MORPHODYNAMICS OF RECHERCHEFJORDEN ACCUMULATIVE COASTS SINCE THE END OF THE LITTLE ICE AGE

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Abstract: The shores of Recherchefjorden in western Spitsbergen have undergone significant changes during the 20th and early 21st centuries, resulting from the end of the Little Ice Age (LIA) and climate warming. In areas exposed by retreating glaciers, paraglacial processes have had an impact, leading to the development of forms such as spits, lagoons and beaches. The main factors that determine the direction of landform development include wave patterns, the role of longshore currents in material transport, and the state of the fjord's sea/coast ice. Archival materials such as aerial and satellite photos and geomorphological mapping were used to analyse changes in the length of accumulation forms in Recherchefjorden. Nine accumulation areas were identified along the fjord's shores. Longshore currents' primary directions were determined by the arrangement of accumulation forms, flowing southward along the western coast from the Chamberlinelva estuary to Rubypynten, and westward on the eastern outwash plain of Recherchebreen. Material transport along the fjord's eastern coast is mainly towards the south. Following the LIA, the accumulation rate increased, with the highest values recorded in the second and early third decades of the 21st century. Longshore currents shape accumulation forms such as spits and beaches, but they appear intermittently depending on favourable wave and tidal conditions, transforming coasts and accumulating material through longshore drift. These conditions occur periodically and independently of water circulation or tidal currents, allowing accumulation forms to develop in leaps under intensive material supply, ensuring their stability.

Key words: spits, accumulation forms, paraglacial coast, Recherchefjorden, Svalbard

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Introduction

The Arctic Ocean, and thus the Svalbard Archipelago, has undergone rapid climate changes over the past few centuries (IPCC 2021). The climatic conditions prevailing during the Little Ice Age (LIA) resulted in an increase in the area of glacial systems (Martín-Moreno, Allende-Álvarez 2016, Zagórski et al. 2023). Following end of the LIA, there was a gradual warming of the climate since the beginning of the 20th century, particularly in the early 21st century (Christiansen, Ljungqvist 2012). Since the end of LIA, there has been a progressive recession of glacial systems, and episodes of surges have appeared with varying intensities (Zagórski et al. 2023). The consequences of such changes have been alterations in the polar environment, including melting glaciers, melting permafrost and changes in the extent of sea ice. These changes

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also directly affect the coastline of Svalbard. As the glacier surfaces decrease, the deglaciated areas, including coastal zones, are being exposed to the interacting marine and land processes, in these so-called paraglacial coasts (Ballantyne 2002, Forbes, Syvitski 1994, Slaymaker 2011).

The last 20 years of research have shown that Svalbard shoreline to have undergone significant changes due to a combination of factors such us intensified delivery of glaciofluvial sediments, erosion of cliffs and beaches by storm waves and exposure of new shores by retreating glaciers (e.g. Bourriquen et al. 2018, Kavan 2019, Kavan, Strzelecki 2023, Mercier, Laffly 2005, Strzelecki et al. 2017, 2018, 2020, Zagórski et al. 2012). These changes have also resulted in the accumulation of coastal forms, such as spits, bars and tombolos, which are the landforms developed by the deposition of sediment along a coastline.

Accumulation coasts (spits, barriers and beaches with storm ridges) occur, among others, in the Recherchefjorden (Recherche Fjord) region (Harasimiuk 1987, Harasimiuk, Jezierski 1991, Jarosz et al. 2022, Zagórski 2011, Zagórski et al. 2012, 2013). In Harasimiuk and Jezierski's 1991 study, the accumulative coasts in Recherchefjorden were classified as beaches with fully developed profiles, sand bars, tidal flats, or deltas. Recently, a more detailed and comprehensive classification of paraglacial coasts has been developed for this region, which can undoubtedly be considered universal for all polar coasts (Jarosz et al. 2022). In this paper, the fjord coasts were classified based on four criteria: coastal material, genesis and origin, morphological and morphodynamic. The accumulative coasts were classified into three groups:

1. Delta/estuary composed of glaciogenic or fluvial gravel;
2. Aligned coast of a marine origin composed of gravel and sandy deposits; and
3. Spit/lagoon composed of marine sediments.

Despite the increasing number of studies on paraglacial coasts, many issues require more detailed research. There are frequent works presenting quantitative changes in the range of coastal areas (e.g. Bourriquen et al. 2018, Kavan 2019, Zagórski et al. 2020), or qualitative ones describing paraglacial coasts and their types (e.g. Harasiumiu, Jezierski 1991, Jarosz et al. 2022), but there is no work focussing on the evolution of accumulation forms that emerged after the LIA. This paper describes the rate of development and factors that allow the formation and development of paraglacial accumulation forms such as spits. In addition, based on the directions of growth of accumulation forms, the system of coastal currents on the Recherchefjorden was reconstructed.

Study area

Recherchefjorden is located in the north-western part of Wedel Jarlsberg Land in western Spitsbergen, the largest island in the Svalbard Archipelago, and flows into Bellsund (Fig. 1). The fjord is approximately 7 km long, 4–5 km wide and covers an area of 34 km^2 (Moskalik et al. 2018). It has a north–south orientation. The relatively small area and the large diversity of coasts make Recherchefjorden an excellent site for observing processes occurring throughout the Svalbard Archipelago, and in a broader perspective, also in the High Arctic. The shores of the fjord are diverse in terms of their origin and material (Jarosz et al. 2022). The fjord is located within several geological formations, which results in a high diversity of lithology in the area (Birkenmajer 2004, NPI 2016).

The shores of Recherchefjorden are an example of paraglacial coasts significantly shaped by marine processes, including wind and oceanic swells as well as longshore currents. Due to its sheltered location, the interior of the fjord beyond the Lægerneset-Reinodden section (the north-western part of the fjord) is shaped by low-energy waves (Zagórski et al. 2013). In the Bellsund area, dominant winds come from the ENE, WNW and S directions, which is conditioned by the terrain's orography (Mędrek et al. 2014, Zagórski et al. 2013, 2019). The wind wave height reaches up to 1.1 m (Majewski et al. 2016). A particular case is waves generated by storms, which occur increasingly often along the western coast of Spitsbergen. Although most of them occur in winter, those occurring in spring and autumn are the strongest (Wojtysiak et al. 2018). Storms waves strongly affect the coastal zone (abrasion), especially when shore ice forms in late winter (Rodzik, Zagórski 2009, Zagórski et al. 2015).

For the study, sections of the coast grouped in several areas were selected (Fig. 1):

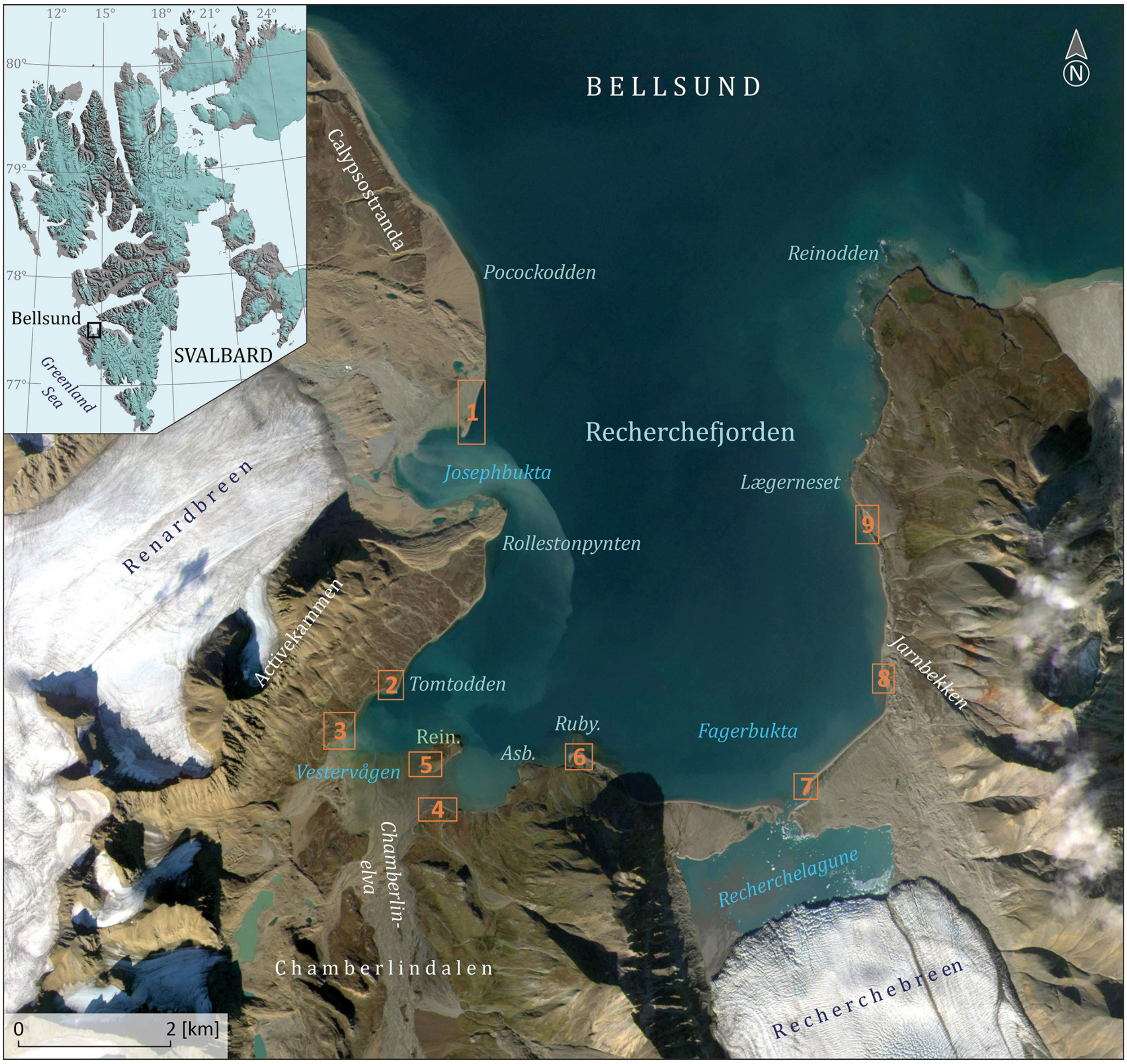

Fig. 1. Localisation of study area: Asb. – Asbestodden, Rein. – Reinholmen, Ruby. – Rubypynten. The orange rectangles denote the location of study areas 1–9. Background: Satellite image, 25 August 2020, Planet Labs, Inc.

