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5.5. Coastal geomorphology

The recently published 'The State of Arctic Coast 2010 Report' (Forbes *et al.* 2011) suggests that the circumpolar coastal zone is the key interface in the entire Arctic characterised by the *'most rapid and severe environmental changes which have serious implications for communities living on coastal resources'*. Despite the potential significance of these changes, relatively little is known of the physical processes that control high latitude coasts or how they might change in the future.

The most recent advances in Arctic coastal geomorphology pertain to the ice-rich permafrost coasts of Siberia and Alaska (Lantuit *et al.* 2012). In contrast, much less work has been done along the coastlines of High Arctic archipelagos such as Svalbard, Franz Joseph Land, the Canadian Arctic Archipelago or Greenland whose melting ice masses contribute the greatest to present-day sea level rise. The unique feature of High Arctic coasts is the fact that throughout the year they are affected by different forms of ice: sea ice, land-fast ice, glaciers and permafrost (Byrne & Dionne 2002; Mercier 2008; Strzelecki 2011).

This study attempts to characterise the southern coast of Bellsund, from Dunderbukta in the west to Recherchefjorden in the east (Appendix 1 and 2). The coastal landscape is very diverse and includes extensive coastal plains with series of well-preserved raised marine terraces, sections of cliffed coasts formed in rocks and unlithified deposits as well wide gravel-dominated barriers (Harasimiuk 1987; Harasimiuk & Jezierski 1988, 1991; Zagórski 2002, 2004a).

Coastal landscape can be divided into relict coastal zone (palaeo-coasts) and modern coastal zone. The relict coastal zone includes: raised cliffs and marine terraces with relict beaches and shore platforms, covered with old storm ridges, former lagoons and palaeoskerries. Higher terraces adjoin the higher denudation-structural levels, usually separated by steep old relict cliffs. The main features of modern coastlines include: underwater rocky shore platforms with a width of between several dozen and several hundred meters, rocky skerries, rocky cliffs, as well as abrasion-accumulation shores and accumulation shores such as gravel-dominated barriers and tidal flats.

Palaeocoasts

The coastal landscape of NW part of Wedel Jarlsberg Land is rich in well-preserved series of raised marine terraces. They form a system of Pleistocene and Holocene abrasive-accumulative levels separated with a palaeo-cliffs. The following levels of marine terraces were identified (Zagórski 2002, 2004b) (Fig. 5.5.1):

- terrace I – 2 to 8 m a.s.l. – mostly of accumulation origin, in some parts strongly eroded or covered with deposits of a terrestrial origin; correlated with the beach level A, found along the western coast of Spitsbergen (Landvik *et al.* 1998);
- terrace II – 10 to 20 m a.s.l. (locally 7 to 12 m) – highly varied in terms of morphology and spatial arrangement, mostly constituting an abrasion-accumulation platform;
- terrace III – 22 to 30 m a.s.l. (locally 17 to 25 m) – extending along almost the entire length of southern coast of Bellsund, represented by rocky shore platform with a thin deposit layer and paleoskerries, and relict beach surface;
- terrace IV – 30-40 m a.s.l. (locally 27 to 35 m) – extending along almost the entire length of southern coast of Bellsund. In many sites the surface of terrace is polygenetic in character and includes sections of abrasive and accumulative landforms;
- terrace V – 40 to 50 meters a.s.l. (locally 37 to 50 m) – extending along almost the entire length of southern coast of Bellsund; for the most part, it is covered with abrasive-accumulative forms and abrasive platform; it can be correlated with the beach level B, previously identified in the NW part of Bellsund (Landvik *et al.* 1998);
- terrace VI – 50 to 65 meters a.s.l. (locally 55 to 65 m) – extending along almost the entire length of southern coast of Bellsund, enters mouths of glacier valleys and often ends with a well-developed cliff;
- terrace VII – 70 to 85 meters a.s.l. (locally up to 95 m) – extending along almost the entire length of southern coast of Bellsund; in general, it is an abrasion surface with traces of glacial transformation; however, there are also abrasion-accumulation forms with a series of deposits of various origin;
- terrace VIII – 105 to 120 meters a.s.l. – this abrasive-accumulative platform was identified only along the Reinsletta in the eastern Recherchefjorden. Marcinkiewicz (1961) classified this surface to terrace VI (90-130 m).

The relief of the raised marine terraces was formed at the turn of the Weichselian and the Holocene through transformations of the older elements of littoral and glacial relief and their overlaying with younger forms. In the southern Bellsund region, at the time of the Saalian Glaciation, in particular the central sections of valleys and the surfaces which now form the high terraces VII and VIII were remodelled. The accumulative role of glaciers manifested itself in till deposition on terrace VII, in the Dyrstaddalen (Reder 1990; Pękala & Reder 1989) and in the Calypsostranda region (Pękala 1987; Landvik *et al.* 1992) (see: Figs. 2.2.2 and 2.2.3). The recession of the Saalian Glaciation caused a rapid rise of the sea level and its transgression into the Dyrstaddalen (terrace

VII) and on Calypsostranda. In the Eemian Interglacial period, a thicker series of gravel and gravel-and-sand deposits covered the Saalian till (Pękala & Repelewska-Pękalowa 1990) (see: Fig. 2.2.10). No deposits from the late Weichselian were found, however, the glacial advance dating back to 41-50 ka BP is well-documented (Pękala & Reder 1989; Pękala & Repelewska-Pękalowa 1990; Landvik *et al.* 1992). Glacial and fluvio-glacial deposits from that period were found, e.g. in the Dyrstaddalen (terrace VI) and in the Calypsostranda region. In the Skilvika cliff, mid-Weichselian deposits bear distinct traces of chemical weathering in the top section (Mangerud *et al.* 1992).

The main stage of the development of the present-day coastal relief is associated with deglaciation from the Late Weichselian Glacial event that took place between 13-10 ka BP (Mangerud *et al.* 1992; Mangerud & Landvik 2007) (Fig. 5.5.3). The retreat of glaciers from fjords was followed by marine transgression, which led to the development of abrasion and abrasion-accumulation levels of terrace VI (50-65 m) deep in the valleys. Fig. 5.5.2 presents the stages of Calypsostranda coast evolution since the end of the Late Weichselian (Zagórski 2007cd). The slowing-down of glacioisostatic movements in relation to the eustatic sea level rise resulted in the formation of terrace V (40-50 m) (Photo 5.5.1). At the same time, the wide storm ridge was formed along the entire coast from Calypsostranda to the Lognedalen and in the Dunderdalen (beach level B, Landvik *et al.* 1998). The storm ridge is well-preserved until present.

