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Letters to ESEX

New fjords, new coasts, new landscapes: The geomorphology of paraglacial coasts formed after recent glacier retreat in Brepollen (Hornsund, southern Svalbard)

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ABSTRACT: Changes in the properties and dynamics of tidewater glacier systems are key indicators of the state of Arctic climate and environment. Calving of tidewater glacier fronts is currently the dominant form of ice mass loss and a major contributor to global sea-level rise. An important yet under-studied aspect of this process is transformation of Arctic landscapes, where new lands and coastal systems are revealed due to the recession of marine-terminating ice masses. The evolution of those freshly exposed paraglacial coastal environments is controlled by nearshore marine, coastal and terrestrial geomorphic processes, which rework glacial-derived sediments to create new coastal paraglacial landforms and landscapes. Here, we present the first study of the paraglacial coasts of Brepollen, one of the youngest bays of Svalbard revealed by ice retreat. We describe and classify coastal systems and the variety of landforms (deltas, cliffs, tidal flats, beaches) developed along the shores of Brepollen during the last 100 years. We further discuss the main modes of sediment supply to the coast in different parts of the new bay, highlighting the fast rate of coastal transformation as a paraglacial response to rapid deglaciation in the Arctic. This study provides an exemplar of likely coastal responses to be anticipated in similar tidewater settings under future climate change. © 2020 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd

KEYWORDS: coastal processes; landscape change; paraglacial; sediment supply; tidewater glaciers

Introduction

The termination of the Little Ice Age (LIA), which in Svalbard occurred around the turn of the 19th and 20th century, brought a major shift in landscape evolution associated with the rapid retreat of glaciers from their Holocene maximum extents (e.g. Małecki, 2016; Martin-Moreno *et al.*, 2017). During the post-LIA period, paraglacial processes (*sensu* Ballantyne, 2002) have been erasing the effects of glacial legacy from the relief of mountains, valleys, coasts and fjords (e.g. Lukas *et al.*, 2005; Mercier *et al.*, 2009; Rachlewicz, 2009, 2010; Szczuciński *et al.*, 2009; Ewertowski and Tomczyk, 2015; Senderak *et al.*, 2017; Strzelecki *et al.*, 2017). The rapid exposure of land from Svalbard glaciers (over 20% of glacierized terrain decrease) activates sediment cascades through which exposed glacigenic sediments are transported and can then be stored in the form of solifluction slope covers, fluvial floodplains, lakes and within the coastal zone in the form of beaches, tidal flats or as marine sediments in the bottoms of fjords (e.g. Lønne & Lyså, 2005; Midgley *et al.*, 2018; Ewertowski *et al.*, 2019; Weckwerth *et al.*, 2019).

Previous studies on the evolution of paraglacial coasts in Svalbard have focused predominantly on the interplay between coastal change and glacifluvial sediment supply from retreating land-terminating glaciers (e.g. Mercier and Laffly, 2005; Étienne *et al.*, 2008; Zagórski, 2011; Zagórski *et al.*, 2012; Bourriquen *et al.*, 2018; Strzelecki *et al.*, 2018). In those systems, development of coastal landforms is controlled by the configuration and shifts of river channels, including their hydrology; the presence and accommodation space of intermediary storage areas within the river system, such as braided floodplains, alluvial fans and bedrock basins, that control the efficiency of fluvial sediment supply; and exposure of coasts to the storm waves/open sea. In general, most of the newly formed coastal beaches, deltas or tidal flats in Svalbard show high rates of progradation during periods of uninterrupted glaciofluvial sediment delivery (Zagórski, 2011; Bourriquen *et al.*, 2018; Kavan, 2019).

Despite these previous studies, little is known about coastal morphodynamics in Svalbard after glacier retreat from the coast, or how coastal systems evolve in response to the transition from glacial to marine drivers. This is particularly important in Svalbard, where tidewater glaciers are the dominant glacial systems existing, and whose cliffed fronts constitute up to 25% (900 out of 3587 km) of the archipelago total shoreline length (e.g. Błaszczyk *et al.*, 2009). Recent years brought a major advance in glacial landscape mapping and transformation of marginal zones of tidewater glaciers in a number of key fjord systems of Svalbard (e.g. Lønne, 2006; Ewertowski *et al.*, 2016; Farnsworth *et al.*, 2016; Lovell *et al.*, 2018; Aradóttir *et al.*, 2019). Although the majority of those studies presented new examples of paraglacial degradation of glacial margins, little or no attention was paid to the coastal landforms derived from remodelling of glacial landforms by marine processes.

In order to address this deficiency, this study describes the geomorphology of coasts that were exposed over the last century (from ~1920 to present) along the shorelines of Brepollen, southern Svalbard (Figure 1). This study is based on the photointerpretation of an historical aerial imagery collection (1936–2011) provided by the Norwegian Polar Institute (NPI; https://toposvalbard.npolar.no), archival maps from NPI collections and recent field observations of coastal change (2016–2019). This paper reports some key findings from this analysis, focusing on new fjord systems and coastal plains and their constituent landforms, revealed by post-LIA glacier retreat in Brepollen.

From the methodological point of view, while describing the recently developed coasts of Brepollen, we have followed the concept of *paraglacial coasts* defined by Forbes and Syvitski (1994) as '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'.