Area 1 – the north-western coast of the fjord – a spit closing Josephbukta (Joseph Bay). The area is located in the marginal zone of Renardbreen. The spit began to form in the 1930s/1940s as the glacier retreated from the Josephbukta area. It is currently about 900 m long, with its southern expanded part, which is the subject of this study, measuring 250 m. The spit is adjacent to the frontal moraines of Renardbreen from the north and to the tidal flat formed by the fluvioglacial waters of Renardbreen from the northwest.

Area 2 – the western coast of the fjord in the Tomtodden area. It is a section of the coast with a developed system of storm ridges, 200 m in length. Behind it is a system of raised marine terraces transformed by solifluction processes, which is adjacent to Activekammen (Active Ridge). The hinterland of the central part of the section is an active alluvial cone, with its outlet located in the western part of the area.

Area 3 – the south-western coast of the fjord adjacent to Vestervågen. It is a 400 m long section of the coast where a system of two spits, along with coastal lakes/lagoons, has formed. As in Area 2, there is a system of raised marine terraces transformed by solifluction processes in the hinterland of the coast. There are outlets of two smaller streams in this area. In the south-western part, it is adjacent to the tidal flat of Vestervågen.

Area 4 – the south-eastern part of Vestervågen at the mouth of Chamberlinelva (Chamberlin River). Within the tidal flat of Vestervågen, there is a system of spits that extends over 200 m. It is located in the zone of influence of the active channel of Chamberlinelva from the west. A smaller stream intersects the central part of the spit system.

Area 5 – the southern coast of Reinholmen. This section of the coast, approximately 200 m in length, constitutes the southern coast of the island adjacent to the tidal flat of Vestervågen. Accumulative forms occur on both sides of the island.

Area 6 – the southern coast of the fjord in the Rubypynten area. The cape has a glacial origin and was formed during the surge of Recherchebreen in the first decades of the 19th century. At the beginning of the 20th century, its length was 250 m, but now it has been reduced to approximately 90 m. There is an abrasion platform from the north that emerges from the water during low tide. To the east of this section, there are beaches and fragments of abraded moraines. The entire cape is adjacent to an old, dead cliff of a terrace from the Weichselian and Holocene periods.

Area 7 – the south-eastern coast of the fjord in the area of the Recherchelagune (Recherche Lagoon) outlet to Fagerbukta (Fager Bay). This section, approximately 500 m in length, occurs between two sand cones of Recherchebreen, formed after its surge in the 1940s. The boundary of the cones is formed by the outlet of the lagoon located in front of the glacier. A spit has formed on the eastern cone since 2016.

Area 8 – the south-eastern coast of the fjord in the area of the Jarnbekken (Jarn Stream) estuary. This section is 300 m long and 50 m wide, consisting of a system of storm ridges that adjoin the lateral moraine of the Recherchebreen glacier. To the north of this area is the Jarnbekken estuary.

Area 9 – eastern coast of the fjord located south of Lægerneset. This is a 230 m-long stretch located between currently abraded moraines of Recherchebreen and cliffs of Lægerneset. It is developed in the form of a spit/sandbar, and behind it there is a system of coastal lakes.

Materials and methods

The source data used for the reconstruction of the development of paraglacial accumulation forms can be divided into the following categories (Table 1):

Table 1. Archival data sources used in the study.

Year	Source	Type	Resolution
1936	S36. Norwegian Polar Institute	Oblique aerial images	3/5 m
1948	S48. Norwegian Polar Institute	Vertical aerial image, orthophotomap	3/5 m
1960	S60. Norwegian Polar Institute	Vertical aerial image, orthophotomap	3/5 m
1990	S90. Norwegian Polar Institute	Vertical aerial image, orthophotomap	2.0 m
2009	Google Earth – 20090812114526484GE10332358_004	Satellite image	1.5 m
2011	S2011. Norwegian Polar Institute	Vertical aerial image, orthophotomap	2.0 m
2013	DigitalGlobe – 13AUG17130953-S2AS-010486906030_01_P001	Satellite image	0.5 m
2016	UAV drone photos	Drone photo	0.02 m
2017	DigitalGlobe – 17JUL31184148-S2AS-010486906040_01_P001	Satellite image	0.5 m
2018	DigitalGlobe – satellites.pro/Norway_map#77.531913,14.571261,15	Satellite image	1.0 m
2020	DigitalGlobe – 20JUL31113940-M2AS-013735816010_01_P001/P002; 20JUL31113940-P2AS-013735816010_01_P001/P002	Satellite image	0.5 m
2021	UAV drone photos	Drone photo	0.02 m
2022	UAV drone photos	Drone photo	0.02 m

1. Field geomorphological mapping of land areas,
2. Photographs:
- archival and contemporary,
- oblique aerial – S36, Norwegian Polar Institute (NPI),
- vertical aerial – S48, S60, S90, S2011 (NPI),
3. Computer analysis and statistical compilation:
- land data – DEM computed from drone photos obtained in 2021 and 2022.

The analysis and determination of the coastline extent for individual research areas were carried out in accordance with the methodology presented in the studies of Zagórski (2011), Zagórski et al. (2020) and Jarosz et al. (2022). The main measured element was the position of the storm ridge formed during high-water levels. A precise representation of the coastline was obtained through photogrammetric imagery (UAV - Unmanned Aerial Vehicle DJI Phantom 4). Absolute calibration was achieved using ground control points, whose accurate positions were determined using Global Navigation Satellite System (GNSS) receivers (Leica System 500 SR 530 and Topcon Hiper HR), relative to the reference station (CALYpoint) (Zagórski 2011). The data processing (DEM - Digital Elevation Model, orthophotomap) was conducted using Agisoft Metashape Professional v. 2.0.1. Changes in the accumulative coasts were determined based on the analysis of aerial photographs in GlobalMapper v23.0_PL. The WGS84 – UTM33 coordinate system was used. A comparison of photographs for individual areas allowed for the determination of the axis of the spit for Areas 1, 3, 4, 5, 6, 7 and 8. In other cases, changes were minimal (Area 2) or the form had developed before the analysed period (Area 9). After determining the axis of the spit, the length of the form along the axis was measured. The change in the length of the form over a specific time interval was divided by the number of years in the period, resulting in an annual growth rate of the form $m \cdot a^{-1}$ (meters per annum). Considering the direction of spit development, the dominant direction of longshore currents can be clearly defined. This made it possible to reconstruct the directions of material transport in the fjord.

Results

Area 1

During the LIA period, the Josephbukta area was largely occupied by the Renardbreen (Zagórski et al. 2023). The oldest part of the spit, dating back to before 1936, was a moraine hill that formed in front of the retreating glacier terminus (Fig. 2A). By 1948, the spit was no longer connected to Renardbreen (Fig. 2B). Continuous delivery of material from the destruction of moraines and outwash planes located to the north

Table 2. Changes of length of axis of spit end and annual length change in Area 1 in selected years.