The progressing, rapid glacioisostatic uplift contributed to the formation of another terrace level – terrace III (25-30 m). In the Reinsletta region, the surface correlated with the terrace III is located at 17-25 m. A slower pace of uplift in this section of the coast could have been caused by a greater glacial loading. In the Calypsostranda the accumulation of the spit led to the development of bay that due to the uplift has shallowed. The wave erosion of landward slope of the spit led to the development a steep escarpment (Photo 5.5.2A). On the seaward slope of spit, the surface of terrace III was developed. In the other sections of the coast, terrace III is preserved as an abrasive platform covered with numerous rocky outcrops (Zagórski 2007d) (Fig. 5.5.2).

Terrace II (10-20 m) is the last raised marine terrace associated with the post-glacial uplift that occurred at the turn of the Weichselian and the Holocene. It is best developed in Dunderdalen, Lognedalsflya and Chamberlindalen. The large part of Dunderdalen, currently characterised by a wide and flat bottom, was submerged and formed a shallow bay. The long-term sea-level standstill led to the formation of a cliff that separated two well-developed abrasion platforms (terrace III and IV). A similar abrasion platform sporadically covered with deposits was formed in Lognedalen. In Blomlidalen, the terrace II was eroded in the terrace III and formed several small bays along the coast (Photo 5.5.2B). For a long time terrace II was the local base level for the Blomlielva, which incised a narrow canyon in the terrace surface. In the river mouth a shallow tidal flat was accumulated. During the development of terrace II the sea submerged most of the Chamberlindalen. The bottom of the valley functioned as a tidal flat shaped by the mosaic of glaciofluvial and coastal processes.

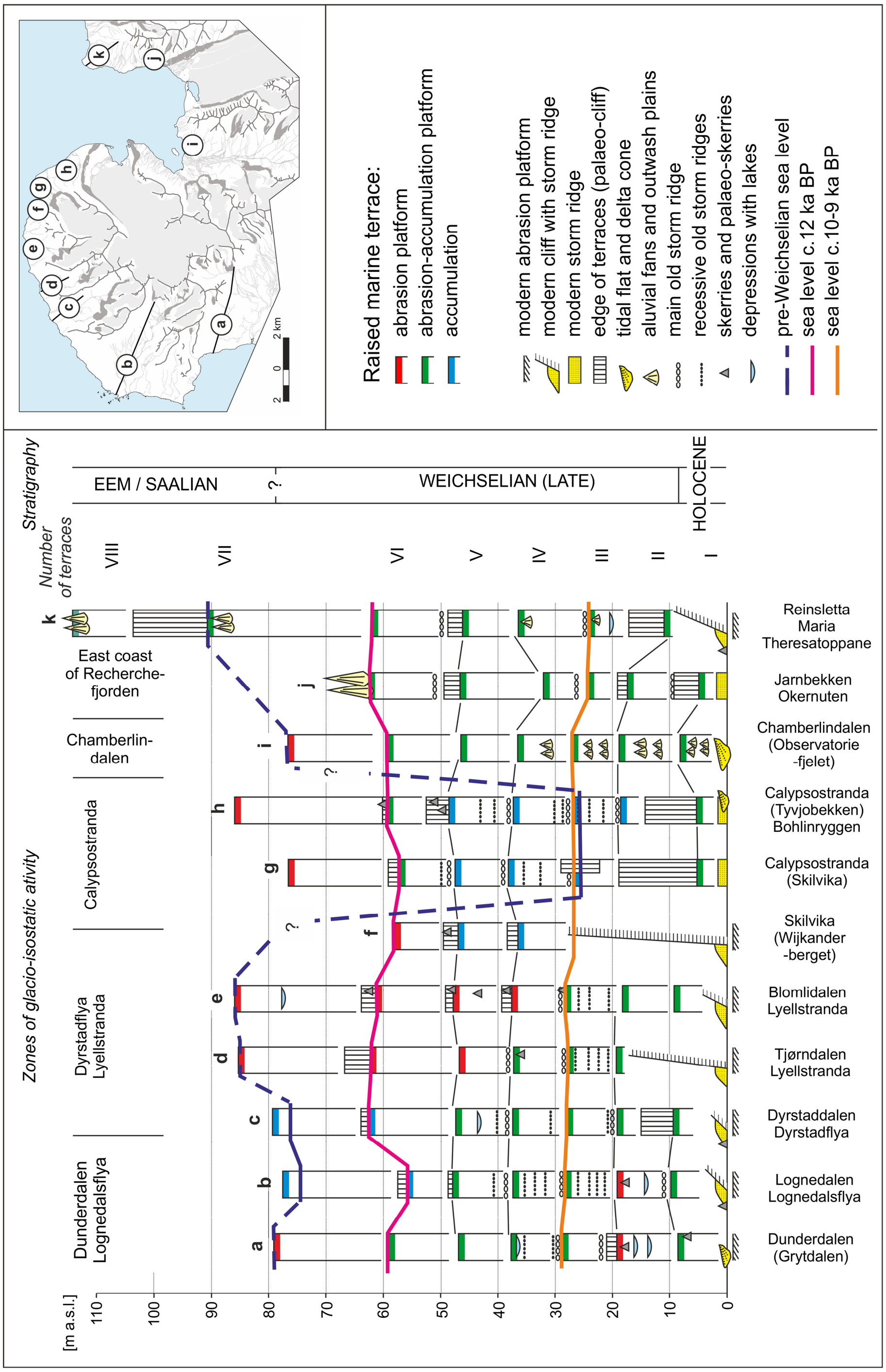

Fig. 5.5.1. Compilation of altitudes and geological profiles of raised marine terraces formed along the southern coast of Bellsund and the Recherchefjorden (after: Zagórski 2002, 2004b, modified).

