	**6.2**	**6.3**
	LYR	7.8	5.9	7.9	**6.9**	6.7	6.4	7.2	**6.8**	**6.8**
	NYA	7.5	2.9	5.4	**4.2**	5.6	4.9	5.1	**5.2**	**4.8**
	CAL	-	4.1	5.3	**4.7**	4.9	4.6	5.8	**5.1**	**5.0**
	HOR	4.7	3.9	4.3	**4.1**	4.2	4.3	5.3	**4.6**	**4.4**
	PYR	-	7.0	7.7	**7.4**	7.3	5.8	4.6	**5.9**	**6.5**
2006	**LYR**	7.4	7.4	7.6	**7.5**	7.6	6.4	5.9	**6.6**	**7.0**
	NYA	6.2	5.7	6.3	**6.0**	6.3	4.2	3.8	**4.7**	**5.3**
	CAL	-	5.1	5.6	**5.4**	5.4	4.7	4.3	**4.8**	**5.0**
	HOR	4.1	4.8	5.1	**5.0**	5.2	4.7	3.8	**4.5**	**4.7**

Fig. 2.2 (**a**) Variability of climatic conditions on Spitsbergen after Rachlewicz (2009) based on Marsz (1995) oceanity index distribution: *horizontal lines – oceanic conditions, vertical lines – sub-oceanic conditions, oblique lines – continental conditions*. *WSC* warm West Spitsbergen Current, *ESC* cold East Spitsbergen Current. *Circles* indicates the location of former coastal studies on Spitsbergen discussed in this study: *PET* Petuniabukta, Billefjorden (this study), *LYR* Longyearbyen, Adventfjorden, *NYA* Ny Ålesund, Kongsfjorden, *CAL* Calypsostranda, Bellsund, *HOR* Hornsund, *SOR* Sørkappland, open coast of Barents Sea; (**b**) Mean annual precipitation [mm] on Svalbard based on Hagen et al. 1993; (**c**) 10-day mean air temperatures between July–August 2005–2006 in PET, LYR, NYA, and CAL sites

exposed to storm waves developed on Greenland and Barents Seas (e.g. Moign and Héquette 1985; Héquette and Ruz 1986; Héquette 1992; Marsz 1996; Mercier and Laffly 2005; Ziaja et al. 2009; Ziaja 2012; Zagórski et al. 2012a, b). On the contrary, the coastal behaviour in inner fjord environments of Spitsbergen, characterised by sheltered location, prolonged sea-ice conditions, low tidal range and ephemeral pulses of sediment delivery from landforms developing in semi-arid, polar desert climate is largely unexplored. Only recently, Lønne and Nemec (2004) have provided a new insight into the nature of High Arctic coastal sedimentation by studying Holocene evolution of a fan delta in Adventfjorden, Sessford (2013) has reported on the rates of coastal erosion in southern Sassenfjorden and Strzelecki (2011) has characterised the degree of surface weathering of rocky coasts using Schmidt hammer rock tests in northern Billefjorden.

Present study aims to address this deficiency in understanding of High Arctic coastal systems by describing coastal evolution in central Spitsbergen focusing on the last two decades of intensified climate warming and associated increased rate of deglaciation. The geographical focus is Petuniabukta (Fig. 2.2), one of the most protected bays of Spitsbergen constituting the exact opposite of storm wave coastal environments of W and S Spitsbergen.

2.2 Regional Setting

Petuniabukta (78°42′ N; 16°36′ E) is a small, sheltered, microtidal bay located in the northern Billefjorden (Fig. 2.3). The mosaic of Precambrian, Devonian and Carboniferous-Permian outcrops disturbed in Billefjorden Fault Zone (BFZ) makes the geology of study area one of the most diverse in Svalbard (Dallmann et al. 2004). This region lies in the zone of semi-arid polar climate, with a mean annual air temperature of −6.5 °C, annual precipitation usually lower than 200 mm and prolonged sea-ice conditions limiting operation of waves to summer months (June–September) (Rachlewicz 2009).

The seasonal thawing of active layer ranges in study area between 0.5 and 2.5 m (Gibas et al. 2005). The present spring tidal range in Petuniabukta is *ca.* 1.5 m, with the active storm ridge located *ca.* 0.25–0.75 m above mean tide level. The longest wave fetch potential is from the south, showing strong relation with the prevailing winds entering central Spitsbergen from the S-SSE (along the axis of Billefjorden). The local wave conditions are influenced also by N and NE katabatic winds descending from major glacier valleys of Hørbyebreen, Ragnarbreen, Ebbabreen and Nordenskiöldbreen (Fig. 2.3).