Length of spit axis (a–b)	Relatively to 1936	Relatively to 1936	Previous observation	Previous observation	Annual length change
[m]	[m]	[%]	[m]	[%]	[$m \cdot a^{-1}$]
1936	80.0	–	–	–	–
1948	109.5	36.9	29.5	36.9	2.5
1960*	138.8	73.5	29.3	26.8	2.4
1990*	187.2	134.0	48.4	34.9	1.6
2005*	214.5	168.1	27.3	14.6	1.8
2006*	218.1	172.6	3.6	1.7	3.6
2007*	224.3	180.4	6.2	2.8	6.2
2011	231.1	188.9	6.8	3.0	1.7
2013	236.3	195.4	5.2	2.3	2.6
2016	243.2	204.0	6.9	2.9	2.3
2017	245.3	206.6	2.1	0.9	2.1
2020	253.1	216.4	7.8	3.2	2.6
2021	254.0	217.5	0.9	0.4	0.9
2022	261.2	226.5	7.2	2.8	7.2

*Data source: Zagórski (2011).

caused the spit to elongate to approximately 100 m, with a growth rate of 2.5 m·a^{-1} (Table 2). From 1948 to 1960, there was a progressive growth of the spit axis by approximately 30 m, i.e. 2.4 m·a^{-1} (Table 2). Accumulation also occurred in the north-western part of the spit, where material accumulated on the tidal flat inside Josephbukta (Figs 2B, C). Until 2011, the spit continued to elongate to the south at varying rates, ranging from 1.6 m·a^{-1} in the 1990s to 6.2 m·a^{-1} in 2006–2007 (Figs 2D, E, 3A and Table 2). After 2013, the growth of the spit towards the south weakened compared to previous years; annual growth was up to 2.6 m·a^{-1} in 2020, but dropped to 0.9 m·a^{-1} the following year (Fig. 2F and Table 2). However, changes occurred in the northern part of the spit. Until 2016, moraine sediments were present within the base of the spit termination (Figs 2G, H). However, after 2017, intense storm conditions significantly remodelled this part of the coastline (Fig. 2I). Large amounts of material were transported westwards by the spit, and the aforementioned moraine was destroyed. After a decrease in the spit elongation rate in 2020–2021 to 0.9 m·a^{-1}, in the last observation period (2021–2022) there was a record increase of 7.2 m, and its total length reached 260 m (Figs 2J–L, 3B and Table 2).

Area 2

The development of this part of the coast was mainly influenced by marine and fluvial processes. In 1936, the river mouth was located in the western part of the cape (Fig. 4A). In the following years, there was a progressive accumulation of material towards the south (1960–2021, 35–40 m) (Figs 3C and 4B–H). The sediment was mainly derived from the erosion of coasts located north of Tomtodden and transported southwards by the longshore drift. In addition, in the western part of the area, there was some deposition of fluvial sediment in the estuary (Figs 3D and 4G,H). The shifting of river outflows towards the southwest occurred in all major watercourses between Tomtodden and Rollestonpynten.

Area 3

This section of the coastline features a system of spits, which have shown the most dynamic development compared to other parts of the Recherchefjorden coastline. Initially, in 1936, there was only one spit (S1) (Fig. 5A). By 1960, it had extended towards the southwest by about 30 m (Table 3). Additionally, there was an alluvial cone behind it (Fig. 5B). Another 14 m displacement of the spit (S1) was recorded in 1990 (0.5 m·a^{-1}) (Fig. 5C and Table 3). Material began to accumulate in the place of the former stream mouth that formed the alluvial cone, giving rise to another spit (S2), which was already well developed in 2011 (Figs 5D, E). The growth rate of the spit (S1) increased to 4.9 m·a^{-1} between 1990 and 2013 (Table 3). From then until 2018, the growth rate increased to 5.5 m·a^{-1} (Figs 3E, 5F and Table 3). In 2013, the tip of the spit (S1) almost reached the western alluvial cone, which was one of the two adjoining the tidal Vestervågen flat (Fig. 5E).

Table 3. Changes of length of axis of spit end and annual length change in Area 3 in selected years.

Length of spit axis (a–b)	Relatively to 1936	Relatively to 1936	Previous observation	Previous observation	Annual length change
[m]	[m]	[%]	[m]	[%]	[m·a^{-1}]
Spit 1					
1960	30.8	–	–	–	–
1990	45.1	46.4	14.3	46.4	0.5
2011	148.7	382.8	103.6	229.7	4.9
2013	158.2	415.3	9.5	6.4	4.8
2018	185.5	502.3	27.3	17.3	5.5
Spit 2					
2011	29.9	–	–	–	–
2013	44.9	50.2	15.0	50.2	7.5
2018	76.7	156.5	31.8	70.8	6.4
2020	92.7	210.0	16.0	20.9	8.0
2022	97.8	227.1	5.1	5.5	2.6

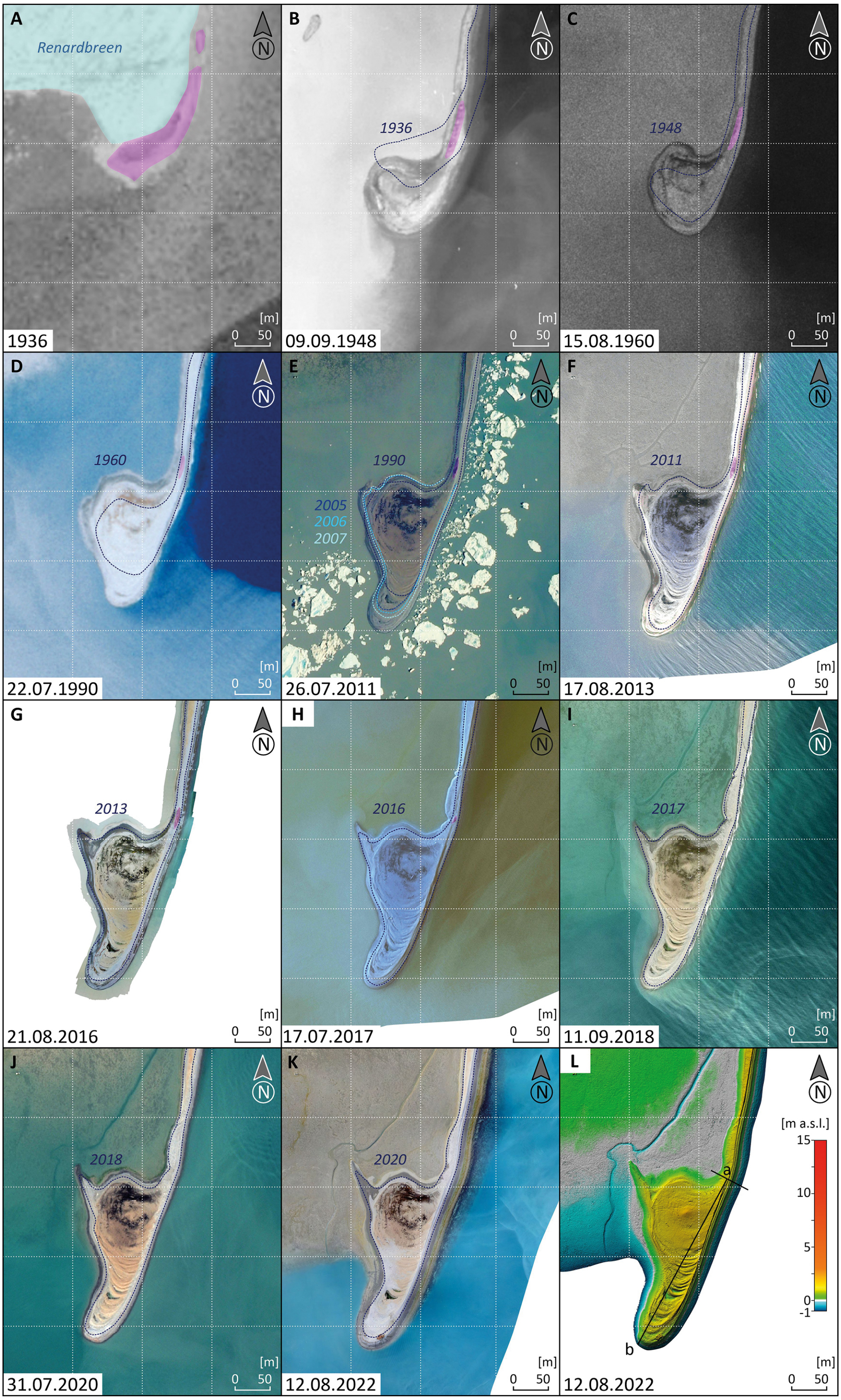

Fig. 2. Shoreline change in a selected section of coast – Area 1: E – 2011 (2005, 2006, 2007 – Source: Zagórski 2011); L – DEM; a–b represents the long axis of the spit (see Table 2). The purple area denotes the moraine surface. For the background source data, see Table 1.

Fig. 3. View on selected section of coast: A,B – Area 1 (Photo: Świtoniak 2008, Zagórski 2022); C,D – Area 2 (Photo: Mędrek 2014, Zagórski 2022); E,F – Area 3 (Photo: Zagórski 2014, 2021); G,H – Area 4 (Photo: Zagórski 2016, 2021); I – Area 5 (Photo: Pawłowski 2016); J – Area 4 and 5 (Photo: Zagórski 2022).

Fig. 4. Shoreline change in a selected section of coast – Area 2. For the background source data, see Table 1.