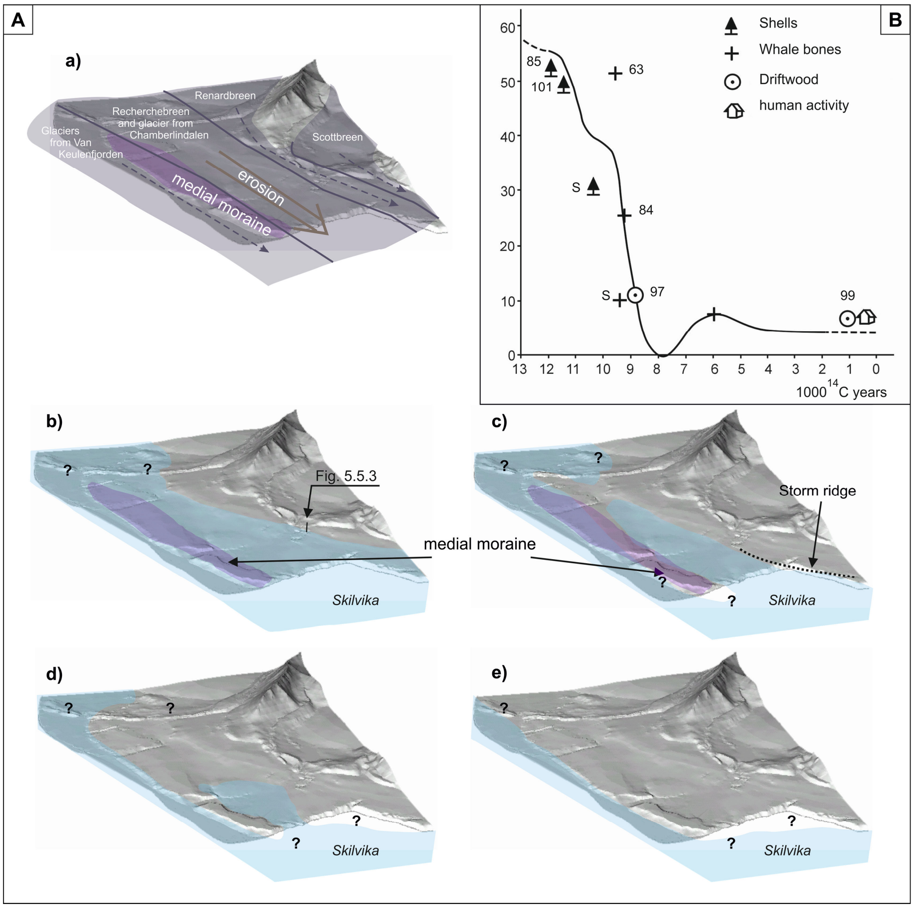

Fig. 5.5.2. A- The evolution of Calypsostranda since the Late Weichselian (Zagórski 2007d): a- area covered by ice streams during the Last Glacial Maximum (about 20 ka BP), b- shoreline at 12 ka yr BP (development of terrace V), c- shoreline at 11-10 ka BP (development of terrace IV), d- shoreline at 10-9 ka yr BP (development of terrace III), e- shoreline at 8 ka BP (development of terrace II); B- shoreline displacement curve for north-western Wedel Jarlsberg Land (Lognedalen) (after: Salvigsen *et al.* 1991).

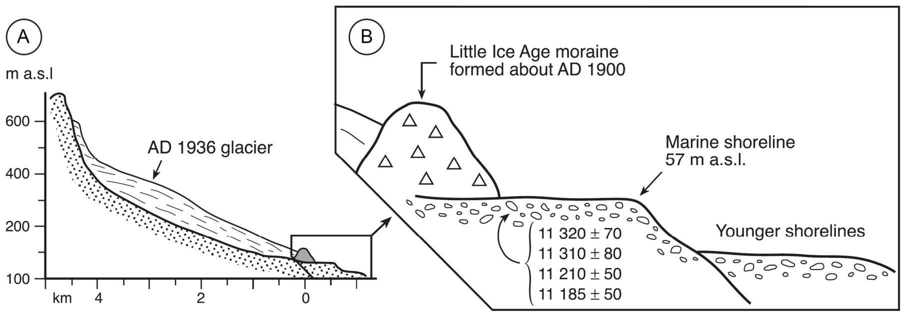

Fig. 5.5.3. Dating of glacio-marine deposits on the Scottbreen forefield (after: Mangerud & Landvik 2007; location of profiles, see: Fig. 5.5.2): A- longitudinal profile of Scottbreen forefield on the base of topographical map, 1:100,000, B11 Van Keulenfjorden (1952), B- stratigraphical relationship between the dated shoreline and the Little Ice Age moraine.

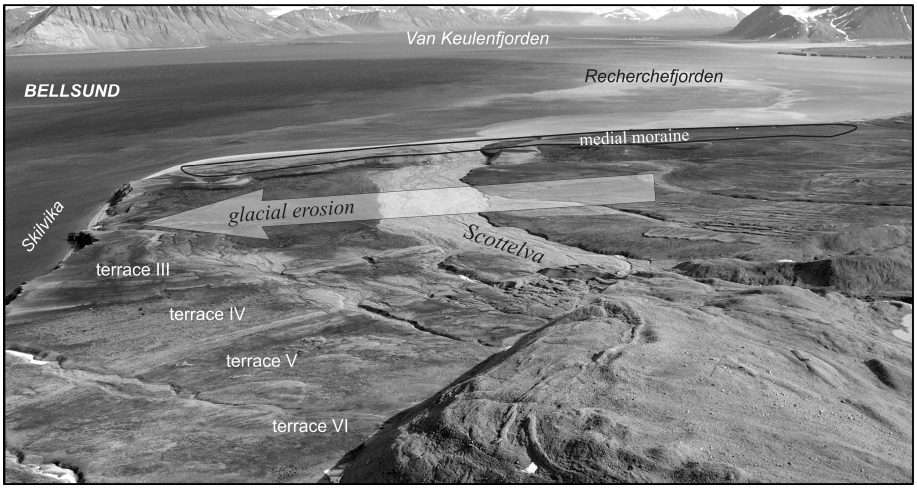

Photo 5.5.1. Relief of Calypsostranda – view from Wijkanderberget (Photo P. Zagórski 2006).

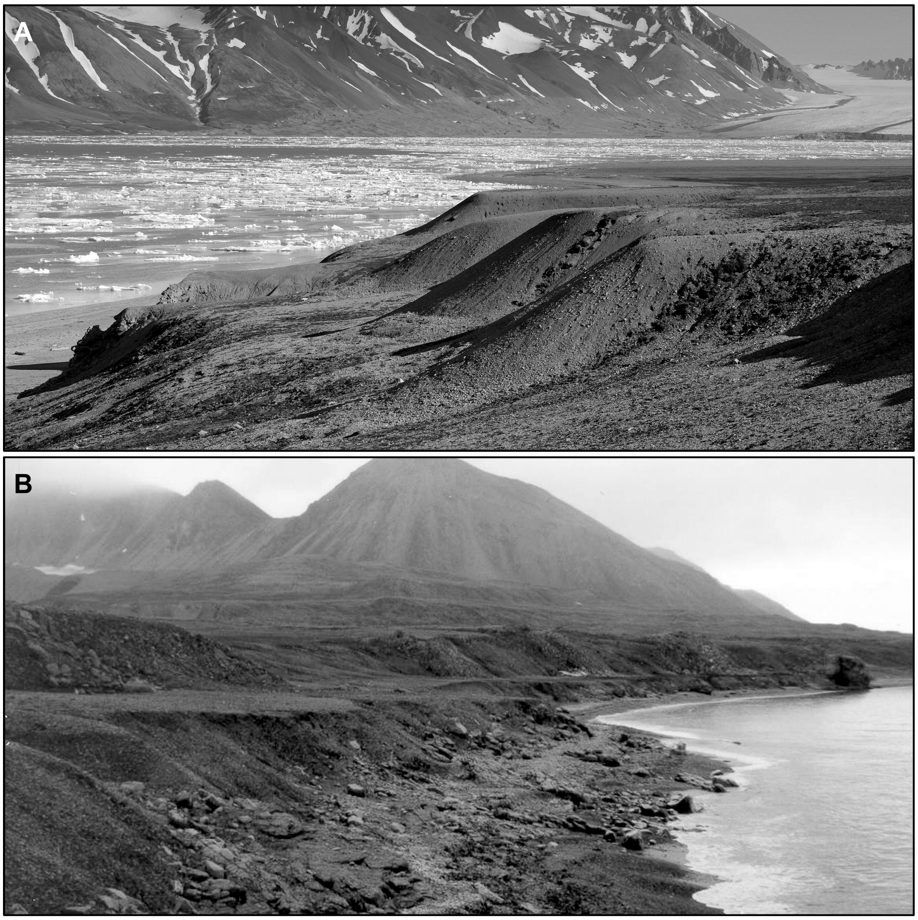

Photo 5.5.2. A- edge of terrace III – Calypsostranda (Photo P. Zagórski 2011), B- raised marine terrace in Blomlidalen region and active cliff in gravel deposits (Photo P. Zagórski 1998).