New Fjords

Brepollen is one of the youngest bays of Svalbard. Its formation led to the extension of Hornsund fjord (Figure 1). The area is known for one of the fastest retreat rates of tidewater glaciers in Svalbard, which accelerated in the 21st century to almost 2 km^2 loss per year (e.g. Błaszczyk *et al.*, 2013). The bay started to form around 1920, when the front of a large tidewater glacier in the inner part of Hornsund passed the narrow (~1900 m wide) strait between two bedrock capes Treskelen Peninsula in the north and Meranpynten in the south (Heintz, 1953). Further evolution of the bay proceeded in five major stages, identified on the basis of significant phases of coastal geomorphic response to ice retreat (Table I). During these retreat stages, the diverse shape of the emergent bay is dependent not only on changes in tidewater glacier frontal position, but also on local geology that influences coastline geometry. As the bay axis is oriented roughly perpendicular to major tectonic structures, numerous

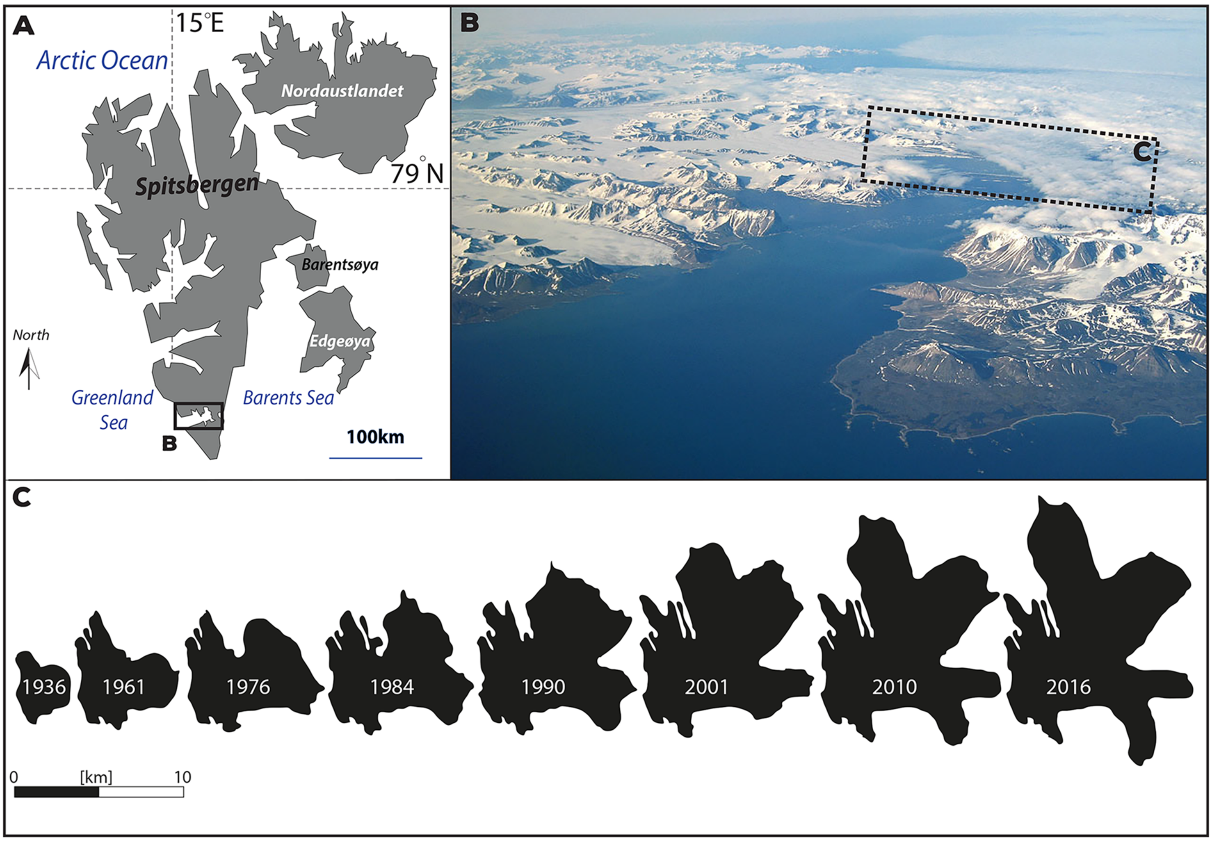

Figure 1. Location of case study. (A) Southern Spitsbergen, largest island of the Svalbard Archipelago. (B) Hornsund fjord system with developing Brepollen bay. Image Michael Hambrey (2009) (www.swisseduc.ch/glaciers/). (C) Post-Little Ice Age evolution of Brepollen due to the fast retreat of tidewater glaciers. The Greenland Sea outlet of the Brepollen system is located to the bottom left of these polygon outlines. [Colour figure can be viewed at wileyonlinelibrary.com]

Table I. Stages of Brepollen evolution during the post-LIA period, based on data derived from Norwegian Polar Institute aerial imagery collections

Stage	Period	Processes and emergent patterns of coastal development	Brepollen area (km^2)	Total coastline length (km)	Ice-cliff coastline length (km)
I	1920–1940	Exposure of Treskellen peninsula and the beginning of formation of Treskelbukta in the northern part of the new bay. In the south, Samarinbreen became divided from the major tidewater glacier system and another new bay started to form (Samarinvågen) at the entrance to Brepollen.	~9.5	11.5	8.5
II	1940–1960	Full exposure of Treskelbukta and beginning of formation of Selbukta with a calving front of Hyrnebreen in the northern part of the bay, and development of Svovelbukta in the south following the calving front of Chomjakovbreen. The central part of the tidewater glacier passed another bedrock ridge (Hornholmen, Ammonittøya, Breholmen) in the north and exposed steep slopes of Starostinfjellet in the south, where one of the few land-terminating glaciers in the study area is located (Bautabreen).	~25.5	29	11
III	1960–1980	The retreating front of the tidewater glacier exposed almost the entire central part of Brepollen and reached the base of the slopes of Ostrogradskijfjella. Two new branches of this bay started to form: the northern branch with retreating fronts of Storbreen and Hornbreen, and the southern branch with retreating fronts of Mendelejevbreen and Svalisbreen. Smaller coves such as Treskelbukta, Selbukta and Svovelbukta experienced significant enlargement. During this period, the presence of sedimentary and rocky coasts limited the length of ice-cliff coasts in the fjord.	~40	43	21
IV	1980–2000	In the southern part of the bay, the ice front reached the slopes of Kinnhøgda and cut the link between Svalisbreen and Mendelejevbreen, forming two separate coves in front of these glaciers. In the north, after reaching the slopes of Mezenryggen, the ice front of Storbeen and Hornbreen separated, forming two large coves. The extension of Svovelbukta was slowed as the glacier had to pass over the Bautaholmen bedrock ridge in the central part of the cove. Therefore, at least until 1990, the Svolvebukta had two separate branches, one to the east and the second to the west of the small rocky island. During the 1990s, Mendelejevbreen and Storbreen started their most recent surge event.	~80	67	14
V	2000–present	By 2002, the surge of Mendelejevbreen and Storbreen terminated and this led to a small decrease in the area of Brepollen. Small advances of glacier fronts were also noted on Hornbreen (2002, 2005) and Mendelejevbreen (2002).	~100	85	19