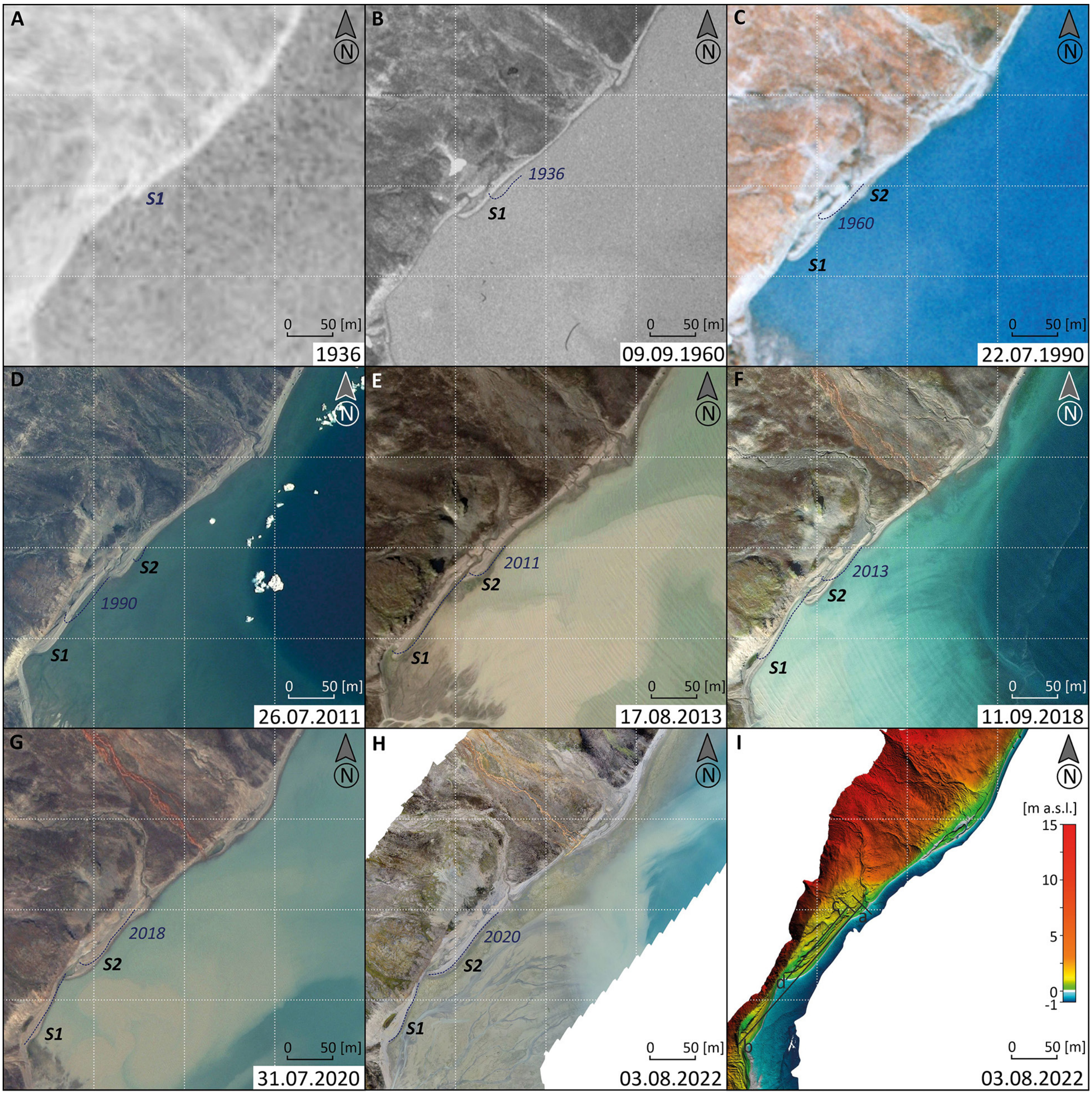

Fig. 5. Shoreline change in a selected section of coast – Area 3: a–b and c–d, respectively, represent the long axes of the spits S1 and S2 (see Table 3). For the background source data, see Table 1.

After 2018, the spit (S1) has become a barrier closing off the lagoon (Figs 3F and 5G–I). The development of spit S2 also involved its continuous extension towards the southwest, growing by approximately 98 m between 1990 and 2022 (Figs 3F and 5C–G). The growth rate was increased to 8.0 m·a^{-1} between 2018 and 2020, before decreasing to 2.6 m·a^{-1} (2020–2022) (Table 3). During this time, an elongated lagoon was formed on the backside of the spit, corresponding to the previous course of the river.

Area 4

The described coastal zone is primarily developed within the tidal flat zone in the Chamberlinelva channel area. It is characterised by the occurrence of several spits. In 1936, there was only one spit, which was intersected in the central part by the mouth of a small river (Fig. 6A). Additionally, to the northwest of the coastal zone, there was a fragment of an old spit or storm ridge. In the following years, it was destroyed,

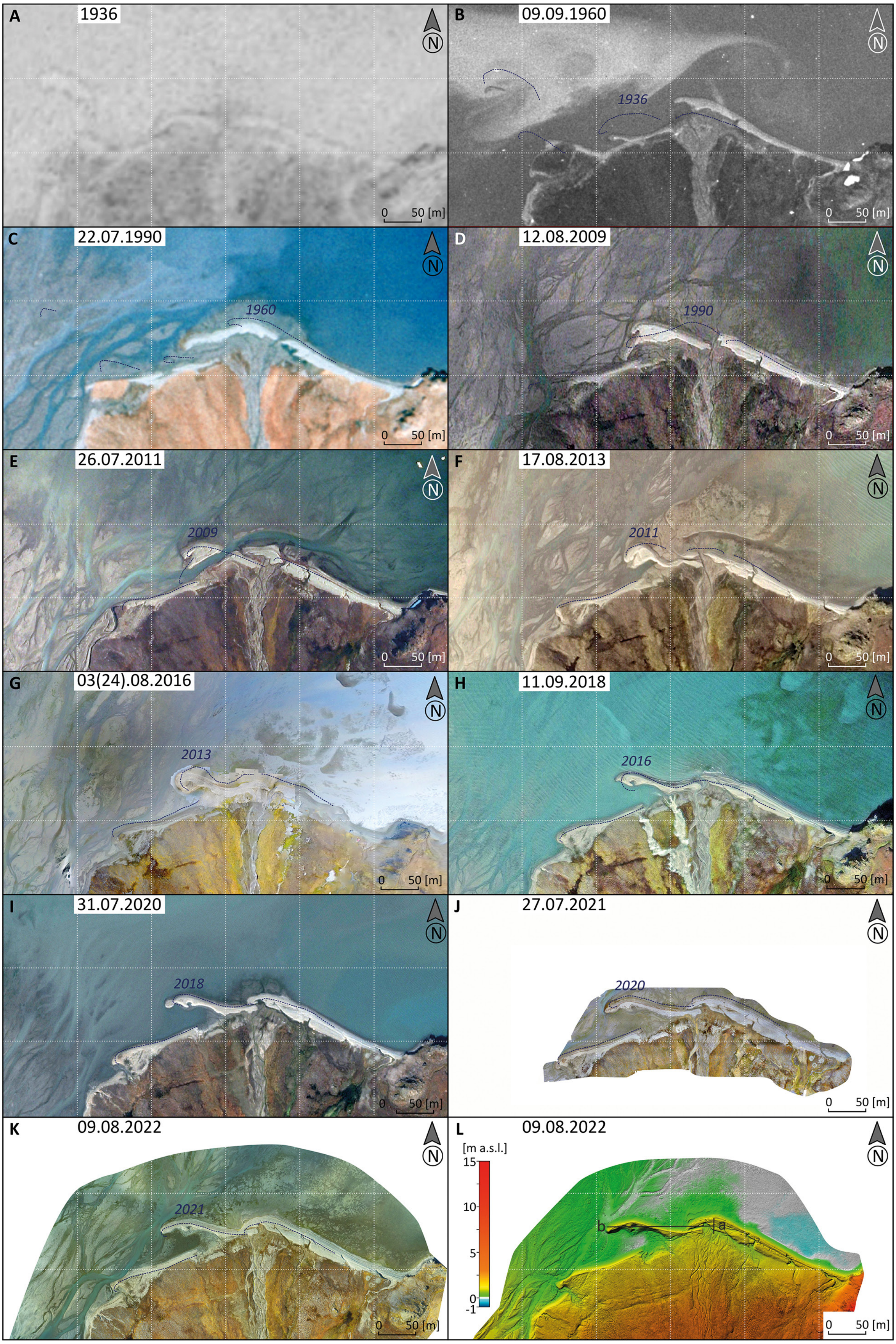

Fig. 6. Shoreline change in a selected section of coast – Area 4: a–b represents the long axis of the spit (see Table 4). For the background source data, see Table 1.

Table 4. Changes of length of axis of spit end and annual length change in Area 4 in selected years.

Length of spit axis (a–b)	Relatively to 1936	Relatively to 1936	Previous observation	Previous observation	Annual length change
[m]	[m]	[%]	[m]	[%]	[m·a^{-1}]
1936	46.4	–	–	–	–
1960	50.7	9.3	4.3	9.3	0.2
1990	116.0	150.0	65.3	128.8	2.2
2009	109.8	136.6	−6.2	−5.3	−0.3
2011	116.9	151.9	7.1	6.5	3.6
2013	117.2	152.3	0.3	0.3	0.2
2016	124.1	167.5	6.9	5.9	2.3
2018	131.6	183.6	7.5	5.7	3.8
2020	138.1	197.6	6.5	4.9	3.3
2021	143.3	208.8	5.2	3.8	5.2
2022	143.4	209.1	0.1	0.1	0.1

and only a small fragment of it remained in 1960 (Fig. 6B). In that year, a group of three spits existed, of which the narrowest, the central one, was destroyed in the following years. The development of the largest and oldest spit is related to the aforementioned river. In 1960, its mouth was located west of the spit, and in the following years, the spit was extended (up to about 116 m at a rate of 2.2 m·a^{-1} up until 1990), and the river mouth moved to the east (Fig. 6C and Table 4). The intersection of the spit on the west initiated the development of another one, which was advancing onto the existing one (Figs 6D–L). The oldest spit was shortened by about 6 m in 2009, which was related to its systematic destruction at a rate of 0.3 m·a^{-1} (Fig. 6D and Table 4). The influence of the smaller river was overlapped by the impact of Chamberlinelva. One of its channels shifted to the east, which caused the intersection of the spit in 2011 (Fig. 6E). Between 1990 and 2022, the largest and oldest spit moved about 27 m, with its growth varying from 0.2 m·a^{-1} in 2013 to 5.2 m·a^{-1} in 2021 (Figs 3G, 6F, H and Table 4). In the last period of 2021/2022, the spit developed only by 0.1 m (Fig. 3H and Table 4). In the western part of the area, located deeper in the mouth of Chamberlinelva, another spit developed. Initially, it developed along a terrace fragment (Figs 6B–F), and after its destruction, it was significantly enlarged, about 30 m between 1960 and 2022 (Figs 3G, H and 6G–K). Further development was limited by the presence of river channels, which removed the accumulating material.