The coastal landscape in Petuniabukta region is rich in cold region littoral landforms created by the interplay of glacial heritage (source of coarse clastic sediments), glacioisostasy (control of access to sediment sources and formation

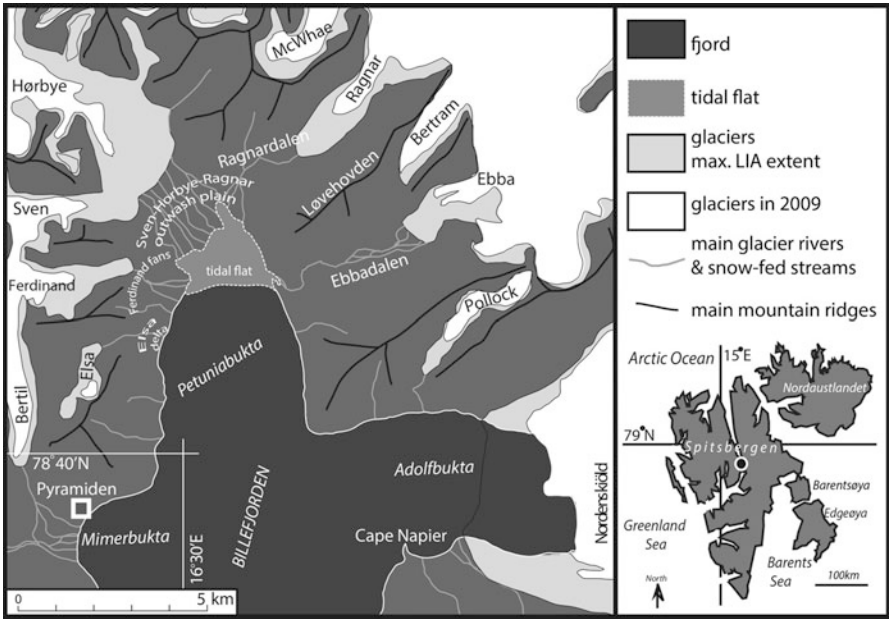


Fig. 2.3 Location of study area, Petuniabukta, Billefjorden. The present-day and LIA extent of glaciers modified after Rachlewicz et al. (2007) and Małecki (2013)

of uplifted/submerged forms) and climate-driven processes (including sea-ice, nival, permafrost and periglacial action).

Due to the common presence of sharp break in beach slope separating sand from gravel parts the modern barrier can be describe as composite gravel beach type *sensu* Jennings and Schulmeister (2002). Active layer thickness in the upper part of the barrier exceeds 1.5 m what allows highest tides to seepage through barrier and flood lagoons and depressions in the back of barrier. In the last decade a gravel-dominated barrier has blocked majority of small snow-fed stream outlets in the surroundings of Petuniabukta what led to the characteristic accumulations of fine sediments (muddy and sandy) in the back of the barrier. Occasional breaching of barriers during summer high discharges related to intensified snow-melting and rainfalls leads to delivery of fine material to the coast and progradation of micro-deltas. We have also noticed the importance of seaweed and driftwood accumulations for reinforcement of barrier structure making them abnormally resilient even for the highest waves in the summer season.

Observations of barrier microrelief over the last decade indicated that regardless the prolonged sea-ice conditions the effects of sea-ice erosion, deposition and melting on the beach are ephemeral and destroyed in the first few days of open water conditions each year. The characteristic for Arctic beaches pitted morphology including kettle-like hollows, kaimoo and ice-push ridges were found in the upper parts of gravel-dominated barriers only in two sites along eastern and western coast, suggesting the decaying role of sea-ice in shaping the shoreface that occurred in recent decades.

Currently, the sculpting of the surrounding landscape is dominated by the reworking of glacial and periglacial landforms left after the last Pleistocene glaciation and LIA glacier advances by paraglacial slope, aeolian, fluvial and coastal processes (Rachlewicz 2010; Szpikowski et al. 2014). Previous studies on the ice-masses in the surroundings of Petuniabukta emphasised the huge variety in terms of size, elevation, thermal state, the geomorphology of marginal zones and retreat rates of local glaciers (Rachlewicz et al. 2007; Rachlewicz 2009; Małecki 2013). According to Rachlewicz et al. (2007) since the termination of LIA all glaciers in the northern Billefjorden experienced rapid retreat exposing ca. 25 km^2 of new areas (Fig. 2.3). Their study indicated that the glacier recession for LIA-2002 period reached up to 5–15 m $year^{-1}$ for land-terminating glaciers and 35 m $year^{-1}$ for the marine-terminating Nordenskiöldbreen. They have also stated that such retreat rates are within typical range for retreat rates in the other parts of Spitsbergen, excluding large fast flowing glaciers, not present in the study area. In general the post-Little Ice Age recession of local glaciers is controlled by the air temperature warming, although several factors modify the rate of change including: the occurrence of glacier surge (faster retreat than non-surging), the elevation of glacier accumulation zone, the aspect of glacier, the shape of glacier margin and the bedrock relief which have the reducing effect on the ice flow speed (Małecki 2013; Małecki et al. 2013).

According to Long et al. (2012) the RSL in study area was about 40–45 m asl ca. 10,000 cal. year BP and fell to within a meter of present sea-level by c. 3,100 cal. year BP. Later the RSL probably fell below present and rose again in the last few millennia. The effect of land uplift related to the post-Little Ice Age deglaciation on RSL fluctuations is not yet determined although continuing accretion of barrier-platform in the mouth of Ebba River or uninterrupted development of beach-ridges on Cape Napier in the neighbouring Adolfbukta observed throughout the twentieth century suggest the counterbalancing of sea transgression by land rebound.