In the Early Holocene the system of older raised marine terraces was subject to intensive abrasion and accumulation. The transformation of terraces surface took place in the absence of significant sea level changes (Fig. 5.5.2B). Abrasion of Calypsostranda occurred from the east and west. A similar process occured between Skilvika and Lognedalsflya. Intensive abrasion significantly reduced the area of raised marine terraces, in particular terrace II and III and, in the region of Skilvika – terrace V. On western Spitsbergen, mid-Holocene transgressive-regressive cycles are recognised (e.g. Landvik *et al.* 1987, 1992, 1998; Mangerud et al. 1998). The transgression did not reach higher than 7 m aht and is limited by a constructional terrace that cuts a early Holocene regressional strandlines. Marine subfossils associated with this transgressive feature were radiocarbon dated and the dates indicated that the sea occupied this level between 6,000 and 4,000 ^{14}C BP (Forman *et al.* 1987; Landvik *at el.* 1987).

Modern coasts

Geomorphological mapping carried out by UMCS Expeditions focused on ca. 60 km long section of Bellsund coast from the estuary of Dunderelva to Reinodden. The coastal landscape is dominated by abrasive sections separated by short accumulative sections. The formation of certain type of coast is dependent on the lithology and tectonics of the bedrock and the exposure to the operation of waves. The coasts have been divided into three main groups on the basis of lithological-morphological criterion (Harasimiuk & Jezierski 1988, 1991; Zagórski 2002; Zagórski *et al.* 2006) (Fig. 5.5.4):

1) a group of abrasive shores, including:
   - active cliffs in Hecla Hoek metamorphic rocks of,
   - active cliffs in Palaeozoic/Mesozoic sedimentary rocks,
   - active cliffs in Palaeogene sandstones,
   - active cliffs in Pleistocene and Holocene gravel deposits,
   - active cliffs in Pleistocene and Holocene moraines,
   - ice cliffs;
2) a group of flat, abrasive-accumulative shores, including:
   - coasts developed in metamorphic rocks of Proterozoic,
   - coasts developed in Quaternary deposits;
3) a group of accumulative shores.

Active cliffs in Hecla Hoek metamorphic rocks constitute approx. 20% of all cliffs in this part of the coast and occur in several places from Dunderbukta to Skilvika and in the area of Asbestodden (Recherchefjorden) (Photo 5.5.3A). They are irregular in character, dependent on the resistance of Kapp Lyell and Dunderbukta Formation rocks as well as the complicated arrangement of tectonic structures (Dallmann *et al.* 1990, Birkenmajer 2004). Almost vertical, craggy edges are subject to weathering and mass movements (rockfalls, slides). Their maximum height is 25 m. In several places the rock cliffs are covered with several meters thick layer of marine gravels.