emergent rocky capes and coves have a north–south orientation (Moskalik *et al.*, 2014). It had previously been noted that the course of major glacier valleys in Hornsund is controlled by geological structures (Jania, 1988).

Currently, Brepollen is up to 13 km long (from the Treskelen to the ice cliff of Hornbreen) and over 16 km wide at its widest section between Mendelejevbreen and Storbreen. Although there are no direct observations of tidal processes in the area, Brepollen, similar to other fjords and bays of Svalbard, belongs to microtidal environments. In nearby Hornsund the tides have an average amplitude of 0.75 m (Herman *et al.*, 2019). Based on bathymetric profile interpolation, Moskalik *et al.* (2013) divided the new bay into eight sub-basins, six of which consist of glacier valleys (Storbreen, Hornbreen, Svalisbreen, Mendelejevbreen, Chomjakovbreen and Hyrnebreen); one separate cove along the eastern shore of Treskelen; and one central open-water part which constitutes ~30% of the bay area and has maximum water depths in excess of 140 m. The recent retreat of Hornbreen/Hambergbreen has also revealed evidence for a submerged channel (Ziaja and Ostafin, 2014, 2019; Grabiec *et al.*, 2018). Radar surveys across Hornbreen/Hambergbreen carried out by Grabiec *et al.* (2018) revealed a 40 m-deep subglacial channel that, by 2055–2065, may evolve into a strait linking the Greenland and Barents seas (Brepollen and Hambergbukta, respectively) if current glacier retreat rates remain unchanged (Figure 2).

New Coasts

Post-LIA formation and extension of Brepollen resulted in the exposure of ~85 km of new coastlines (~66 km of sedimentary and rocky shores and 19 km of ice fronts of tidewater glaciers), and at least nine new islands. During 2016–2017 we have groundtruthed information derived from aerial images by field observations, and distinguished the following types of Brepollen coastlines: (1) ice cliffs, which correspond to the active ice fronts of tidewater glaciers as they undergo retreat, or as remnants of stagnant glacier ice left along the coast; (2) rocky coasts with rock shore platforms; (3) coasts formed along abandoned glacial landforms or ice cliffs; (4) fluvial deltas and intertidal flats (Figure 3A). These different coastline types are located in different areas around Brepollen, largely determined by proximity to the retreating glacier fronts, bedrock geometry and properties, and clastic sediment supply.

Taking into consideration the key controls of coastal morphodynamics and dominant coastal landforms found in different areas of the Brepollen shoreline, we can distinguish three coastal systems in Brepollen, defined according to sediment source to sink systems:

Treskelen peninsula–Breholmen coastal system

This is the most diverse coastal system of the analysed region, characterized by numerous embayments and islands with a dominant bedrock control but covered by a relatively thin layer of glacigenic deposits (Figure 4A). Coastal geomorphological features include gravel-dominated barriers, spits, lagoons, coarse-sand beaches and small prograding tidal flats, to a large degree controlled by the protection of local shorelines from storm waves. Treskelen peninsula blocks the impact of storm waves to the northwest, while fragmentation of the shoreline

Figure 2. Brepollen coastal and glacial environments. (A) Aerial view of southern Spitsbergen in 1936 with both 'future' Brepollen and Hambergbukta filled with glaciers (after Toposvalbard Norwegian Polar Institute). (B) Same view in 2018 with new bays: Brepollen and Hambergbukta revealed after the post-LIA retreat of glaciers with new shorelines exposed (photo M. Michalski 2018). [Colour figure can be viewed at wileyonlinelibrary.com]

by elongated rocky ridges defines capes (Selodden and Strykejernsodden) or the cores of small islands (Longøya, Ammonittøya, Hornholmen and Breholmen), breaking larger oceanic waves entering the bay. This sector of the coastal zone is supplied with sediments through direct reworking of glacial landforms, such as remnants of frontal moraines along the eastern shore of Treskelen peninsula (Figure 4B), and crevasse-squeeze ridges (CSRs) and ground moraines on Selodden and Nytangen (Figure 4C). Other characteristic elements of the coastal landscape are small lakes developed along the northern shores of Treskelbukta and small coves between Selodden and Nytangen (Figure 4B). These lakes may also have influenced sediment delivery to the coast, where they function as intermediate sediment storage areas and deliver excess sediments to the coast during episodic lake drainage events. The western shores of Selbukta are dissected by numerous small streams (100–200 m long) that drain from lateral moraines of Hyrnebreen. Apart from fluvial sediment delivery, the narrow beach system developed in Selbukta is supplied by direct mass wasting from these lateral moraines. The elongated Longøya island (Figure 3B), providing protection from waves, and a large amount of unstable glacial sediments in the small valley between Storbreen and Strykejernet, contributed to the formation of tidal flats at the head of the cove at Selbukta. The youngest paraglacial beach system in this sector of bay (Figure 3B) is still forming at the base of the eastern part of Hyrnebreen glacier front, which has now retreated on land. Here the morphology of beaches and initial spits is modified by waves produced by episodic calving, and supplied by glacial sediments through direct melt-out of the ice cliff. On the opposite shore (western coast of Hyrnebreen), the glacial-fed streams and ephemeral streams from deglacierized slopes are building a new tidal flat system which shows rapid progradation (Figure 4D).