The twentieth century glacier retreat has exposed valley systems filled with fresh, unstable glacigenic sediments which are easily reworked by proglacial meltwater streams and modified by paraglacial slope processes (slumping, gullying and debris flows). This paraglacial sediment cascade is additionally reinforced by melting of ice-cores in glacial landforms (controlled ridges, eskers, lateral moraines) that maintain high rates of sediment flux to the tidal flat and fjord system. A recent study of sediment accumulation rates in Billefjorden (Szczuciński et al. 2009) suggests that the post-LIA transfer of sediment released from decaying glaciers to the bay is almost four times higher than during the LIA and the rest of Holocene.

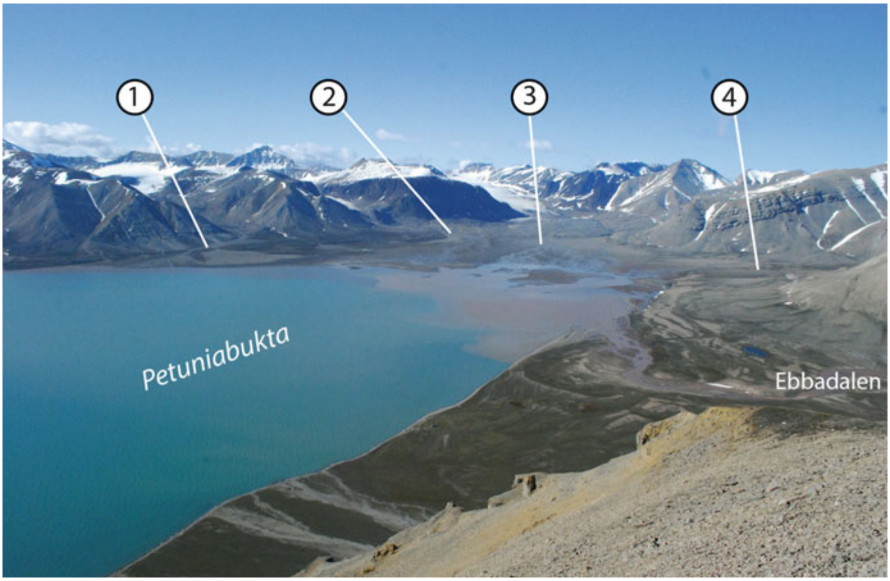


Fig. 2.4 Main features of the glacial and coastal landscape in N Petuniabukta investigated in this case study. *1* – alluvial fans fed by Ferdinandelva; *2* – Svenbreen outwash plain; *3* – Hørbyebreen outwash plain; *4* – Ragnarbreen outwash plain

Taking into the consideration the post-LIA rates of ice-mass loss, the geomorphology of exposed forelands and the diversity of coastal landforms – one of the most intriguing zones for investigations of the '*glacier retreat – coastal zone response*' is a system of prograding tidal flat merging with an extensive outwash plain accumulated by rivers of Svenbreen, Hørbyebreen and Ragnarbreen in N Petuniabukta (Fig. 2.4).

This paper will now explore the main patterns of proglacial and coastal landscape changes that occurred in N Petuniabukta the last two decades (1990–2009) – the warmest period on Svalbard since the termination of the Little Ice Age (Nordli et al. 2014).

2.3 Methods

In order to describe and quantify recent coastal zone changes in N Petuniabukta we applied geomorphological field observations, differential GPS (DGPS) surveying, aerial photogrammetric analysis and digital elevation modelling (DEM) in geographic information systems (GIS).

In years 2008–2010 geomorphological mapping was carried out during each summer season. This was combined with field sketches and interpretation from aerial photos and old maps (ground truthed in the field) to produce the final geomorphological maps. For the purpose of this study we collected and analysed the following maps of the central Spitsbergen region:

- Karczewski et al. (1990) geomorphological map of Petuniabukta region, 1: 40,000;
- Dallmann et al. 2004 Geological map of Billefjorden, 1: 50,000;

Field verification of images was accompanied with DGPS surveying. In 2008 and 2009 Leica A500 system was used to carry out barrier profiling and coastal landform mapping which was replaced by Leica 1200 system in summer 2010. DGPS receivers provided horizontal and vertical accuracy of 0.02 m. All surveys were tied back to a benchmark established during the 2008 expedition, so their elevation indicates height above mean tide level in meters.

DGPS was used to precisely measure the altitude of stable surfaces on bedrock or large boulders for orthorectification of images and DTM (Digital Terrain Model) production. Over 50 points from stable surfaces were complemented by DGPS measurements of several reference markers (2×3 m white geofiber rectangles) placed in advance of the Norwegian Polar Institute aerial photography flights carried out in summer 2009 as part of this research project. Rectangles were placed on stable natural points for ground control such as rocky outcrops and boulders to improve the precision of the constructed orthophotos and DTMs.

A selection of sites in N Petuniabukta including tidal flat, coastal barriers, alluvial fans and proglacial landforms was investigated for patterns of multidecadal change using information from aerial imaginary spanning the period 1990–2009 taken by Norwegian Polar Institute and old maps.

The following aerial images have been used in the study:

- fifteen 1990 NPI aerial images lines: S90 1706-1711; S90 1760-61; S90 1796-1807
- twenty-eight digital 2009 NPI aerial lines: s2009_13822_00001-00008; 00027-00034; s2009_13833_00477-00485;00491-493

The 2009 aerial photographs were also used to produce a set of DTMs which serve as a basis for morphometric analysis of landscape changes in the N Petuniabukta. A ground-truthing was carried out on the majority of sites using DGPS surveys, ground (oblique) photography and surface sediment sampling of selected landforms.

