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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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Running head: New paraglacial coasts of Brepollen, Svalbard
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.

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., Malecki, 2016; Martin-Moreno, Álvarez, & Hagen, 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; Rachlewicz, 2009, 2010; Mercier et al., 2009; Szczuciński, Zajączkowski, & Scholten, 2009; Ewertowski & Tomczyk 2015; Strzelecki, Long, & Lloyd, 2017; Senderak, Kondracka, & Gądek, 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 then can 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; Weckwerth, Gren, & Sobota, 2019; Ewertowski et al., 2019).

Previous studies on the evolution of paraglacial coasts in Svalbard have predominantly focused on the interplay between coastal change and glaci fluvial sediment supply from retreating land-terminating glaciers (e.g. Mercier & Laflly, 2005; Étienne, Mercier, & Voldoire., 2008; Zagórski, 2011; Zagórski, Gajcy, & Demczuk 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 limited previous studies, little is known about coastal environments and dynamics 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 km out of 3587 km) of the archipelago total shoreline length (e.g. Błaszczyk, Jania, & Hagen, 2009). Recent years brought a major advance in glacial landscapes mapping and transformation of marginal zones of tide-water glaciers in 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 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 photo-interpretation of an historical aerial imagery collection (1936 – 2011) provided by 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 20th century 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 that in the 21st century accelerated to almost 2 km² loss per year (e.g. Błaszczyk, Jania, & Kolondra, 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). 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 1). 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 emergent rocky capes and coves have a north-south orientation (Moskalik, Błaszczyk, & Jania, 2014).

It had been previously 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 is 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, Wojtysiak, & Moskalik 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 constitute ~30% of bay area and has maximum water depths in excess of 140 m. 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 ground-truthed 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 the 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:

1. **Treskelen peninsula – Breholmen coastal system**

   This is the most diverse coastal system of the analysed region, characterised by numerous embayments and islands with a dominant bedrock control but covered by a relatively thin layer of glaciogenic deposits (Figure 4A). Coastal geomorphological features include gravel-dominated barriers, spits, lagoons, coarse-sand beaches and small prograding tidal flats are 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, and fragmentation of the shoreline by elongated rocky ridges which define capes (Selodden, Strykejernsodden) or the cores of small islands (Longøya, Ammonitttoya, Hornholmen, Breholmen) also break 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 have also 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. 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 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 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).

2. 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 4 F). 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 cover with CSRs, eskers and many hundreds of small kettle lakes (Figure 4A). A major feature of this coastal section is 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 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 air photo 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 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 (Figure 5 B-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 provided 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 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.
3. **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 Signybreen, Bautbreen and Noname glacier (covering 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 (Figure 5C,D). A significant role in sediment delivery from mountain slopes of Starostinfjellet is played by dozen 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 (Svoovelbukta). Here, the irregular shape of the shoreline reflects a strong bedrock structural control. Bedrock outcrops follow the axes of three capes (Meranpynten, Konglomeratodden, 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 Bautaen and Meranfjellet massifs. Partly-submerged rocky outcrops form several skerry islands along the shores of Svoovelbykta (Figure 5 F). 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, northeast USA, Ireland, Great Britain, the Baltic region and New Zealand (e.g. Forbes and Syvitski, 1994; Forbes et al., 1995; FitzGerald & van Heteren, 1999; Orford, Forbes, & Jennings, 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 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 events 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, surge of Fridtjovbreen, between 1991-2002, is a perfect example of the significance of extreme glacial process on re-supply of sediments to the coast. Study by Lønne (2006) showed that the surge deposited a subglacial thrust moraine on top of post-LIA beach, that 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 were reported from Coraholmen Island by Farnsworth et al. (2016) in Ekmanfjorden. The number of well-developed storm-ridges and complexity of spit systems...
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 paraglacial period where glacial landscape is exposed to the constant operation of non-glacial processes. Coraholmen shores are remodelled by waves and tides since the end of 19th century and local beaches have been recycling glaciogenic deposits left by Sefströmbreen surge ca. 1890.

Some sections of Brepollen coasts, in particular those exposed by Hornbreen and Svalisbreen, resemble early stages of development of coastal landsystems mapped by Lovell et al. (2018) in Van Keulenfjorden. In our opinion, terrestrial margins of Nathorstbreen (Nordre and Søre Nathorssmorenen) represents a unique type of post-surge paraglacial landscape with former (LIA and post-LIA) accumulative coastal systems (beaches, deltas, 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 coasts beaches.