Storbreen–Hornbreen–Svalisbreen valley coastal system

The coastal environment in this sector of Brepollen is dominated by extensive ice cliffs formed by tidewater glaciers (Figure 4F). The typical coastal landforms are young and narrow beaches that develop along land-terminating parts of glacier snouts. Such a young beach system is developed along the western coast of 'Storbukta', where glacial sediments slump directly to the coast from the surface of the joined snouts of Krohnbreen and Storbreen (Figure 4E).Freshly exposed land between Storbreen and Hornbreen is fringed by a narrow beach dissected by many ephemeral streams (over 30 active inlets were observed in the 2016 season). The coastal plain drained by these streams has a very diverse geomorphology, with a glacial till covered with CSRs, eskers and many hundreds of small kettle lakes (Figure 4A). A major feature of this coastal section is

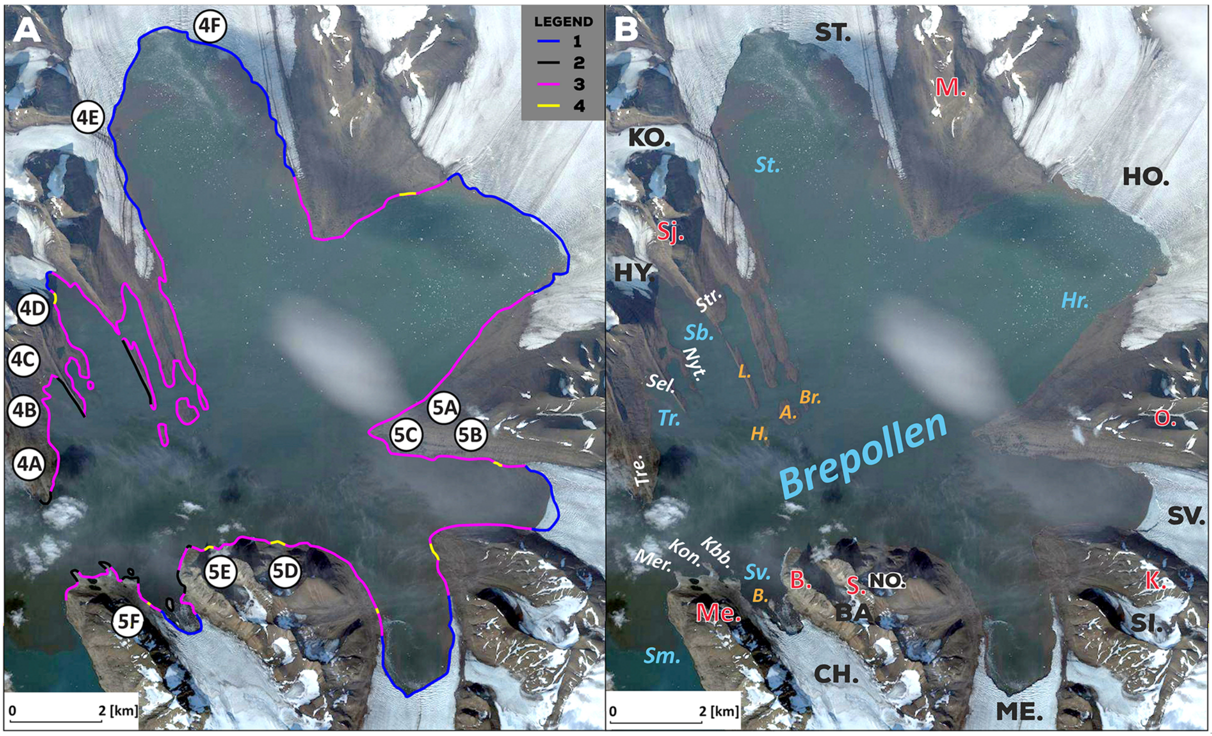

Figure 3. (A) Paraglacial coastal systems of Brepollen: 1, ice cliffs; 2, rocky coasts; 3, coasts formed along abandoned glacial landforms or ice cliffs; 4, fluvial deltas and intertidal flats. Numbers in white circles refer to images of selected paraglacial coasts in Figures 4 and 5. (B) Names and locations of glaciers, mountains, capes, embayments and islands used in the text. Glaciers (black letters): H. – Hyrnebreen; K. – Krohnebreen; ST. – Storbreen; HO. – Hornbreen; SV. – Svalisbreen; SI. – Signybreen; M. – Mendelejevbreen; B – Bautabreen; N – Noname glacier; CH. – Chomjakovbreen. Mountains (red letters): Sj. – Strykejrenet; M. – Mezenryggen; O. – Ostrogradskijfjella; K. – Kinnhøgda; S. – Starostinfjellet; B. – Bautaen. Capes (white letters): Tre. – Treskelen; Sel. – Selodden; Nyt. – Nytangen; Mer. – Meranpynten; Kon. – Konglomeratodden; Kbb. – Konglomeratnabben; Str. – Strykejernsodden. Embayments (light blue letters): Tr. – Treskelbukta; Sb. – Selbukta; St. – Storbukta; Hr. – Hornbukta; Sv. – Svovelbukta; Sm. – Samarinvågen. Islands (orange letters): H. – Hornholmen; L. – Longøya; A. – Ammonittøya; Br. – Breholmen; B. – Bautaholmen. Map background LAND INFO/DigitalGlobe 2016 (Combination of images from 2016/08/22 and 2016/08/24) [Colour figure can be viewed at wileyonlinelibrary.com]