Delimitation of shorelines position was estimated using the middle of the first, fully emerged storm ridge visible on the image to minimise the error stemming from different phases of tidal cycle captured on individual photographs. In general, shoreline changes smaller than 2.5 m were not considered in interpretation of results. This is because it was impossible to distinguish if the emerging forms comprised ephemeral gravel berms or storm ridges.

The error cited was also based on the observations of the present-day shoreface where the distance between these shoreline elements is ca. 2 m.

DTMs based on 2009 images were automatically produced in ERDAS Leica Photogrammetry Suite 2010 (LPS). Software employs the bundle block adjustment, using least squares estimation, to establish the relationship between the positions of a set of photographs and a ground coordinate system, based on the interior and exterior parameters input into the software and the location of ground control points. As aerial images from summer 2009 (27 July and 11 August) were taken by NPI with an UltraCam Xp Large Format Digital Aerial Camera manufactured by Vexcel the interior parameters were already inserted in image files so only exterior parameters had to be manually entered into the software. Each set of photographs was then processed as for a digital camera. The projection used was UTM, with the spheroid WGS 84 for zone 33 N. The selection of strategy parameters was based on a visual inspection of DTMs and orthophotos output using different strategy parameters.

For each 2009 image used for DTM creation at least five ground control points were collected using DGPS. Set of DTMs were generated from the 2009 images with ground resolutions ranging from 1 to 20 m. DTM of 20 m resolution covered the whole study area and was suitable for comparison with the DTM produced by NPI from the set of 1990 images obtained for this project.

Differencing of the 2009 and 1990 DTMs was done for the N part of Petuniabukta. The difference was calculated by subtracting two DTMs in ArcGIS software. Estimation of surface elevation changes is an extremely useful method for landscape evolution studies and allows identification of zones of surface erosion and surface aggradation. In high latitudes this technique has been commonly applied to measure surface elevation changes of glaciers (e.g. Wangensteen et al. 2006; Muskett et al. 2009; Barrand et al. 2010) and proglacial landforms (e.g. Schomacker and Kjær 2008; Irvine-Fynn et al. 2011; Bennett and Evans 2012). In this study the subtracting of DTMs was carried out to investigate surface elevation change in the proglacial zone of Ferdinandbreen, Svenbreen and Hørbyebreen and to estimate the amount of sediment removed by paraglacial processes (fluvial, slope, aeolian activity) towards the coastal zone.

2.4 Results

Previous studies on recent Svalbard coastal zone changes have focused on the rate of shoreline progradation and erosion (Mercier and Laffly 2005; Ziaja et al. 2011; Zagórski 2011; Zagórski et al. 2012a, b). In this study we sought to estimate the vertical relief changes associated with sediment erosion and deposition over last two decades. To do this we used the 20 m resolution DTM of 2009 and 20 m resolution DTM of 1990 from the Norwegian Polar Institute to calculate the vertical surface change by subtracting the 1990 model from the 2009 model in ArcGIS software (Fig. 2.5).

To calculate data on surface elevation changes between the proglacial and the coastal zone of N Petuniabukta the following steps were made in the analysis:

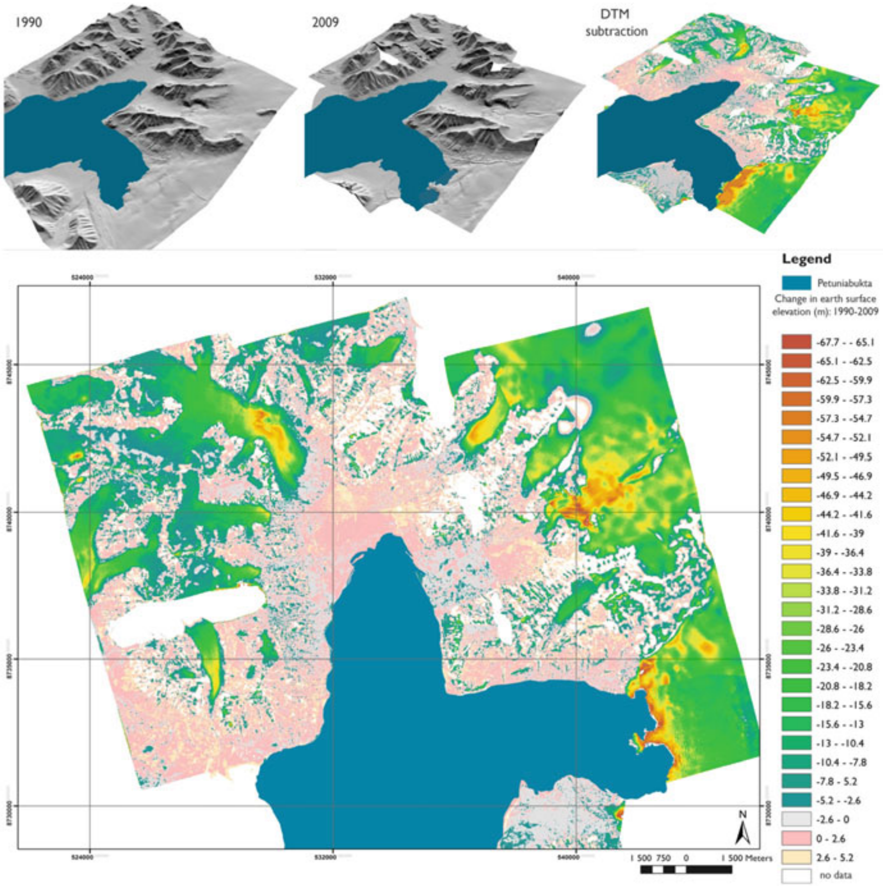


Fig. 2.5 DTM differencing of 1990 and 2009 models. The map summarises surface elevation changes (m) that occurred between 1990 and 2009 in Petuniabukta region

(a) Having two DTMs from 1990 to 2009 it was possible to study surface elevation changes only for a short phase of post-LIA period (19 years). This period was characterised by a rapid increase in retreat rates of all Petuniabukta glaciers apart from Ferdinandbreen and Svenbreen (Rachlewicz et al. 2007; Małecki 2009). We hypothesised that such conditions significantly increased sediment availability and the efficiency of sediment release and transport processes from deglacierised areas towards the coastal zone.

(b) Between 1990 and 2009, recession of Petuniabukta glaciers exposed *ca.* 5 km^2 of area covered by fresh and unconsolidated material which was easy to transport and further modify by paraglacial processes dominated by fluvial, mass-wasting and wind action.

(c) Amongst the glaciers supplying sediments to the N coast of Petuniabukta the largest area was exposed in front of Hørbyebreen (*ca.* 2.5 km^2). Small valley glaciers along western coast exposed in total *ca.* 0.66 km^2: Elsabreen (*ca.* 0.28 km^2), Svenbreen (*ca.* 0.22 km^2) and Ferdinandbreen (*ca.* 0.16 km^2). Ragnarbreen supplies sediments to the tidal flat via an outwash plain that is linked with the Hørbyebreen outwash plain, exposed *ca.* 0.6 km^2 of new area. The role of Ragnarbreen in sediment delivery to the coast is limited by a proglacial lake that acts as a sediment trap for sediments released from the glacier and ice-marginal zone (Ewertowski et al. 2012; Ewertowski 2014).

(d) The retreat of small glaciers (Elsabreen, Ferdinandbreen, and Svenbreen) led to the elongation of their rivers (815 m, 105 m, 95 m respectively). Since 1990, these glaciers were already hidden deep in their valleys (Elsabreen, Ferdinandbreen) and behind a bedrock sill (Svenbreen) that significantly focused sediment transfer from freshly exposed proglacial areas towards the coast.

(e) To check the vertical accuracy of surface elevation change, a vertical elevation error resulting from a potential mismatch of models during the overlying process was estimated. To do so 54,000 points lying along the contour lines on the 1990 DTM were selected from stable surfaces i.e. rocky outcrops, edges of rockwalls, coastal lowlands with bedrock outcrops avoiding unstable glacial and glaciofluvial landforms. Points were then re-measured on the 2009 DTM and the resulting elevation difference was plotted with height above sea-level and slope inclination ascribed to each point. Error analysis showed that the DTMs were matched closely and that the calculated surface elevation differences were not related to slope inclination or height a.s.l with both values close to 0 m. To estimate the vertical error range between models the root mean squared error (RMSE) was calculated. As the RMSE increases exponentially with the slope inclination it was assumed that detailed calculations of sediment volume change should be limited only to low-inclined areas distant from steep-sided mountain slopes.

(f) The largest surface lowering, excluding that resulting from ice thickness changes of retreating glaciers fronts (over 60 m $\pm$ 1.6 m), occurs in the ice-marginal zones of glaciers: up to 50 m $\pm$ 8 m (Hørbyebreen); up to 39 m $\pm$ 10.2 m (Svenbreen); up to 35 m $\pm$ 4.7 m (Ferdinandbreen), up to 24 m $\pm$ 2.8 m (Elsabreen) and up to 55 m $\pm$ 3.9 m (Ragnarbreen). Such large decreases of surface elevation cannot be associated solely with sediment erosion and redistribution and likely records decay of dead-ice in ice-cored landforms. Dead-ice melting is a characteristic process controlling surface lowering over ice-cored landforms (moraines, eskers, kames) in ice-marginal and proglacial areas (Schomacker 2008). It was assumed that the mean annual downwasting rate of ice-cored areas is *ca.* 0.9 m following the measurements made by Schomacker and Kjær (2008), across the ice-marginal zone of Holmströmbreen which is a glacier located in central Spitsbergen that supplies an extensive outwash plain that merges into the muddy tidal flat of Ekmanfjorden. We treated surface elevation change values observed in these areas as a sum of dead-ice melting and sediment removal. Using Schomacker and Kjær (2008) calculations, the estimated surface lowering related to decay of dead-ice is *ca*. 17 m over the 19 years of analysis. In support of this assumption are slower lowering rates observed over the Hørbyebreen frontal moraine, which according to a DC resistivity survey by Gibas et al. (2005) is devoid of ice, compared with faster lowering of the frontal moraine of Ebbabreen, which is ice-cored. Thus, the maximum surface lowering of moraines in front of Ebbabreen was *ca*. 28 m $\pm$ 5.4 m, whereas remnants of Hørbyebreen frontal moraine lowered up to 13 m $\pm$ 3.9 m.