Area 5

The southern coast of the island (Reinholmen) adjoins the Vestervågen tidal flat. Archived materials from before 1990 indicate a fairly stable character of this part of the coast, formed as a narrow strip of beach with a well-developed profile (Figs 7A, B). However, after 1990, there were changes in the accumulative conditions that began to favour the development of a spit towards the southwest (Figs 3I, J and 7C–H). From 1990 to 2018, its length increased to 25 m, with an initial annual growth rate of 0.1 m·a^{-1} (until 2009), followed by about 1 m·a^{-1}. By 2020, the spit had grown by another 14 m, with an annual growth rate of 7.2 m·a^{-1} (Table 5). Similarly, starting in

Table 5. Changes of length of axis of spit end and annual length change in Area 5 in selected years.

Length of spit axis (a–b)	Relatively to 1936	Relatively to 1936	Previous observation	Previous observation	Annual length change
[m]	[m]	[%]	[m]	[%]	[m·a^{-1}]
1990	13.6	–	–	–	–
2009	15.9	16.9	2.3	16.9	0.1
2011	18.1	33.1	2.2	13.8	1.1
2016	23.4	72.1	5.3	29.3	1.1
2018	25.0	83.8	1.6	6.8	0.8
2020	39.3	189.0	14.3	57.2	7.2

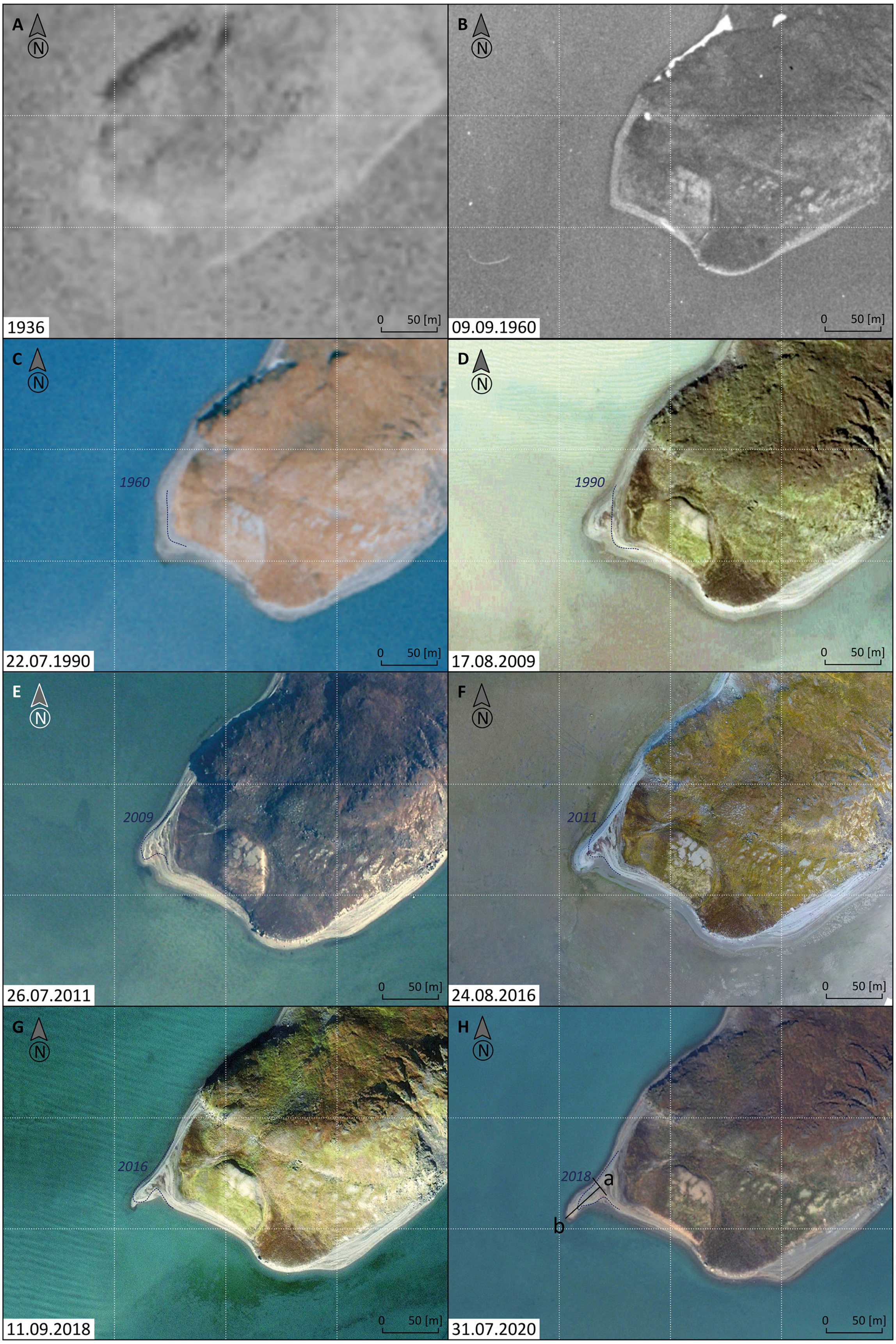

Fig. 7. Shoreline change in a selected section of coast – Area 5: a–b represents the long axis of the spit (see Table 5). For the background source data, see Table 1.

1990, sediment accumulation was observed on the south-eastern coast of the island, where a beach was formed (Figs 3I, J and 7C–H).

Area 6

The formation of Rubypynten is related to the advance episode (surge) of Recherchebreen, which took place in the first decades of the 19th century (Zagórski et al. 2023). At that time, a system of moraine ridges was formed. After that period, the area took on a paraglacial character, with a predominance of marine processes. By 1936, a narrow storm ridge had formed along the cliff formed by the moraine deposits (Figs 8A and 9A). A lake functioned between the fragments of the moraine in the central part of the cape. In the period 1936–1960, there was significant abrasion of the northern part of Rubypynten, by about 100 m (Figs 8A, B). On the eastern side, there was a concave bay, systematically filled with accumulative material in the form of a system of storm ridges. On the western side, a convex beach was formed, also with ridges. A lake continued to function between the fragments of the moraine, whose surface area systematically decreased in subsequent years (Figs 8B–G). The destroyed area to the north was transformed into an abrasion platform (Figs 8E, G). Between 1960 and 1990, the northern part underwent further erosion, amounting to about 10 m. The destroyed moraine divided into two fragments, and the lake, separated from the sea, was only a narrow strip of a storm surge (Figs 8C and 9B). The concave eastern beach was overlaid with sediments from the destroyed moraine. At that time, on the western side, a system of storm ridges in the shape of a spit was formed, which elongated by 66 m from 1960 to 1990, i.e. 1.4 m·a^{-1} (Figs 8B, C and Table 6). In subsequent years, the destruction of the cape continued (from 1990 to 2022, the value of erosion fluctuated between 35 m and 50 m). After 2011, the most significant changes occurred on the western side of the cape, where the spit was continuously extended southward by 31 m, and in 2022, it nearly cut off the bay, leaving only a narrow outflow (Figs 8D–H and 9C). The development of this form was variable; having remained at 0.5 m·a^{-1} until 2011, it subsequently (2018–2020) increased to 6.1 m·a^{-1}, and currently it has reached 3.8 m·a^{-1} (Table 6).

Area 7

After the Recherchebreen surge event in the early 1940s, two outwash plains began to form in front of the glacier (Zagórski et al. 2023). In 1960, there were areas of marine accumulation along the glacier cliff (Fig. 10A). In the following years, as the glacier receded, a lagoon formed between the outwash plain and the glacier cliff. By 1990, the western outwash plain was inactive, while the eastern outwash plain was constantly being built up by the outflow of fluvioglacial waters, which lasted until the mid-1990s (Figs 9D and 10B). From that point on, the coastal zone of the eastern outwash plain was only influenced by marine processes. Around 2010, there was a change in the position of the main outflow channel from the lagoon (Fig. 9E). The zigzag course of the channel was straightened, and the concave part of the coast that had been shaped by the inflow and outflow of water from the lagoon began to be filled with sediment (Figs 10C, D). During detailed geomorphological mapping conducted in 2016, this part of the coast was classified as an aligned coast with a beach (Jarosz et al. 2022). After this period, sediment transport along the northern coast of the eastern outwash plain caused a spit to develop at the base of the concave part of the coast, which extended by almost 208

Table 6. Changes of length of axis of spit end and annual length change in Area 6 in selected years.