a stream mouth system developed by a glacier river draining the eastern part of Storbreen. The river originates from a supraglacial channel network covering the eastern lobe of Storbreen and forms a glacial lake between the lateral moraine belt and the western slopes of Mezenryggen (Figure 3B). Sediments derived from lake drainage and erosion of CSRs on the coastal plain supply river sediments to the mouth, forming well-developed mouth bars separating small lagoons. Towards the Hornbreen front, a narrow beach is incised by a small cove formed by the submergence of the low-lying network of kettle lakes. Approximately 1 km from the current position of the Hornbreen ice front, the coast is dissected by three deltas fed by glacier streams. Based on aerial photographic evidence, streams that were formed less than 20 years ago already show a well-developed braided-channel network and have incised through a series of CSRs and eskers. In the southeastern part of the bay formed by the retreat of Hornbreen, we have mapped a previously undescribed coastal environment where a narrow beach system is fed by slumping of glacial drift from a debris-covered glacier snout. This mode of sediment supply dominates ~500 m length of the 'Hornbukta' shoreline; most of the shoreline (2 km length of a linear beach system) is fed by erosion and downwasting of moraines, CSRs and eskers (Figure 5A). The northern shores of a bay exposed by the recession of Svalisbreen are exposed to the longest fetch from the Greenland Sea. The geomorphological effects of strong longshore drift are well-developed barriers and spits along the 3 km-long coastal section. The coast is provided with an excess of glacial sediments from a rapidly eroding lateral moraine formed by the retreat of Svalisbreen from the southern slopes of Ostrogradskijfjella (Figure 5B). The area between the moraine and present coast is largely ice-cored and covered by networks of CSRs and numerous recessional moraines. Inter-moraine depressions are filled by kettle lakes (Figures 5B and C). A significant volume of glacial sediments is delivered to the coast by direct undercutting of ridges or breaching of lake shores by wave erosion. Large fluxes of glacial sediments, together with favourable longshore current circulation, result in accumulation of long (200–300 m) curved spit systems that provide enough protection for the formation of lagoons in the bay (Figure 5C). Most of the spits are breached in places by ephemeral streams draining kettle lakes. Another distinctive coastal landform developed close to the Svalisbreen margin is a delta system deposited by a stream that originates in a small hanging valley on the southern slopes of Ostrogradskijfjella. Adjacent to this delta are several pocket beaches formed by direct sediment supply from the glacier surface. Landforms present on the southern shores of the bay exposed by Svalisbreen retreat include narrow beaches reworked from small recessional moraines, representing a sediment-starved coastal system.

Signybreen delta–Merapynten coastal system

This coastal sector, located at the southern side of Brepollen, is similar to previously observed paraglacial coastal systems in Svalbard, where coasts evolve in response to glaciofluvial sediment pulses released by land-terminating, valley-type glaciers (e.g. Zagórski *et al.*, 2012; Bourriquen *et al.*, 2018; Strzelecki *et al.*, 2018). Rivers draining glacierized catchments of