Work of Lovell et al., (2018) revealed also a new glacial-derived coastal environment – partly submerged mud apron system, characterized by flat and muddy shoal with numerous tidal channels and pits left after melting of stranded icebergs. We have not discovered similar coastal feature in Brepollen. On the contrary to Van Keulenfjorden coasts, some features of Trygghamna coastal landscapes recently depicted by Aradóttir et al., (2019) on glacial geomorphology map can be also found in Brepollen. For instance, coastal zone fed in glacigenic sediments by erosion of CSRs field between Protektorbreen and Harrietbreen are congruent to section of CSRs- coasts in marginal zone of Svalisbreen (Fig.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 cliffed coast of recently exposed roches moutonées 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. Overduin et al., 2014). 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 emphasises 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 deglaciation, 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;

and (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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at the University of Wrocław. M.C.S wrote a paper as a NAWA Bekker Programme Fellow (PPN/BEK/2018/1/00306) at Alfred Wegener Institute in Potsdam.

Author contribution
M.C.S designed the study, guided the intellectual direction of the research and wrote the paper. W.S. led a wider project on post-LIA fjord evolution in Svalbard and ground-truth the observations together with A.D., who also provided GIS calculations and figures. P.Z. helped with the fieldwork and archival images search. J.K. developed the discussion on wider paraglacial environment context. J.D. provided insight into glaciological changes and evolution of southern Svalbard landscape.

Data Availability Statement: The data sets used and/or analyzed 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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<table>
<thead>
<tr>
<th>Stages</th>
<th>Period</th>
<th>Processes and emergent patterns of coastal development</th>
<th>Brepollen area (km²)</th>
<th>Total coastline length (km)</th>
<th>Ice-cliff coastline length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage I</td>
<td>1920–1940</td>
<td>Exposure of Treskellen peninsula and the beginning of formation of Treskelbukta in the northern part of the new bay. In the south, Samaribreen became divided from the major tidewater glacier system and another new bay started to form (Samarinvågen) at the entrance to Brepollen.</td>
<td>~9.5</td>
<td>11.5</td>
<td>8.5</td>
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<tr>
<td>Stage II</td>
<td>1940–1960</td>
<td>Full exposure of Treskelbukta and beginning of formation of Selbukta with a calving front of Hyrneweabreen 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, Breholm) in the north and exposed steep slopes of Starostintjellet in the south, where one of the few land-terminating glaciers in the study area is located (Bautabreen).</td>
<td>~25.5</td>
<td>29</td>
<td>11</td>
</tr>
<tr>
<td>Stage III</td>
<td>1960–1980</td>
<td>The retreating front of the tidewater glacier exposed almost the entire central part of Brepollen and reached the base of the slopes of Ostogradskijfjella. 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 Svoelbukta experienced significant enlargement. During this period, the presence of sedimentary and rocky coasts limited the length of ice-cliff coasts in the fjord.</td>
<td>~40</td>
<td>43</td>
<td>21</td>
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<tr>
<td>Stage IV</td>
<td>1980–2000</td>
<td>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 Storbreen and Hornbreen separated, forming two large coves. The extension of Svoelbukta 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 Svoelbukta 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.</td>
<td>~80</td>
<td>67</td>
<td>14</td>
</tr>
<tr>
<td>Stage V</td>
<td>2000–present</td>
<td>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).</td>
<td>~100</td>
<td>85</td>
<td>19</td>
</tr>
</tbody>
</table>
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) https://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.
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).
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 Figure 4 & 5.


Capes (white letters): Tre. – Treskelen; Sel. – Selodden; Nyt. – Nytangen; Mer. – Meranpynten; Kon. – Konglomeratoddten; Kbb. – Konglomeratnabben; Str. – Strykejernsodden. Embayments (light blue letters): Tr. - Treskelbukta; Sb. - Selbukta; St. - Storbukta; Hr. - Hornbukta; Sv. - Svoelbukta; Sm. - Samarinvågen. Islands (orange letters): H. – Hornholmen; L. – Longøya; A. – Ammonittøya; Br. – Breholmen; B. – Bautaholmen.
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. Images by Piotr Zagórski (2015-2018).
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. Images by Piotr Zagórski and Witold Szczuciński (2015-2018).
PARAGLACIAL COASTAL SYSTEMS IN BREPOLLEN-NEW BAY IN SOUTHERN PART OF SVALBARD FORMED AFTER POST-LITTLE ICE AGE GLACIER RETREAT