Length of spit axis (a–b)	Relatively to 1936	Relatively to 1936	Previous observation	Previous observation	Annual length change
[m]	[m]	[%]	[m]	[%]	[m·a^{-1}]
1960	25.6	–	–	–	–
1990	66.1	158.2	40.5	158.2	1.4
2011	75.8	196.1	9.7	14.7	0.5
2018	87.6	242.2	11.8	15.6	1.7
2020	99.8	289.8	12.2	13.9	6.1
2022	107.4	319.5	7.6	7.3	3.8

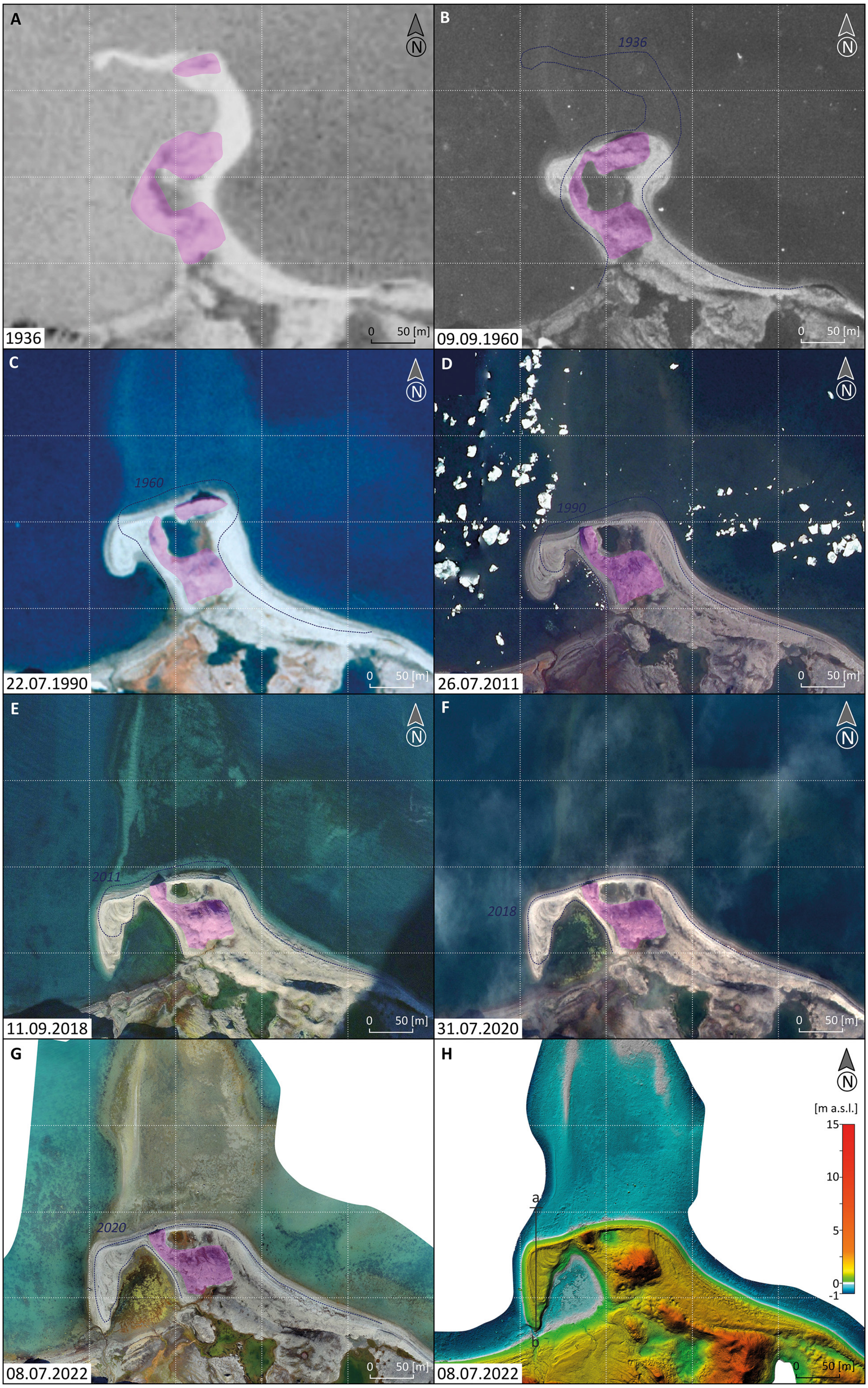

Fig. 8. Shoreline change in a selected section of coast – Area 6: a–b represents the long axis of the spit (see Table 6). The purple area denotes moraine surface. For the background source data, see Table 1.

Fig. 9. View on selected section of coast: A–C – Area 6 (Photo: Hamberg 1898. Source: Alvin; Uppsala University Library; Photo: Demczuk 2009, Zagórski 2022); D–F – Area 7 (Photo: Pękala 1987, Zagórski 2014, 2021); G,H – Area 8 (Photo: Zagórski 2016, 2021); I,J – Area 9 (Photo: Hamberg 1898. Source: Alvin; Uppsala University Library; Zagórski 2021).

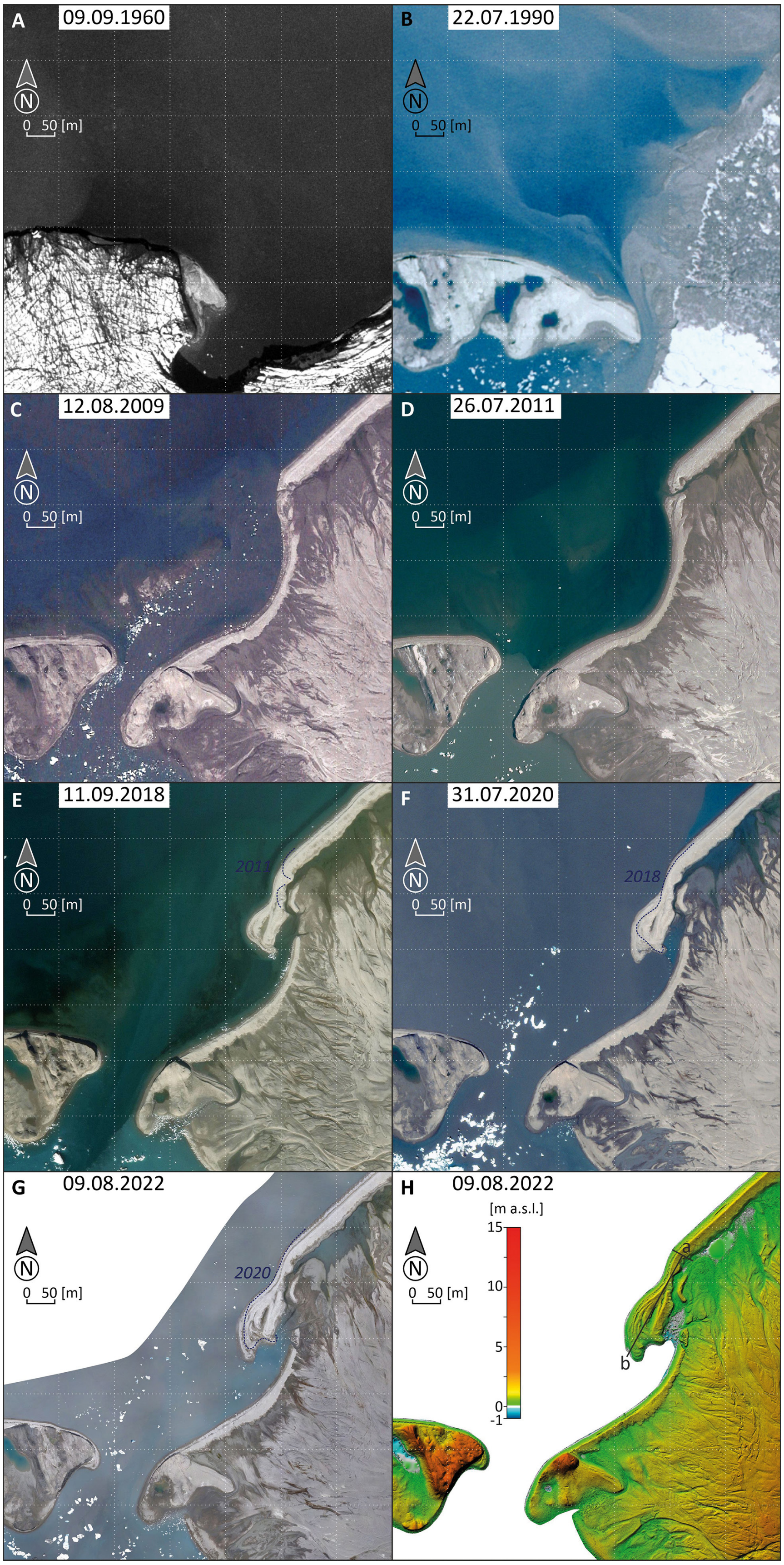

Fig. 10. Shoreline change in a selected section of coast – Area 7: a–b represents the long axis of the spit (see Table 7). For the background source data, see Table 1.

Table 7. Changes of length of axis of spit end and annual length change in Area 7 in selected years.