(g) Finally, it was assumed that the ice-marginal and proglacial zones acts as the largest sediment supplier to the N coast of Petuniabukta, and the sediment removal from these environments is recorded in accumulation of material on alluvial fans, outwash plains and tidal flat system.

Taking into consideration the input assumptions described above, an attempt was made to calculate the volume of sediments accumulated and eroded in 19 years over the outwash plains and fans formed by Hørbyebreen, Ragnarbreen, Svenbreen, Ferdinandbreen and Elsabreen (Table 2.1). This shows that the alluvial fans and outwash plains of N Petuniabukta act as an effective trap for sediment released from decaying ice-marginal and proglacial landforms. During the analysed 19 years the majority of landforms gained more sediment than they lost due to erosion.

Erosion dominated the sediment budgets of only two landforms – the outwash plain of Svenbreen and the fan formed by Elsaelva. In the case of the former, this may be related to the presence of dead-ice in remnants of the frontal moraine and eskers eroded by Svenelva. Melting of dead-ice may have caused the loss of up to 603,309 m^3 of landform volume that would significantly reduce the amount of eroded sediments (to *ca*. 544,777 m^3). Regarding the latter, this relates mainly to the remnants of old features (relict fans, uplifted beaches) that form islands dividing braided streams of the glacier river. It is important to note that the area of Elsaelva fan and river channel has been commonly washed out and incised by snow-melt

Table 2.1 Volumes of sediments stored and eroded from selected landforms in N Petuniabukta between 1990 and 2009

Landform	Area [m^2]	Accumulation [m^3]	Erosion [m^3]	Net change [m^3]
Hørbyebreen outwash plain	3,824,847	6,133,192	−87,109	6,046,083
Ragnarbreen outwash plain	1,308,222	2,391,380	−352,242	2,039,138
Svenbreen outwash plain	917,943	423,800	−1,148,086	−724,286
Ferdinandbreen relict and modern fans	1,286,584	1,195,849	−517,270	678,579
Elsabreen fan and delta	132,464	21,450	−196,253	−174,803
Tidal flat	1,839,156	2,396,362	−112,061	2,284,301
Total:	9,309,216	12,562,033	−2,413,021	10,149,012

streams with reduced glaciofluvial sediment supply from the decaying Elsabreen (*ca*. 46 m year^{-1} of glacier front retreat over 1990–2009 period) and this explains the process of sediment loss quite well. It was also observed in years 2005–2010 that fragments of uplifted beaches located in the Elsaelva fan delta area were subject to wave erosion.

Between 1990 and 2009 the modern and relict alluvial fans supplied from Ferdinandbreen were the biggest sediment storage systems along the western coast of Petuniabukta. Interestingly, sediment accumulation dominated the areas abandoned by Ferdinandelva channels (Ferdinand fans) suggesting a significant role of sediment influx from snow-melt streams, slope movements (solifluction) or aeolian deposition. Conversely, in those parts of fans where the modern Ferdinandelva was active, erosion was dominant. According to the DTMs subtraction a relatively strong surface lowering occurred over small snow-fed fans that accumulated between the relict lagoon and the prograding alluvial fan. The erosion of the barrier and opening of outlets linking the lagoon with Petuniabukta that occurred between 1990 and 2009 may have led to increased erosion from fan aprons and the back of the barrier, but it is also probable that the results are biased by the presence of a steep rockwall that may have distorted the elevation change calculations processed in ArcGIS.

Certainly the largest sediment storage system in the analysed area was the outwash plain of Hørbyebreen in which over 60 % of sediments accumulated in the studied landforms between 1990 and 2009. Sediment loss was observed only along the sandur margins which border on remnants of the ice-cored western lateral moraine of Hørbyebreen and a retreating cliff formed in uplifted marine sediments (NW margin), the eroding slopes of the Hørbyebreen LIA frontal moraine (N margin) and the eroding slopes of old rock glacierised moraine of Late Weichselian age (NE margin).

The second largest sediment storage was found in the Ragnarelva outwash plain and alluvial fans formed on southern slopes of Ragnardalen that supplies sediments to outwash plain and directly to tidal flat during snow-melt flood events.

Since the formation of a proglacial lake in the late 1980s, the sediment supply from Ragnarbeen ice-marginal had been significantly reduced. The surface analysis changes suggest that the major source of sediments accumulated in outwash plain comes from three sources: erosion and redistribution of sediments accumulated in the Ragnarbeen LIA frontal moraine, lateral erosion of river banks in the central sector of Ragnardalen and incision of river channel close to the proximal sector of Ragnar outwash plain (Ewertowski 2014).

One of the largest surface changes in the entire area occurred over fans that accumulated on slopes of Løvehovden in Ragnardalen. During the 19 years these gained *ca*. 2,400,000 m^3 of sediments derived mainly from ephemeral snow-fed streams, debris flows, slush avalanches and solifluction.