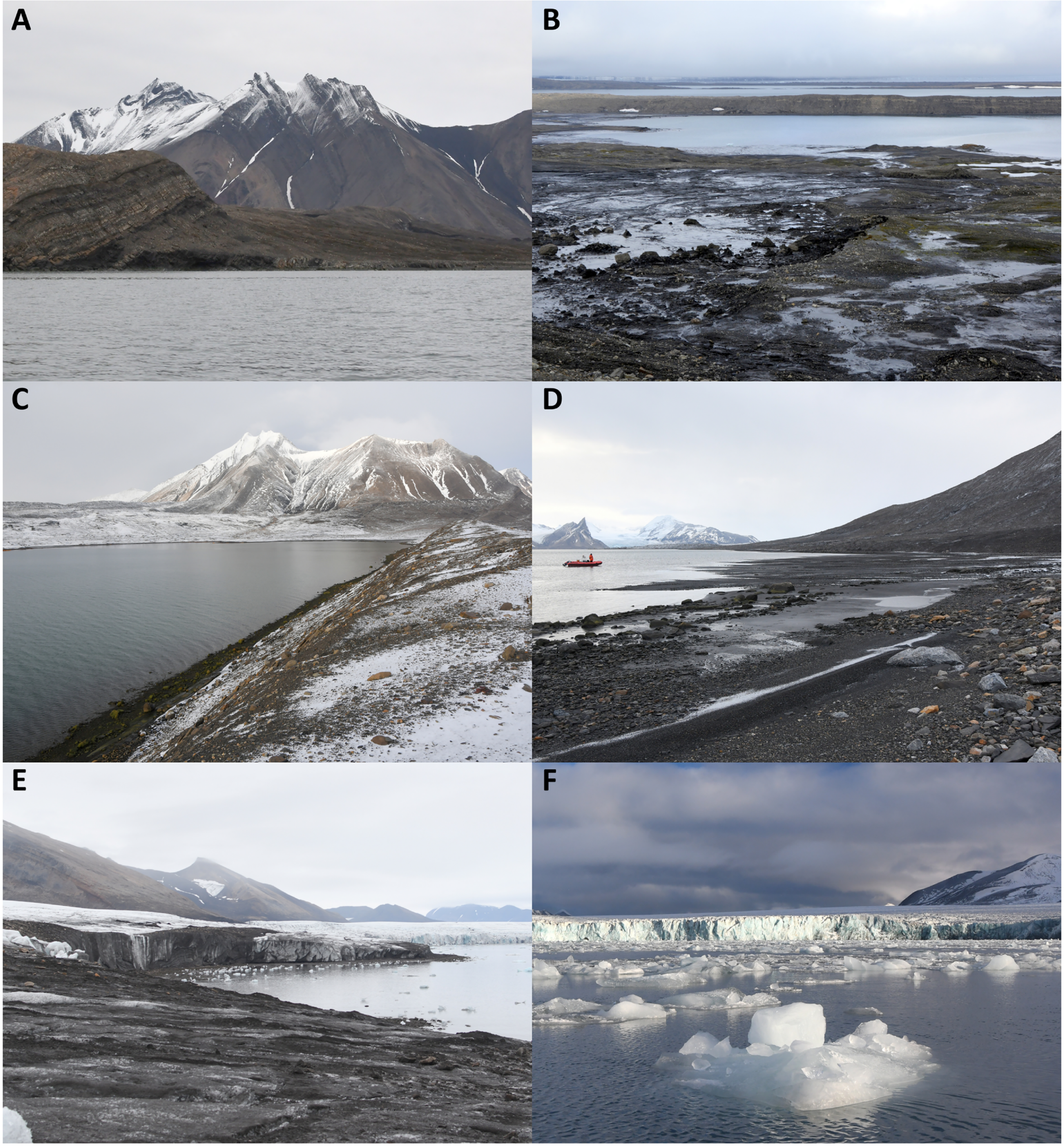

Figure 4. Examples of Brepollen paraglacial coastal systems between Treskelen peninsula and Storbukta. (A) Rocky cliffs along the eastern coast of Treskelen peninsula covered with thin layer of glacial deposits. (B) Young beaches and lagoons formed along degraded glacial landforms and CSRs dissected by network of small lakes in inner Treskelbukta. (C) Narrow beach formed along western coast of Selodden. (D) Prograding tidal flat in Selbukta. (E) Young paraglacial beaches fed by deposition of glacial sediments from the ice cliff of joint snouts of Krohnebreen and Storbreen. (F) Ice cliff of Storbreen. Check Figure 3A for location of images (photos P. Zagórski 2015–2018). [Colour figure can be viewed at wileyonlinelibrary.com]

Signybreen, Bautbreen and Noname glacier (covering the northern slopes of Starostinfjellet) are major sediment feeders to the southern Brepollen coast. All three rivers have accumulated delta systems with well-developed mouth–bar systems (Figures 5C and D). A significant role in sediment delivery from the mountain slopes of Starostinfjellet is played by dozens of ephemeral streams. Most of these originate from local snow patches or are fed by remnants of glacier ice (e.g. Mendelejevbreen), still buried under slope deposits. In this sector of Brepollen, rocky paraglacial shorelines are also present, where eroded bedrock is revealed following retreat of Chomjakovebreen (Svovelbukta). Here, the irregular shape of the shoreline reflects a strong bedrock structural control. Bedrock outcrops follow the axes of three capes (Meranpynten, Konglomeratodden and Konglomeratnabben). The exposed bedrock shore platform surface is discontinuously covered by boulder beaches, where boulders and rock fragments are delivered by rockfall from destabilized rocky slopes of the Bautaen and Meranfjellet massifs. Partly submerged rocky outcrops form several skerry islands along the shores of Svovelbykta