Length of spit axis (a–b)	Relatively to 1936	Relatively to 1936	Previous observation	Previous observation	Annual length change
[m]	[m]	[%]	[m]	[%]	[m·a^{-1}]
2011	33.1	–	–	–	–
2018	157.4	375.5	124.3	375.5	17.8
2020	191.2	477.6	33.8	21.5	16.9
2022	207.8	527.8	16.6	8.7	8.3

m between 2009 and 2022. The initial accumulation rate was almost 18 m·a^{-1}, and dropped to 8.3 m·a^{-1} in 2020–2022 (Table 7). During this time, the spit continued to grow with the formation of additional storm ridges (Figs 9F and 10E–H).

Area 8

In this region, the coast forms a system of storm ridges adjacent to lateral moraines that were formed during the surges of Recherchebreen in the first decades of the 19th century and in the 1880s (Zagórski et al. 2023). In 1936, a narrow strip of beach was adjacent to the moraine ridge, which in the following years enlarged to the south, by about 87 m by 1960, another 50 m by 1990 and another 30 m by 2020 (Figs 11A–H). The rate of growth was variable; initially it was 3.0 m·a^{-1}, then it decreased to 0.6 m·a^{-1} (2009) and thereafter it increased to 9.8 m·a^{-1} in the last period of growth (2011) (Table 8). The successive stages of beach formation can be traced based on the arrangement of coastal berms, which were built towards the southeast (Figs 9G, H). Material from the destruction of moraines and fluvial cones located to the north of this area was transported by the longshore current flowing to the south.

Area 9

This part of the coast, similar to Area 8, was shaped during the surge of Recherchebreen in the first decades of the 19th century in the form of moraine ridges (Zagórski et al. 2023). Between 1898 and 1936, the surface was shaped by intensive construction of successive storm ridges (Fig. 9I). To the north, it adjoined the cliffs of Lægerneset. By 1936, a complete form of a spit had been formed, along with a lagoon (coastal lake) (Fig. 12A). After 1936, the moraine that limited this section of the coast from the south was destroyed. From that moment on, there was a period of abrasion of the storm riders. As a result, the material was mainly transported southward. During the period from 1936 to 2021, destruction of mainly moraine sediments dominated, while accumulation was observed in the spit zone (Figs 12A–H). In 1936 and since 2009, an estuary has formed in the section adjacent to the southern moraines, connecting the lake with the sea (Figs 12A, D). However, after 1990, stabilisation of the coast with a slight domination of longshore currents from the north can be observed, as evidenced by the movement of the outflow of the internal lagoon waters towards the south (Fig. 9J).

Table 8. Changes of length of axis of spit end and annual length change in Area 8 in selected years.

Length of spit axis (a–b)	Relatively to 1936	Relatively to 1936	Previous observation	Previous observation	Annual length change
[m]	[m]	[%]	[m]	[%]	[m·a^{-1}]
1936	86.9	–	–	–	–
1960	159.6	83.7	72.7	83.7	3.0
1990	208.5	139.9	48.9	30.6	1.6
2009	220.6	153.9	12.1	5.8	0.6
2011	240.2	176.4	19.6	8.9	9.8

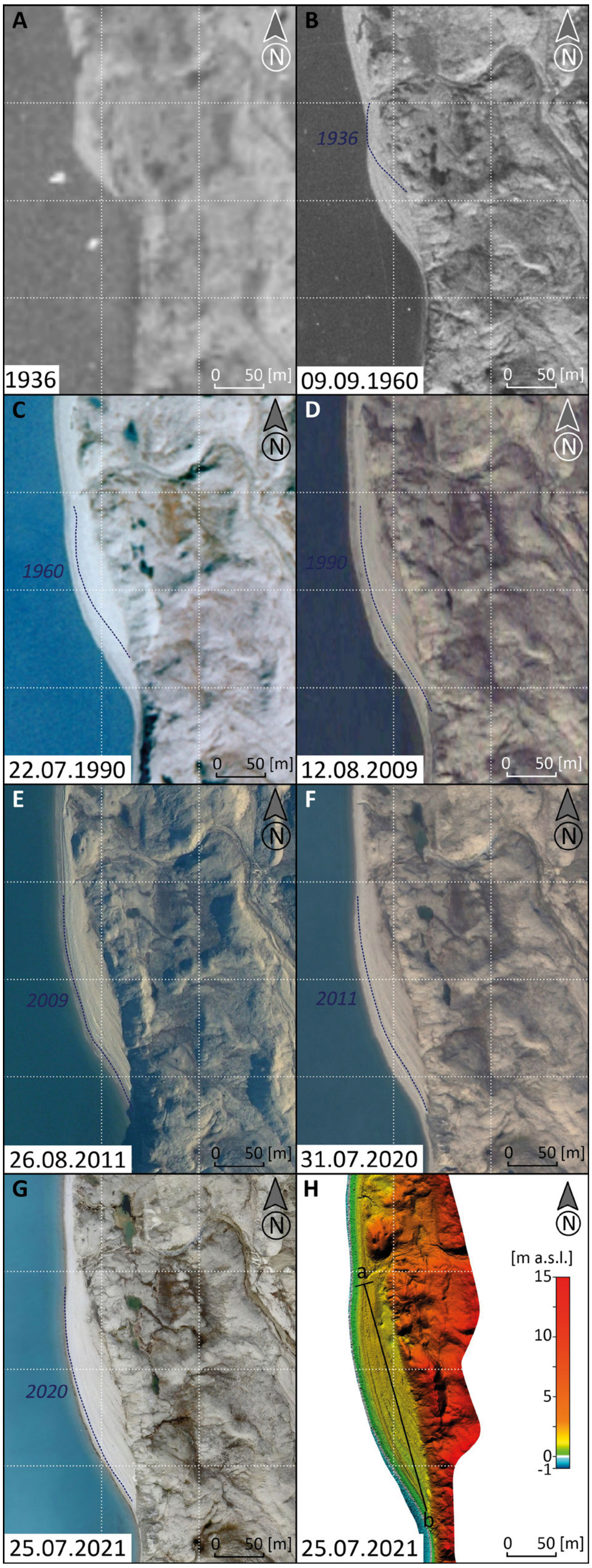

Fig. 11. Shoreline change in a selected section of coast – Area 8: a–b represents the long axis of the beach (see Table 8). For the background source data, see Table 1.

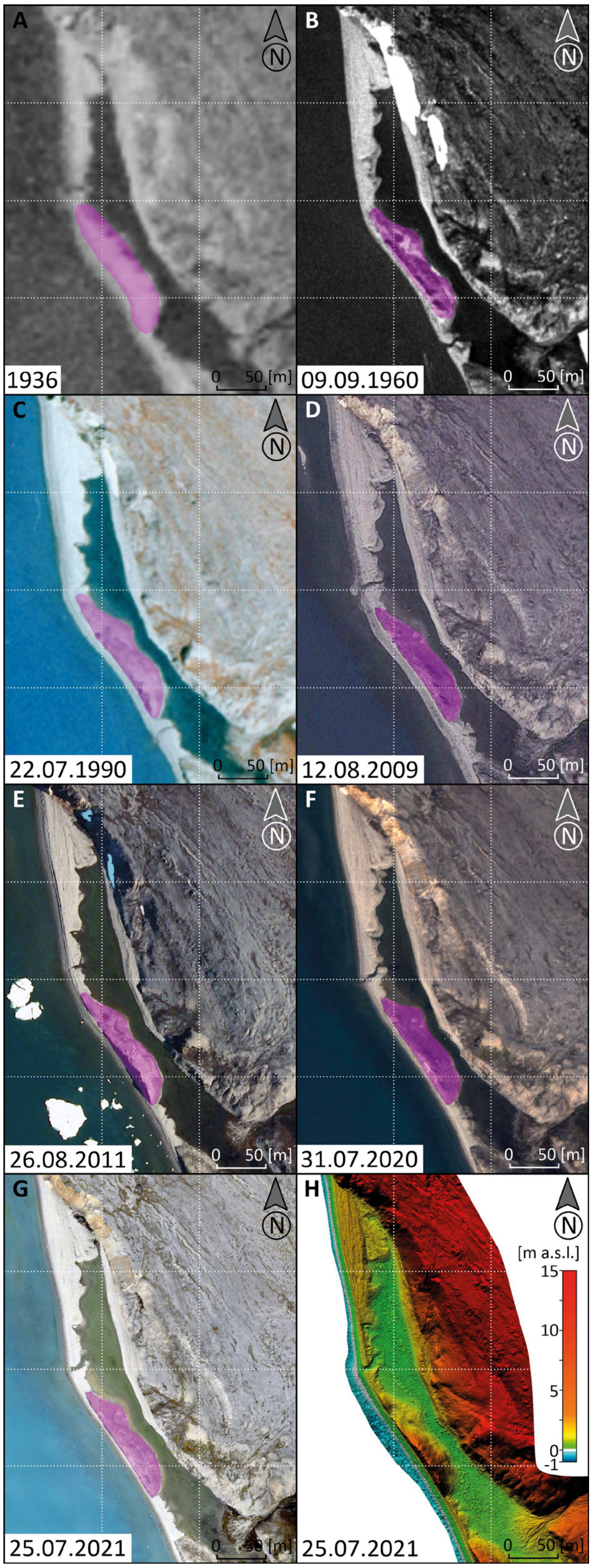

Fig. 12. Shoreline change in a selected section of coast – Area 9. The purple area denotes moraine surface. For the background source data, see Table 1.