The final feature selected for sediment volume change analysis was the tidal flat system. The lower part of tidal flat was fully flooded in 1990 and it was partly flooded in 2009, so it was assumed that the elevation difference over this area was unsuitable for further calculations. Therefore, only that sector of the tidal flat adjacent to the Hørbyebreen outwash plain to the north, and limited to the southern extent of main tidal islands to the south, was considered in calculations.

Interestingly, the amount of sediments stored in the upper part of tidal flat (2,396,362 m^3) was about the same as the total amount of sediments eroded from the rest of analysed landforms (2,413,021 m^3). This shows that the tidal flat is a very effective sediment trap for sediments eroded from outwash plains and fans. The further progradation of the tidal flat is expected to facilitate the development of the barrier coast in N Petuniabukta by providing the stable submarine platform for future spits and barriers supplied by proglacial rivers and snow-fed streams.

2.5 Discussion

The post-LIA retreat of glaciers has arguably triggered the most dramatic change of Svalbard landscape since deglaciation at the start of the Holocene. Retreating glaciers have exposed vast areas of fresh glacigenic sediments that were easily released, eroded, transported and redistributed by an array of processes: dead-ice melting (e.g. Schomacker and Kjær 2008), meltwater streams (e.g. Etzelmüller et al. 2000), jökulhlaups (e.g. Etienne et al. 2008), slope processes (e.g. Mercier et al. 2009), wind action (e.g. Rachlewicz 2010) and finally coastal processes (e.g. Mercier and Laffly 2005). Intensified operation of those processes was strengthened by warming of the climate that thawed permafrost and destabilised unlithified river banks or fjord shores because of thinner ice cover and/or weaker thermal insulation of slopes and rockwalls by reduced snow cover. The response of the Svalbard coastal zone to the post-LIA paraglaciation, which in theory constitutes 'the ultimate sink' (Ballantyne 2002) for paraglacially eroded, reworked and transported sediments before they are moved further offshore, has been observed in several sites along W and S Spitsbergen. Previous studies have linked coastal progradation and rapid development of depositional landforms with uninterrupted periods of sediment supply from glacial rivers (Héquette 1992; Mercier and Laffly 2005), episodes of dramatic coastal erosion in areas no longer covered or protected by glacier ice (Ziaja et al. 2009), and coastal reworking of glacigenic landforms (mainly frontal moraines, margins of outwash plains and smaller proglacial features) exposed after the retreat of glaciers (Zagórski et al. 2012a, b).

It is important to note that despite the enhanced post-LIA sediment supply to the coastal zone in all previously investigated sites (Sørkappland – Ziaja et al. 2009, 2011; Hornsund – Zagórski et al. 2012b; Bellsund – Zagórski 2011), except for the section of Kongsfjorden coast described by Mercier and Laffly (2005), the observed rates of coastal erosion exceeded the rates of coastal progradation. These observations contradict the picture of Svalbard coastal zone as classified on the most recent map of Arctic coast erosion rates as being a 'stable' or 'aggrading' coastline (Lantuit et al. 2012).

The dominance of erosion along those mostly open-type coasts in W and S Spitsbergen can be explained by: the prolongation of exposure of coasts to the operation of waves and more frequent storms caused by the earlier disappearance and later formation of sea-ice and ice-foot; the increased influx of warmer Atlantic waters that weaken sea-ice cover and disturb the thermal state of coastal permafrost; the thickening of the active layer in coastal areas that leads to the destabilization of coastal sediments and increases their permeability by both groundwater and seepage of seawater, and; the rutting of the coastal sediments by heavy machines in the vicinity of research stations (e.g. the Polish Polar Station in Hornsund or bases in Ny-Ålesund).

The general image of the post-LIA paraglacial coasts in Svalbard that can be determined from previous studies suggests very responsive and unstable systems that rapidly react to changes in sediment supply delivered from retreating glaciers and climate-driven forcings of coastal erosion (retreat of tide-water glaciers, prolongation of open water conditions and influx of warmer waters).

The results of the research presented in this paper confirm an increase in the post-LIA sediment delivery to the coastal zone, but have also shown that the link between coastal evolution and glacier retreat and sediment supply change seen along the W and S coasts of Spitsbergen has been less dramatic in the protected, inner-fjord environment of Petuniabukta.

Geomorphological evidence and information derived from aerial imagery indicate that the recent development of the coasts of N Petuniabukta is strongly influenced by local factors that include local climate, basement topography and inherited landscape, wave climate and surface circulation pattern, and to some extent the pattern of relative sea-level change.

Since summer periods in Petuniabukta are warmer and drier than along W and S coasts of Spitsbergen (see climate conditons on Fig. 2.2), retreat of glaciers drives them high into their valleys. This, in turn, increases the distance between glacier snouts and the coastal zone. On average glacier rivers draining to the N Petuniabukta have to overcome almost twice the distance to the coast compared with rivers transporting sediments from comparable proglacial zones of W and S Spitsbergen (e.g. Bayelva, Scottelva, Werenskioldelva). This decreases the stream power, reduces sediment transport and increases the sediment load loss in intermediate sinks such as river banks, river bars, floodplains or proglacial lakes. Therefore, even though glacier retreat rates in Petuniabukta are similar with those observed in the other parts of Spitsbergen (Rachlewicz et al. 2007; Małecki 2013) coastal responses are less dramatic than in W and S Spitsbergen.