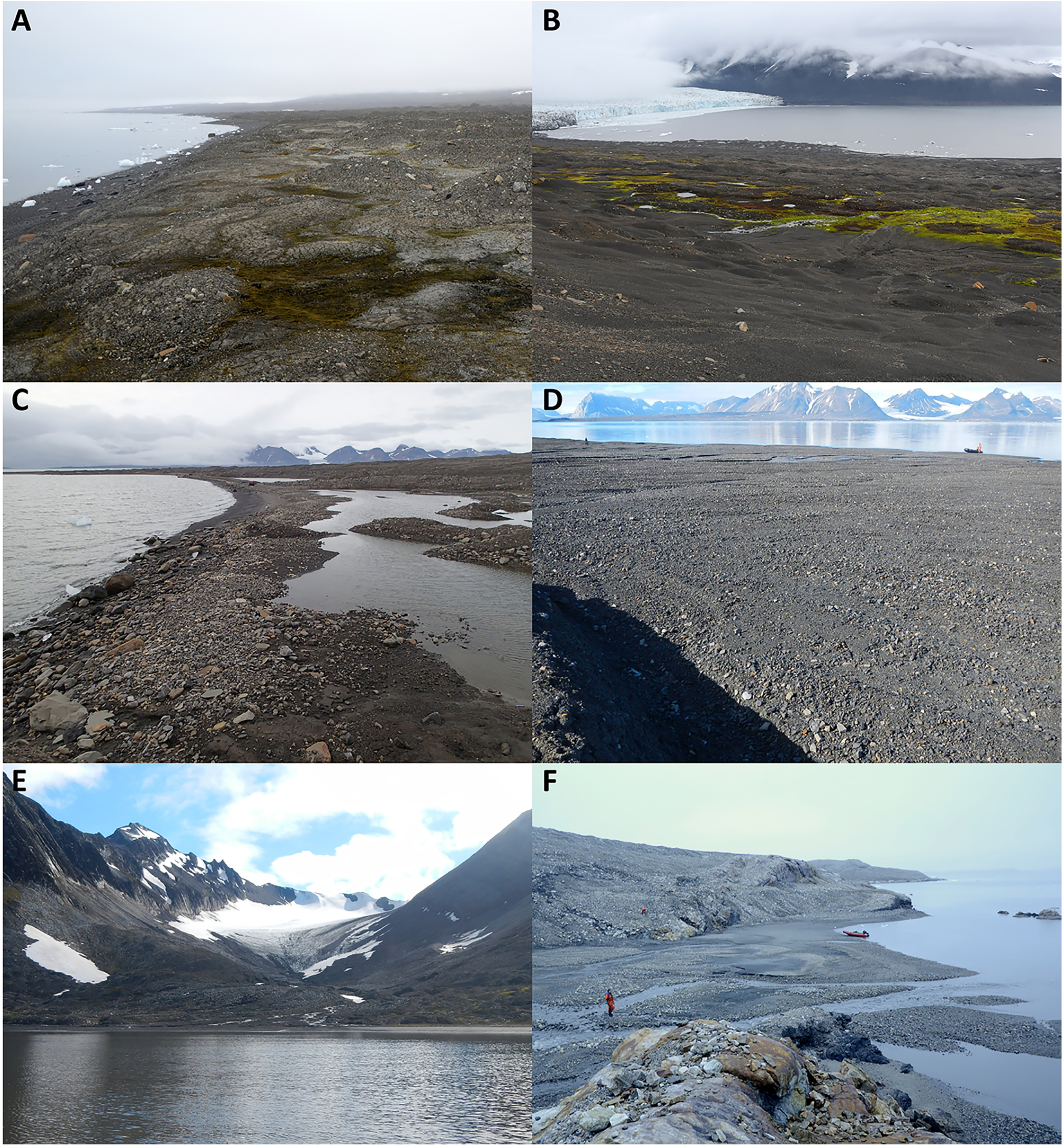

Figure 5. Examples of Brepollen paraglacial coastal systems between Hornbukta and peninsula and Svovelbukta. (A) Southern coast of Hornbukta with degraded hummocky moraine landscape. (B) Coast exposed by the retreat of Svalisbreen with well-developed barriers and spits with sediment supply from degrading glacial landforms (CSRs). (C) Lagoons and spits along northern coast of bay exposed by Svalisbreen. (D) Fluvial delta formed by Noname glacier river along southern coast of Brepollen. (E) Delta system and beaches supplied in sediments by Bautabreen glacier river. (F) Rocky coasts intersected by prograding deltas recently exposed from Chomjakovbreen in Svovelbukta. Check Figure 3A for location of images (photos P. Zagórski and W. Szczuciński 2015–2018). [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 5F). Bautaholmen – the largest island exposed by the retreat of Chomjakovbreen – is also rocky and almost completely scoured of glacial sediments.

New Paraglacial Coastal Landscapes

The deglaciation of Hornsund fjord and associated opening of the new bay of Brepollen throughout the 20th century led to the exposure of over 85 km of new shorelines and also formed a mosaic of new and dynamically evolving paraglacial coastal systems characterized by high sediment mobility. In comparison with models of mature paraglacial coastal system evolution known from Atlantic Canada, the northeast United States, Ireland, Great Britain, the Baltic region and New Zealand (e.g. Forbes and Syvitski, 1994; Forbes *et al.*, 1995; FitzGerald and van Heteren, 1999; Orford *et al.*, 2002; Reimann *et al.*, 2011; Hein *et al.*, 2012; Knight and Harrison, 2018), the recently formed paraglacial coasts of Svalbard – such as those along Brepollen – are still controlled by active glacier systems. Their dynamics may not fit with these previously proposed models, which focus on changes in sediment yields over long (centennial to millennial) time periods (e.g. Ballantyne, 2002). The presence and proximity of glaciers in Svalbard is a key difference in coastal morphodynamic response between polar and mid-latitude paraglacial coastal systems. In most of the mid-latitude examples, coastal morphodynamic responses are linked to sediment supply released by erosion of pre-existing (legacy) glacial sediment bodies, and commonly driven by sea-level change.

In Svalbard, the state of the glacier system and its sediment productivity determines the amount and location of sediment delivery to the coast. Previous coastal studies in Svalbard have shown the strong relationship between rates of coastal progradation (mainly delta growth) and glaciofluvial activity (e.g. Bourriquen *et al.*, 2016; Strzelecki *et al.*, 2018). Similar observations were made along the coasts of Greenland, where rapid retreat of glaciers not only exposed new lands but also released significant amounts of sediment, leading to progradation of delta systems (Bendixen *et al.*, 2017). Calving of Greenlandic glaciers can also produce extreme waves, over 10 m high, that are powerful enough to erode glacial landforms or beaches (Nielsen, 1992; Lüthi and Vieli, 2016). This can lead to substantial degradation of paraglacial coastal landscapes. No similar study exists on the impact of these waves on Svalbard paraglacial coasts.

Glacier surges reported from Mendelejevbreen, Storbreen, Hornbreen and Svalisbreen over recent decades, and contributing to the Brepollen catchment (Błaszczyk *et al.*, 2013), are another extreme glacial event that have potential for coastal zone transformation. Although an advancing glacier can push beach sediments in front of its snout (e.g. Qiu, 2017), we have not mapped any pushed beach landform along the affected coasts. This may mean that any surge-related beach landforms and sediments were rapidly eroded away soon after the event, or that the surge event accumulated a small amount of new sediments along the coasts. This suggests the ephemeral nature of post-surge coastal landforms and raises questions about paraglacial coastal system relaxation after extreme events such as surging, or by tidewater glacier oscillation.

In other parts of the archipelago, glacial surges had much stronger impact on coastal zone development. For instance, the surge of Fridtjovbreen, between 1991 and 2002, is a perfect example of the significance of extreme glacial processes on the resupply of sediments to the coast. A study by Lønne (2006) showed that the surge deposited a subglacial thrust moraine on top of the post-LIA beach, which was developed from ice-cored moraine sediments between 1936 and 1990. One of the best sites to observe how hummocky moraines left by the surge are reshaped into paraglacial beaches and spits was reported from Coraholmen Island by Farnsworth *et al.* (2016) in Ekmanfjorden. The number of well-developed storm ridges and complexity of spit system morphologies found along the banks of the island contrast with narrow and poorly sorted beaches dominating along Brepollen. This case illustrates the significance of the length of the paraglacial period where the glacial landscape is exposed to the constant operation of non-glacial processes. Coraholmen's shores have been remodelled by waves and tides since the end of the 19th century, and local beaches have been recycling glaciogenic deposits left by the Sefströmbreen surge ca. 1890.