Discussion

The interior of the fjord is influenced by weakened and dispersed swells that come from the open sea (Herman et al. 2019, Wojtysiak et al. 2018). Under favourable conditions, the waves can reach the tidal flat in Vestervågen, especially during the occurrence of spring tides (Fig. 13). From the open sea, the waves entering from the west undergo refraction in the area of Pocockodden and then Rollestonpynten before penetrating into the fjord (Zagórski et al. 2019). These conditions were observed in satellite images from 2013 and 2018 (e.g. Figs 2F, I, 4E, F and 5E, F). On Area 1, the material is transported along the spit and deposited at its end. Waves

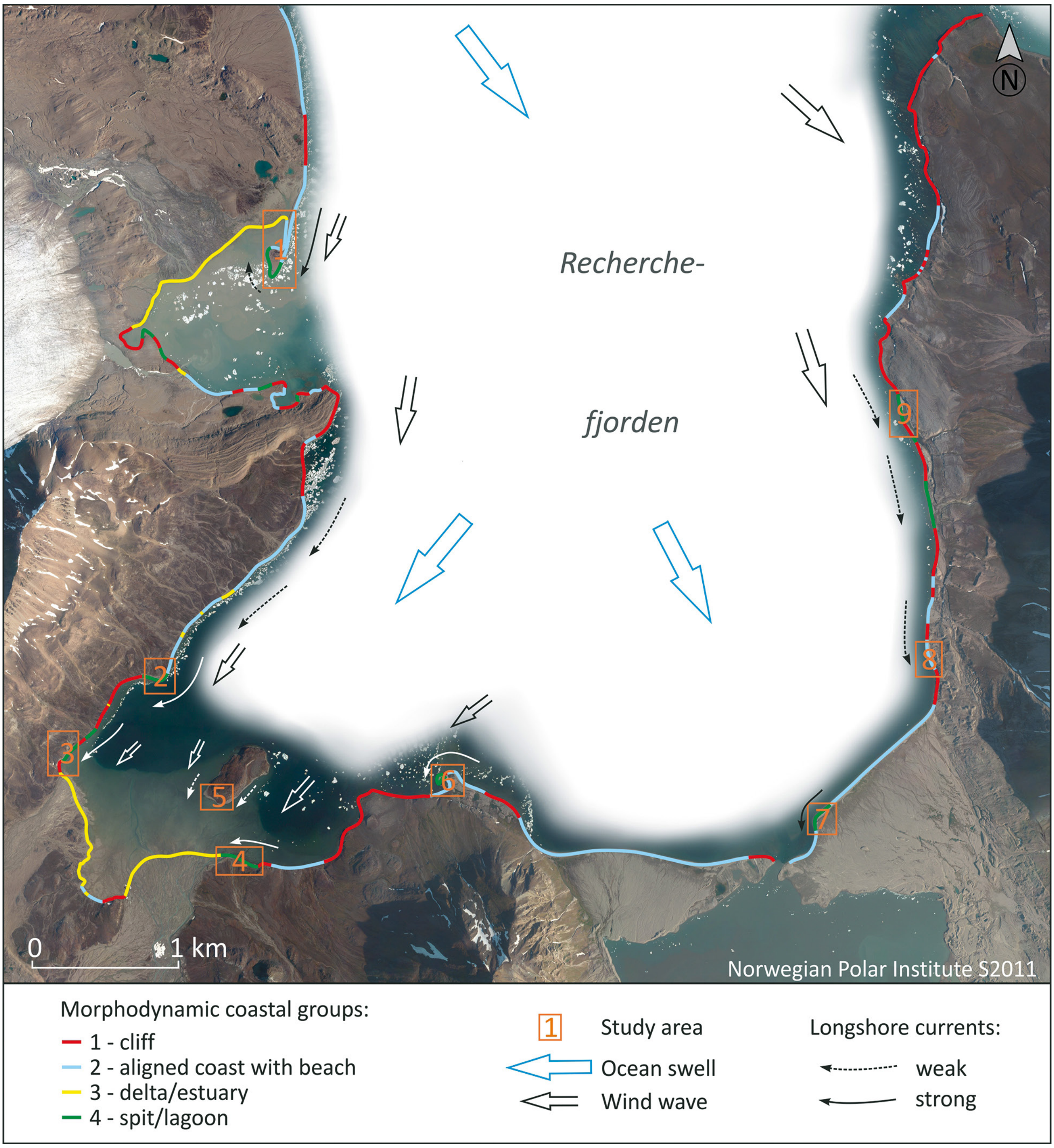

Fig. 13. Classification of the Recherche Fjord coastline (according to: Jarosz et al. 2022, modified) and the main factors determining the formation of accumulative forms. Background: Orthophotomap, NPI S2011.

approaching from the NE broke at the end of the spit, and changed direction to the west along its edge. The more frequent occurrence of such waves may have contributed to the formation of the spit headland in the NW part of the spit (Fig. 2I). A similar impact of waves from the NE was recorded in the satellite images from 2013 and 2018 in Areas 2 and 4 (Figs 4E, F and 6F, H).

The formation of the system of accumulation forms (spits, beaches with a developed profile) is mainly influenced by the system of longshore currents. They cause the transformation of the already existing coasts and the transport of material (longshore drift) and its accumulation in some sections (Zagórski et al. 2013, 2019). Conditions favouring the above-mentioned phenomena are shown in Figure 13. They occur episodically or periodically, independently of the general circulation of water in the fjord or the phenomena of tidal currents. During the increased supply of material with a favourable wave pattern, tides and longshore current, subsequent stages of spits development are created. This can be seen in the formation of storm ridges, the next generation of which are clearly visible, for example, in Areas 1, 5, 8 and 9. Also during favourable conditions, more spits develop, as is the case in Areas 3, 6 and 7. Therefore, the conclusion is that the accumulation forms currently observed in the fjord develop 'in leaps', i.e. in conditions of intensive supply of material, which guarantees their stabilisation and the possibility of long-term survival.

There is a whole system of longshore currents in Recherchfjorden (Fig. 13). The western coast of the Recherchefjorden is shaped by the longshore current flowing from the north (Harasimiuk, Jezierski 1987, 1991, Jarosz et al. 2022, Zagórski 2002, 2011). This is evidenced by the elongation of Josephbukta (Area 1) and the development of spits on the west coast between Rollestonpynten-Tomtodden-Vestervågen (Areas 2 and 3). Along the shores of the island of Reinholmen (Area 5), the longshore currents flow south. Along Rubypynten (Area 6), a local material transport system has developed from the east to northwest, and after crossing the northernmost point of the cape, the current turns south and flows towards the Chamberlinelva estuary (Area 4). Another longshore current flows from the east along the eastern outwash plane, causing the development of spits at the mouth of the Recherche Lagoon (Area 7). The east coast of the Recherchefjorden (Areas 8 and 9) has been shaped mainly by wave action and the transport of material by longshore drift flowing south.

With climate fluctuations, the conditions prevailing in the coastal zone change (Mędrek et al. 2014, IPCC 2019, 2021, Zagórski et al. 2019). One of the factors directly affecting Arctic coasts is the state of sea ice. In recent years, a significant shortening of the ice cover period has been observed inside fjords and along the coast (Urbański, Litwicka 2022). Consequently, this has led to the prolongation of the period of shore shaping by waves, especially storm waves, which often occur in winter, thus increasing the dynamics of coastal processes (Barnhart et al. 2014). Along with the increasingly shorter ice cover period in this part of the fjord, the coast is deprived of protective ice cover (Rodzik, Zagórski 2009, Zagórski et al. 2019). This is particularly evident in Area 5, where the development of a spit in the southwestern part of Reinholmen began with the increasingly shorter ice cover period in Vestervågen since the 1990s.

Conclusions

Due to climate change, the coasts of Recherchefjorden have undergone increasingly significant transformations in recent years. The phenomena and processes occurring in the Recherchefjorden are typical of other areas in the High Arctic.

The end of the 20th century, and especially the 21st century, were characterised by an increasing pace of development of accumulative forms in the distinct internal parts of Recherchefjorden. The process itself was episodic (periodic) in nature. Under favourable conditions, there was an intensification of material transport processes and the construction of forms, which over time became stable forms.

Contemporary changes in the morphology of accumulation forms depend on the intensity of marine processes. In the case of Recherchefjorden, the greatest impact is from wave action (wind and swell), which penetrates deeply into the interior of the fjord, as well as longshore currents. More frequent winds from the W, NE and NW sectors lead to the expansion of spits in a southerly direction. Additionally, the fact that the period of fjord ice coverage is getting shorter leads to an increase in the intensity of coastal processes.

Considering the development of accumulative forms along the Recherchefjorden coast, it is possible to reconstruct the dominant patterns of longshore currents that determine the direction of material transport. The western coast is influenced by a southward-flowing longshore current, as are the Reinholmen coasts. The area from the Chamberlinelva river mouth to Rubypynten and the Recherchebreen eastern outwash plain are influenced by a westward-flowing longshore current. Meanwhile, along the eastern coast of the fjord, patterns of southward-directed coastal longshore currents dominate.

Author's contribution

KF and PZ: created the concept, designed the study, collected field data, performed analysis of shoreline and spatial changes, wrote manuscript, and prepared the figures.

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