In W and S Spitsbergen it is common to observe erosional and depositional shorelines that are distributed in time and space according to sediment supply and delivery rates or the appearance of protective sea-ice before the arrival of storms (e.g. Calypsostranda responding to pulses of sediment supply from Scottbreen and Renardbreen as described by Zagórski (2011)).

In N Petuniabukta, coastal erosion in the last two decades was limited to a short (300–350 m) section of coastline located between the Elsaelva delta and the

Ferdinand fans (Fig. 2.3). This occurred despite continuous sediment delivery to the coast by the Elsaelva and Ferdinandelva and continued severe sea-ice conditions throughout the last century. It is difficult to explain this section of erosion coast, although it is possible that the coastline orientation with reference to the prevailing winds and surface water circulation directions in the fjord has been influential.

Sea ice is another important factor in controlling coastal change. The western and southern coasts of Spitsbergen are generally ice-free for longer periods and exposed to storms originating far away in the Barents and Greenland Seas that define local wind directions and shape coastal geomorphology. In contrast to Petuniabukta, coastal development at a site like Hornsund (SW Spitsbergen) is strongly influenced by the rapid decay of tide-water glaciers and an associated influx of warm Atlantic waters delivered by West Spitsbergen Current. Due to the post-LIA retreat of glaciers the fjord areas here have increased by over 172 km^2 (Błaszczyk et al. 2013). The post-LIA ice decay not only lengthened Hornsund shorelines, but also increased the exchange of waters between the fjord and open sea, leading to the acceleration of tidal currents velocity that might have intensified the coastal erosion (Piotr Głowacki pers. comm.).

Another important difference between N Petuniabukta coast and coasts from W and S Spitsbergen is the lack of a direct connection between the coastal zone and glacial landforms (moraines, eskers, kames, crevasse fills etc.). The erosion of landforms left by retreating glaciers by waves and longshore currents constitutes an important source of coarse-clastic sediment delivery to Kongsfjorden, Bellsund, Hornsund and to the bays around Sørkappland. This mode of glacigenic sediment delivery make them similar to mid-latitude paraglacial coasts supplied with sediment from erosion of drumlins and other landforms left along the coast by last ice sheets (e.g. the paraglacial coasts of Ireland and Nova Scotia (Taylor et al. 1986; Shaw et al. 1990; Orford et al. 1991)). Evolution of this type of paraglacial coastal systems is characterised by episodes of rapid reorganization associated with gaining access to and reworking of glacigenic landforms. According to Forbes et al. (1995) the lifespan of paraglacial coast is dependent on the volume and endurance of the (glacial) sediment source, so that often the phase of intensified growth and migration of paraglacial barriers is abruptly terminated by the exhaustion of sediments supply that occurs when a glacigenic landform is fully eroded.

The relatively dry and warm climate of the study area (compared with the W Spitsbergen coast) limits the growth of local glaciers to high elevations. This meant that the post-LIA sediment supply to the N Petuniabukta coast was more distant to that in W Spitsbergen. Therefore it can be assumed that the shorelines here experienced the decaying phase of paraglacial sedimentation associated with reworking of former glacigenic sediments already transported and modified by non-glacial fluvial, slope and aeolian processes.

This situation resembles the fourth stage of fjord evolution model proposed by Syvitski and Shaw (1995) who determined the following steps of fjord infilling: Stage One – the complete coverage of fjord by glacier ice; Stage Two – the ice-contact sedimentation associated with retreating tide-water glacier; Stage Three – distal proglacial sedimentation after transformation of the glacier into a land-based type; Stage Four – paraglacial sedimentation associated with the reworking of glacigenic deposits left by a retreating and later a fully disappearing glacier; and Stage Five – complete infilling of the fjord basin. As noted by Ballantyne (2002) such a sequence of events can be disturbed, stopped or reversed by a shift of climate conditions, and can be either slowed down or accelerated by sea-level change.

2.6 Conclusions

This paper provides a new insight into the functioning of High Arctic paraglacial coastal environments developing in sheltered fjord settings and supplied by sediments derived from glacial (glacierised catchments) and non-glacial (snow-fed streams and talus slopes) sources. In such low energy environments one might expect the limited modification of coastal landforms. However, information from aerial photogrammetric analyses and geomorphological mapping shows that Petuniabukta coastal zone quickly adjusts to climatic and geomorphic changes.

The formation of new coast landforms here is to a large degree dependent of the rate of sediment excavation from relict sediment storage systems, such as alluvial fans and outwash plains that developed across a wide coast plain between the glacier valleys and the fjord. Majority of the sediments eroded between 1990 and 2009 from outwash plains and alluvial fans has been stored in a prograding tidal flat system. Progradation of tidal flat over the study period provided the depositional platform on which new coastal features have developed.

Rates of coastal evolution, over the analysed period, in these contexts are comparable to those seen along the W and S coasts of Spitsbergen.

Our work highlights the need for a greater understanding of the controls on High Arctic coastal sediment budgets, especially given the potential for accelerated warming and sea-level rise in the coming decades and centuries.

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