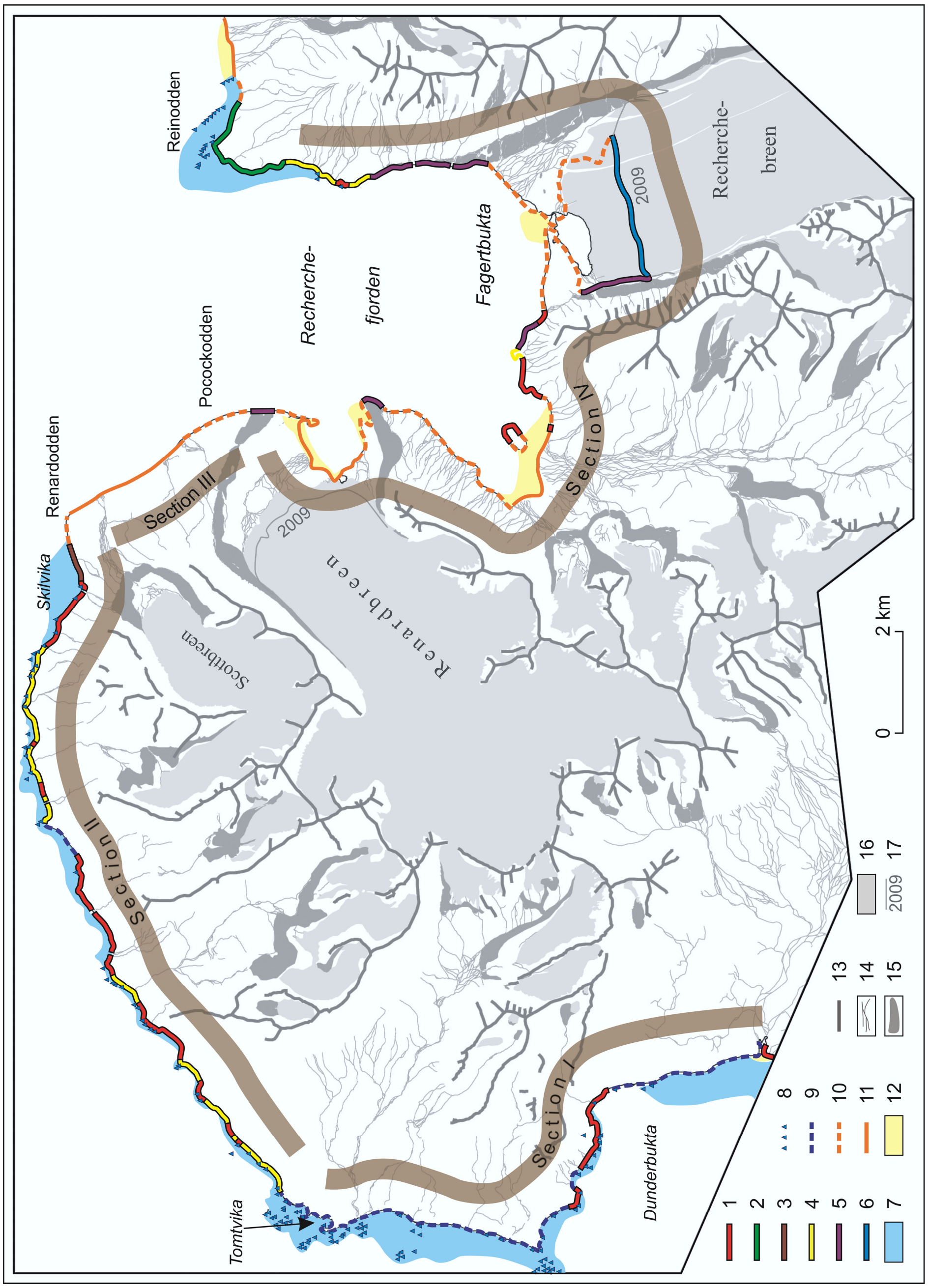

Fig. 5.5.4. Geomorphological classification of coastal environments in the NW part of the Wedel Jarlsberg Land and location of coastal sections (Sections I-V) selected for detailed studies (after: Harasimiuk & Jezierski 1991; Zagórski 2002; Zagórski *et al.* 2006, revised and enlarged): 1- active cliffs in Hecla Hoek metamorphic rocks, 2- active cliffs in Palaeozoic/Mesozoic sedimentary rocks, 3- active cliffs in Palaeogene sandstones, 4- active cliffs in Pleistocene and Holocene gravel deposits, 5- active cliffs in Pleistocene and Holocene moraines, 6- ice cliffs, 7- abrasion platforms, 8- rocky skerries, 9- abrasive-accumulative coasts developed in Proterozoic metamorphic rocks, 10- abrasive-accumulative coasts developed in Quaternary deposits, 11- accumulative coast, 12- tidal flats and deltas, 13- mountain ridges, 14- rivers, 15- moraines, 16- glaciers, 17- extent of glacier fronts (Renardbreen and Recherchebreen) in 2009.

Photo 5.5.3. A- active cliffs in Hecla Hoek metamorphic rocks in Dunderdalen (Photo P. Zagórski 2012), B- active cliffs in Palaeozoic/Mesozoic sedimentary rocks in Reinsletta region (Photo P. Zagórski 2011), C- active cliffs in Palaeogene sandstones in Skilvika (Photo P. Zagórski 2011)

Active cliffs formed in Palaeozoic/Mesozoic sedimentary rocks occur on the eastern side of the Recherchefjorden in the Reinsletta region, where rocks of the following groups undergo abrasion: Gipsdalen, Billefjorden, and Sassendalen (Dallmann *et al.* 1990) (Photo 5.5.3B). The cliff line is irregular and jagged here, due to the fact that rock layers of differing resistance are placed slantwise to the shoreline. In Reinodden cliff heights reach up to 15-20 m and they are supported by shore platforms and skerries.

Active cliffs formed in Palaeogene sandstones extend along a relatively short fragment (about 1 km) of the coast that marks the eastern border of Skilvika (Photo 5.5.3C). They are formed in Skilvika Formation rocks represented by grey to black, fine-grained, often laminated sandstones alternating with grey to black shales and coalshales, with thin black coal seams and in Renardodden Formation rocks represented by sandstones with coal-accentuated cross-bedding at the bottom (Birkenmajer & Gmur 2010). The cliff height reaches up to 25-30 m. Additionally, the Palaeogene substratum covers the polygenetic (glacial, fluvioglacial, marine) deposits from the Late Pleistocene. In consequence, the western section of the cliff, where the sediment layer is relatively shallow, is very steep, but the eastern layer, with a Pleistocene sediment layer of greater thickness, has a varying inclination. Lithological diversity results in an uneven rate of transforming the cliff by different mass movements (Pękala & Repelewska-Pękalowa 1990; Landvik *et al.* 1992).

Active cliffs in Pleistocene and Holocene gravel deposits are a product of abrasion of raised marine terrace edges (Photo 5.5.4A). These occur in sections, starting from Lognedalsflya all the way to Skilvika and on the eastern side of the Recherchefjorden to the north of Lægerneset. They often form the so-called 'discordant shoreline' characterised by an alternating occurrence of bays and headlands, at the extension of which rocky skerries are located (Harasimiuk & Jezierski 1988). Small bays provide space for the formation of narrow gravel-dominated barriers.

Formation of cliffs in Quaternary deposits is related to the abrasion of frontal and lateral moraines of Renardbreen (Josephbukta) and Recherchebreen (Fagerbukta) (Photo 5.5.4B). These sections of the coasts are characterised by the highest dynamic of relief transformation, both due to intensive abrasion as well as dead-ice melting and solifluction of moraine slopes. Ice cliffs in the region of NW part of Wedel Jarlsberg Land are of marginal importance. At present, only Recherchebreen forms 3 km long and 15-20 m high ice-cliff which terminates in a lagoon (Photo 5.5.4C). Second glacier – Renardbreen – formed an ice-cliff until the beginning of the 1990s and later on retreated on land.

Abrasive-accumulative type of coast are related to the development of modern shore platforms, both in the Hecla Hoek rocks as well as in Quaternary deposits (Photo 5.5.5A). Abrasive-accumulative coasts on metamorphic rocks are characteristic for coasts of Dunderdalen and Lognedalsflya in the western part of study area. The typical element of coastal landscape are extensive coastal plains covered with thin layer of beach ridge sediments.