Some sections of Brepollen coast, in particular those exposed by Hornbreen and Svalisbreen, resemble the early stages of development of coastal land systems as mapped by Lovell *et al.* (2018) in Van Keulenfjorden. In our opinion, the terrestrial margins of Nathorstbreen (Nordre and Søre Nathorsmorenen) represent a unique type of post-surge paraglacial landscape with former (LIA and post-LIA) accumulative coastal systems (beaches, deltas and barriers) fed by glacial rivers overridden during the 2008–2016 surge. The 21st-century glacier advance remodelled fjord shores and accumulated a thick layer of hummocky moraine on former outwash plain coast beaches.

The work of Lovell *et al.* (2018) also revealed a new glacial-derived coastal environment – a partly submerged mud apron system, characterized by flat and muddy shoals with numerous tidal channels and pits left after melting of stranded icebergs. We have not discovered any similar coastal feature in Brepollen. Contrary to the Van Keulenfjorden coasts, some features of the Trygghamna coastal landscapes recently depicted by Aradóttir *et al.* (2019) on a glacial geomorphology map can also be found in Brepollen. For instance, the coastal zone-fed glacigenic sediments from erosion of the CSR field between Protektorbreen and Harrietbreen are congruent to the section of CSR coasts in the marginal zone of Svalisbreen (Figure 5B).

The current rates of glacial sediment transfer in freshly activated sediment cascades along Brepollen, dominated by downwasting of steep slopes and relatively short stream lengths, were capable of forming beach, spit and lagoon systems very quickly (shorter than decades) after initial ice retreat. Field observations show that this paraglacial geomorphic signature is strongly controlled by the presence and geometry of rocky outcrops. In most of the coves between Treskelpynten and Breholmen, rocky promontories have provided anchor points for narrow and fragile barriers or spits. As noted by Strzelecki *et al.* (2018), bedrock topography is also one of the key controls on sediment storage capacity in Svalbard coastal plains.

Most of the observed rocky landforms in Brepollen – including skerry islands, cliffs and shore platforms – were smoothed and planated by glacier erosion. Currently, those fresh rock surfaces are affected by waves, tides and subaerial weathering by wetting/drying and salt intrusion (e.g. rocky coasts in outer Hornsund: Lim *et al.*, 2020). However, the efficiency of these processes in geomorphic change is still unknown. The only known examples of rocky paraglacial coastal systems in Svalbard had been reported from Billefjorden, where Strzelecki (2011) mapped a cliffed coast of recently exposed roches moutonnées and Ewertowski *et al.* (2016) distinguished sections of ice-moulded bedrock coasts in front of the Nordenskioldbreen.

Another unknown factor is the role of coastal permafrost in increasing (where present) or decreasing (when thawing) shoreline stability or affecting sediment yield from the coastal hinterland (e.g. Lantuit *et al.*, 2012). No research has been focused on the permafrost distribution along recently deglaciated coasts of Svalbard fjords. It is likely that deglaciation of Brepollen (<80–100 years) was too recent to allow development of coastal permafrost. In nearby Hornsund fjord, geophysical surveying of the coastal zone by Kasprzak *et al.* (2017) revealed a lack of frozen ground conditions in rock-dominated capes and limited possibility for coastward aggradation of permafrost due to seawater influence. Such a lack of frozen ground conditions is an important difference between the coasts of High Arctic archipelagos (e.g. Svalbard, Greenland) and Siberian or northwest Canadian/Alaskan counterparts where the state of permafrost controls coastal stability (Overduin *et al.*, 2014).

Wider Context and Future Research Directions

Understanding the evolution of deglacierizing coasts is an important research priority in the context of ongoing climate change and glacier retreat, in particular along tidewater margins in the High Arctic where glaciers and coastlines meet, but also along much lengthier sediment transport paths from interior mid-latitude mountains (Knight and Harrison, 2014). This case study from Svalbard can be used as an exemplar to consider short timescale (10^{-1} to 10^{2} years) coastal responses to ice retreat. This case study is important because it highlights the varied rates and styles of geomorphic change, and differences between rocky and sedimentary coasts, even within one small emergent embayment, and the critical role of glaciological controls on coastal response, which has not been previously identified. Further, this case study also fills a gap in existing paraglacial models that are focused on much longer timescales. A key discussion point is the longevity (permanence) of the coastal landforms identified and discussed in this study. This preliminary work shows that geomorphic change is rapid and that landforms may be formed and destroyed or reworked over short timescales (years) or in response to short events such as glacier surges. This contrasts with much of the paraglacial coastal literature that emphasizes the longevity of landforms such as moraines or drumlins on glaciated coasts, despite being reworked over thousands of years by coastal erosion (Forbes *et al.*, 1995; Orford *et al.*, 2002; Knight and Burningham, 2014).

The pilot study presented here demonstrates the richness of landforms and processes that have been activated along recently exposed paraglacial coasts of Brepollen, and this has global-scale relevance with respect to how paraglacial coasts respond to deglacierization, both now and during the Late Glacial.

Future research directions therefore include:

1 Coastal sediment systems and budgets, and their geomorphic expressions along deglacierizing coasts.
2 The role of extreme events (hazards) during ice retreat, their role in coastline transformation and risk to human populations.
3 Ecological responses to paraglacial coastal change, including for biodiversity and the carbon cycle.

Such research directions can help evaluate the sensitivity of paraglacial coasts to present global change, and inform on the evolutionary trajectories of paraglacial coasts of the past.

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Author Contribution

MCS designed the study, guided the intellectual direction of the research and wrote the paper. WS led a wider project on post-LIA fjord evolution in Svalbard and groundtruthed the observations, together with AD, who also provided GIS calculations and figures. PZ helped with the fieldwork and archival images search. JK developed the discussion on wider paraglacial environment context. JD provided insight into glaciological changes and evolution of the southern Svalbard landscape.

Data Availability Statement

The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest Statement

The authors declare no conflict of interest in the work undertaken in this manuscript.

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