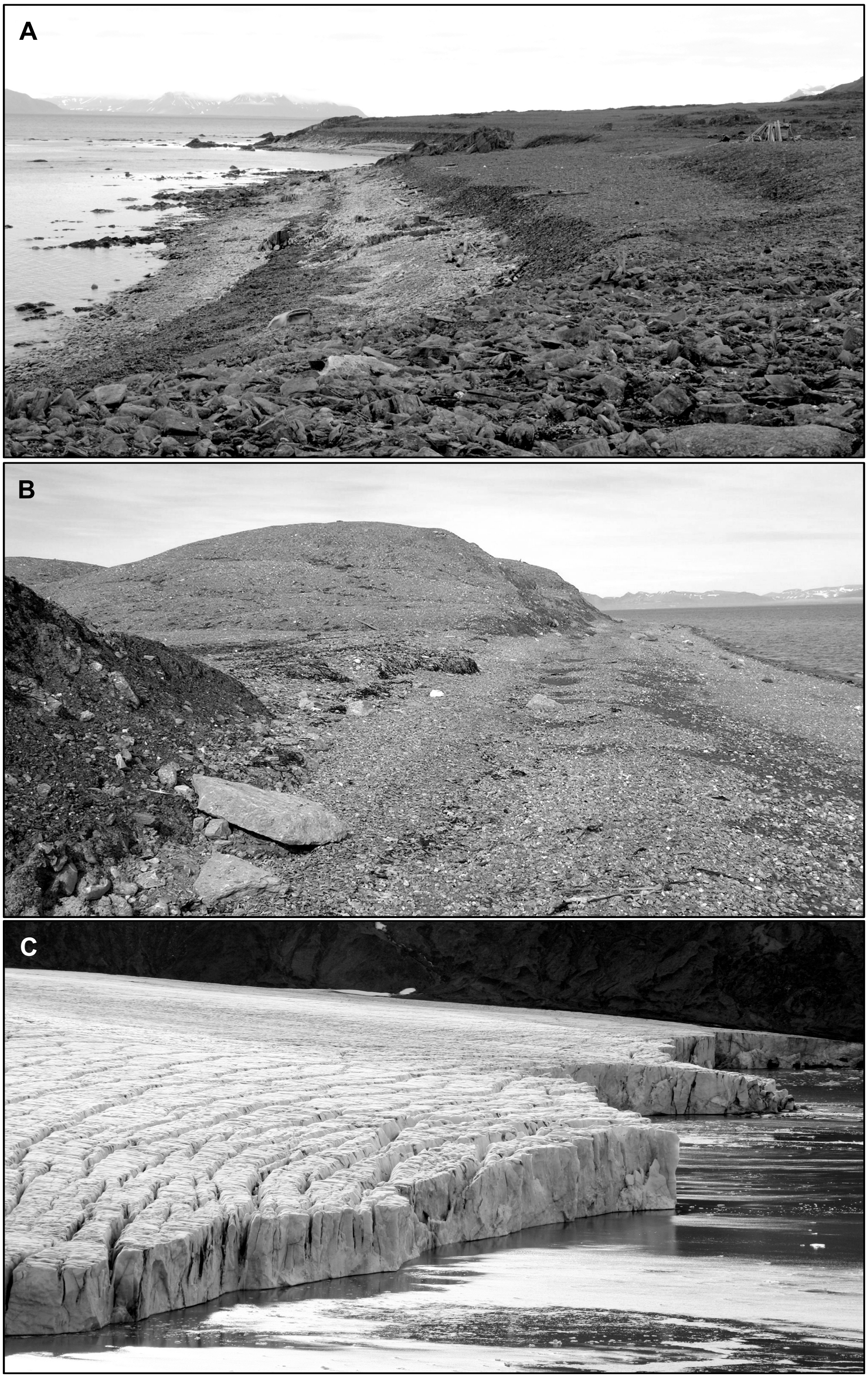

Photo 5.5.4. A- active cliff in Pleistocene and Holocene gravel deposits near Klokkefjellshytta (Photo P. Zagórski 2012): B- active cliff in moraine of Renardbreen – Renarddbreen-1 archaeological site (Photo P. Zagórski 2005), C- active ice-cliff of Recherchebreen (Photo M. Łodziński 2009).

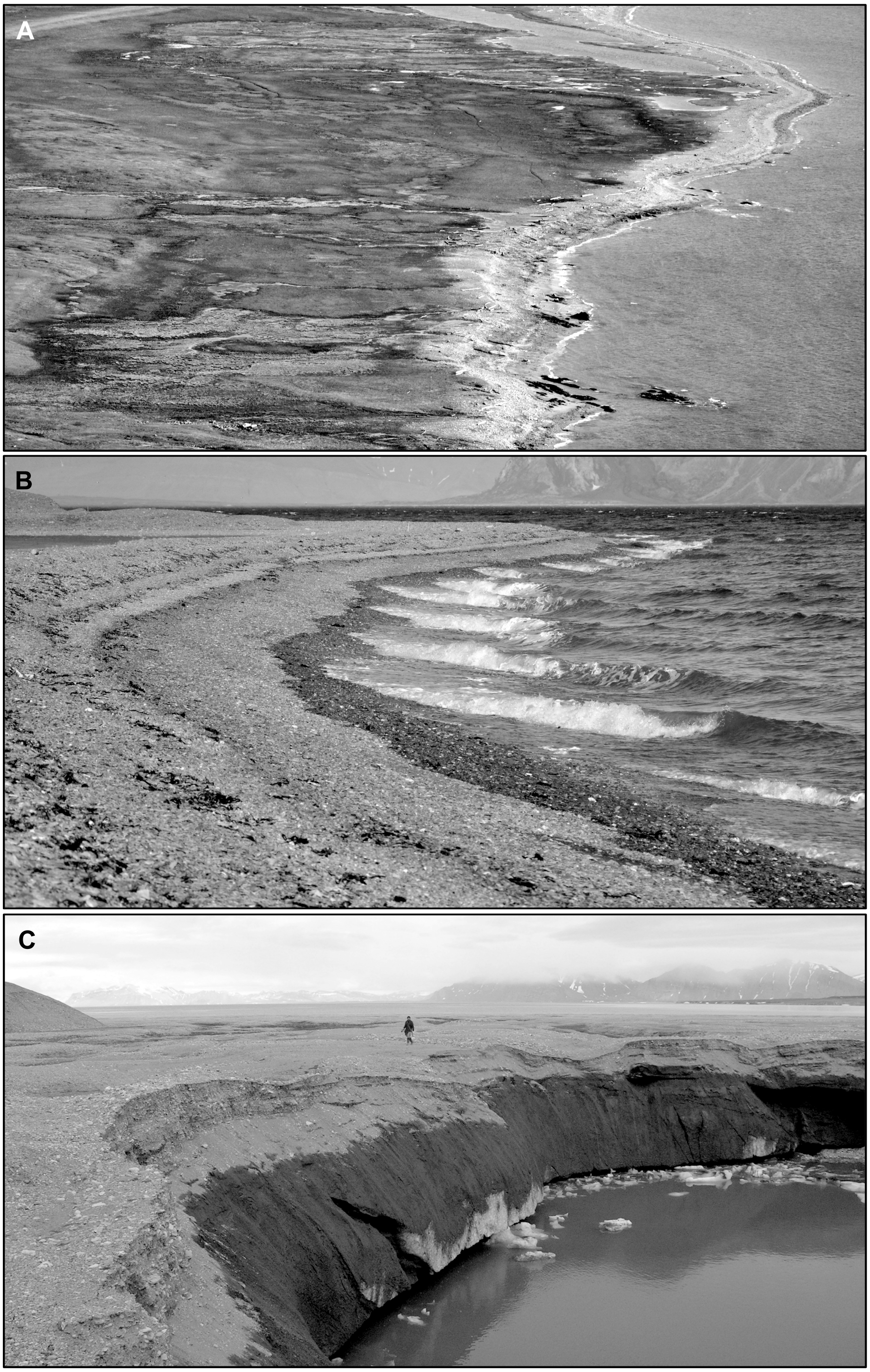

Photo 5.5.5. A- abrasive-accumulative type of coast in Dunderbukata (Photo P. Zagórski 2012), B- abrasive-accumulative type of coast developed in Quaternary deposits – wind waves approaching gravel-dominated barrier developed along Josephbukta spit (Photo P. Zagórski 2011), C- inactive outwash plain of Recheche-breen eroded due to thermoabrasion (Photo P. Zagórski 2008).

Long sections of coastal plains are separated from the open sea by numerous skerry islands (Fig. 5.5.4). A similar relief can be observed in certain sections of the coast that were formed in Quaternary deposits, located inside the Recherchefjorden (Photo 5.5.5B). In the surroundings of Pocockodden, Josephbukta and Fagerbukta the margins of inactive outwash plains are subject to thermoabrasion (Photo 5.5.5C). Along the Tomtodden (Vestervågen) – thermoabrasion affects the coasts developed in solifluction deposits.

In few places glacial-fed and snow-melt-fed rivers accumulated deltas. Due to the operation of strong waves and longshore drifts most of the deltas are not fully-developed. Only in inner part of Recherchefjorden, where the impact of waves is not so strong e.g. at the mouth of the Chamberlindalen the intensive sediment accumulation occurs and leads to the development of an extensive tidal flat.

In general, accumulative coasts occur in places, where there is a positive balance of sediments transported along the coast, i.e. in regions with high supply of terrigenous sediments such as deltas and tidal flats fed by proglacial rivers, and in areas of convergence of longshore drifts (Harasimiuk 1987; Zagórski 2004a) (Photo 5.5.6ABC). A classic example is the coast of Calypsostranda, where an accumulation features include several dozen meters wide belt of storm ridges adjoining a dead cliff formed in the uplifted marine deposits (Photo 5.5.6B). Transport of and deposition of sediments along the coast led to the development of characteristic landforms such as spits, tombolos and lagoons (Josephbukta, Tomtodden, Rubypynten) (Photos 5.5.5B and 5.5.6A).

Modern transformation of the coastal zone

The present shape of the coast of NW part of Wedel Jarlsberg Land is the result of impact of different morphogenetic factors. These include: (1) marine factors (waves, tidal, long shore drifts), (2) ice factors (polygenetic shore ice, fast ice, pack ice, growlers), (3) glacial factors (glaciers) and (4) fluvial and fluvioglacial factors (water supply and supply of terrigenous materials).

<u>Marine factors and their impact on the development of coastal zone</u>

The main factor that shapes the shoreline is wave action (Leontiev *et al.* 1982). Three specific types were distinguished on Spitsbergen: wind waves, swells and long-term waves (Marsz 1996) (Photo 5.5.5B). Usually the most important role is played by wind waves, the intensity of which depends on wind velocity and duration, as well as the wave run-up distance (Marsz 1996).

The western coast of Spitsbergen is relatively rarely hit by strong storms. Although the dominant air masses over southern Spitsbergen are those from eastern direction the weather conditions, particularly during winter months, are also shaped by lows coming from Iceland (Niedźwiedź 2007). Winter is dominated by strong eastern winds. However, when the route of the winter cyclones moves between Greenland and

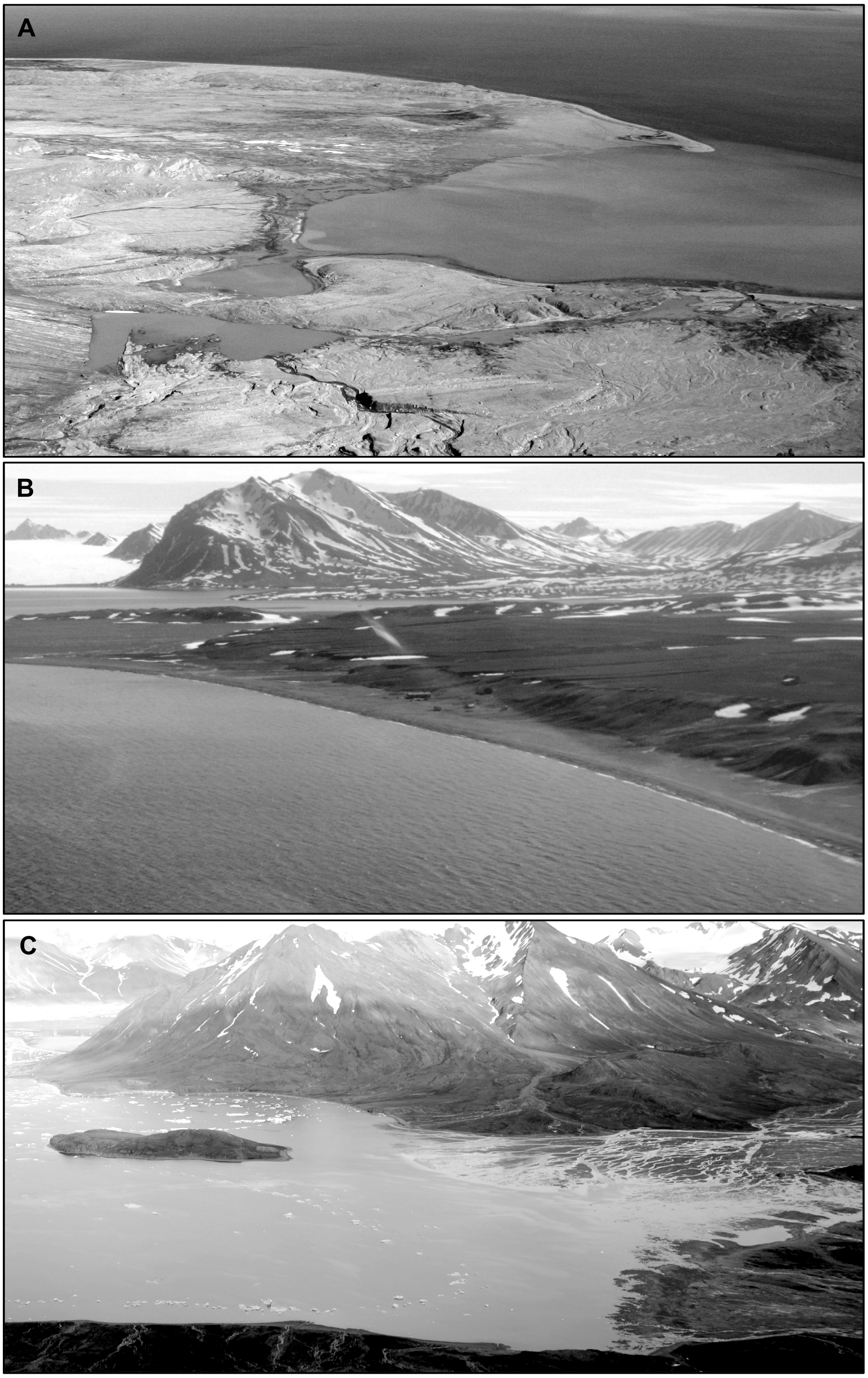

Photo 5.5.6. A- accumulative shores and active outwash plain of Renardbreen – Josephbukta (Photo J. Jania 2008) , B- accumulative shores near Calypsobyen (Photo P. Zagórski 1998), C- tidal flat (Vestervågøyra) in the Chamberlindalen mouth (Photo P. Zagórski 2011).

Spitsbergen the short periods of southern, western and northern winds may occur (Niedźwiedź 2007). During summer seasons the island is hit by western winds, but in the low-gradient pressure field these winds are rather weak (Styszyńska 2007).

Long-fetch waves directly impact the section of the coast that is exposed to the Greenland Sea, usually all the way to Straumneset or, exceptionally – when the waves travel from NW – to Kapp Lyell. Storms on the Greenland Sea may result in a formation of swell that affect the coasts of Bellsund (Styszyńska 2007; Rodzik & Zagórski 2009).

The configuration of Bellsund causes the diffraction of long-fetch and swell waves that loose energy the further they travel towards the inner-fjord area and disappear around Pocockodden. In Recherchefjorden the impact of these waves is very limited.

Ground-level circulation of air in the region is significantly modified by the arrangement of valleys, mountain ridges and fjords. The Bellsund, 25 km long and 20 km wide, is connected with three fjord systems: from the ENE – Van Mijenfjorden, from the ESE – Van Keulenfjorden and from the SSE – Recherchefjorden (Fig. 5.5.5). The configuration of fjords and their extensions in the form of glacial valleys enhances the atmospheric circulation and leads to the dominance of the eastern winds over Bellsund during summer months, often strengthened by the foehn effect (Gluza 1988ab; Brázdil *et al.* 1991; Kejna *et al.* 2000). Nevertheless, the waves moving from the east are relatively short, because both of eastern fjords are sheltered by the group of rocky islands and the wave fetch is limited to 10-20 km. The only section of the coast affected by waves triggered by eastern winds blowing from Van Keulenfjorden is the Calypsostranda (Photo 5.5.7AB). The diffraction of waves around Renardodden leads to their significant weakening. Waves from the NE (with winds blowing from Van Mijenfjorden) crash slantwise on the southern coasts of Bellsund to the west of Renardodden. During autumn months, the coasts are hit by southern strong winds descending Recherchebreen and Renardbreen and forming short-fetch waves (Fig. 5.5.5).

The formation of longshore drifts is strongly linked with wave activity. The slantwise approach of oceanic waves to the western section of the coast results in the development of local currents of longitudinal directions. The longshore drift forms to the east of Tomtvika and at first flows from SW to NE, then after passing Rochesterpynten shift towards the W-E direction, and after passing Renardodden – change to the NE-SW direction (Fig. 5.5.6). On the base of studies conducted at the end of 1980s, it is known that longshore drift is produced during weather by short waves from the NE and E sectors (Harasimiuk & Jezierski 1991). In the Pocockodden region, they divide and one of them heads north while the other heads south. It was acknowledged that their role was decisive in shaping the evolution of zones zone between Scottelva mouth and Josephbukta especially until the 1990s (Harasimiuk 1987; Zagórski 2004, 2011). They were responsible for the spread of material from the extra-marginal outwash plains from Renardbreen and for its subsequent deposition in shore near Tyvjobekken mouth and spit in Josephbujta, especially until the beginning of 1990s (Fig. 5.5.6). However, in last dozen or so years, the role of longshore drifts heading north has weakened considerably (Zagórski 2011). The stronger influence of open ocean swell, together with the occurrence of wind waves from NW sector, led to excessive transport of material south from mouth of Scottelva (Fig. 5.5.6).

The complex arrangement of ocean currents forms under the influence of eastern winds. The direction of wind flow is often constrained by the fjord configuration. Relatively short waves from NE that originate in Van Mijenfjorden effectively undercut the cliffs of Skilvika. Close to the cliffed coast of Skilvika ocean currents converge. The stronger current, consistent with the dominant wind direction, flows westwards and later south-westwards along the coasts of Lyellstranda, Dyrstadflya and Lognesflya. Second, counter current, flows eastwards along the eastern coast of Skilvika towards the Renardodden. Around the cape a counter current clashes with a strong SE-NW current flowing along the Calypsostranda associated with short and high waves coming from the Van Keulenfjorden. As a result Renardodden is systematically prograding (Zagórski 2004a, 2011).

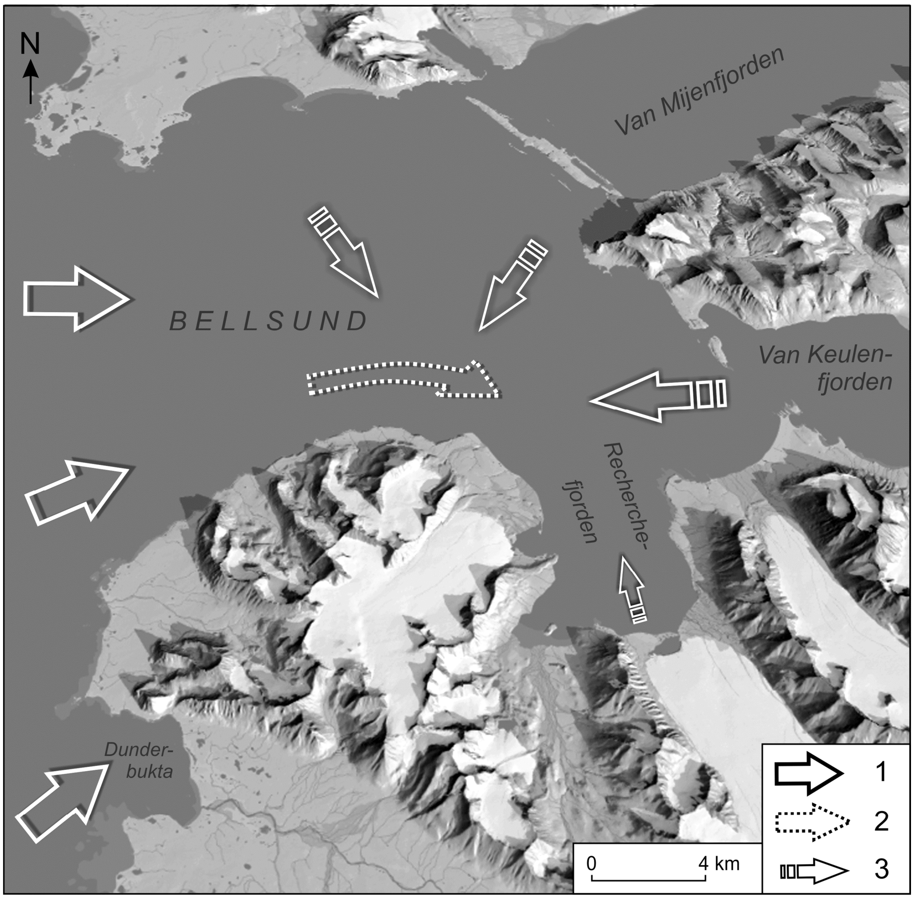

Fig. 5.5.5. Directions of waves reaching the coast of NW part of Wedel Jarlsberg Land (background: Topo Svalbard, Norwegian Polar Institute): 1- swell and ocean storm waves, 2- diffracted ocean swell, 3- short wind waves.

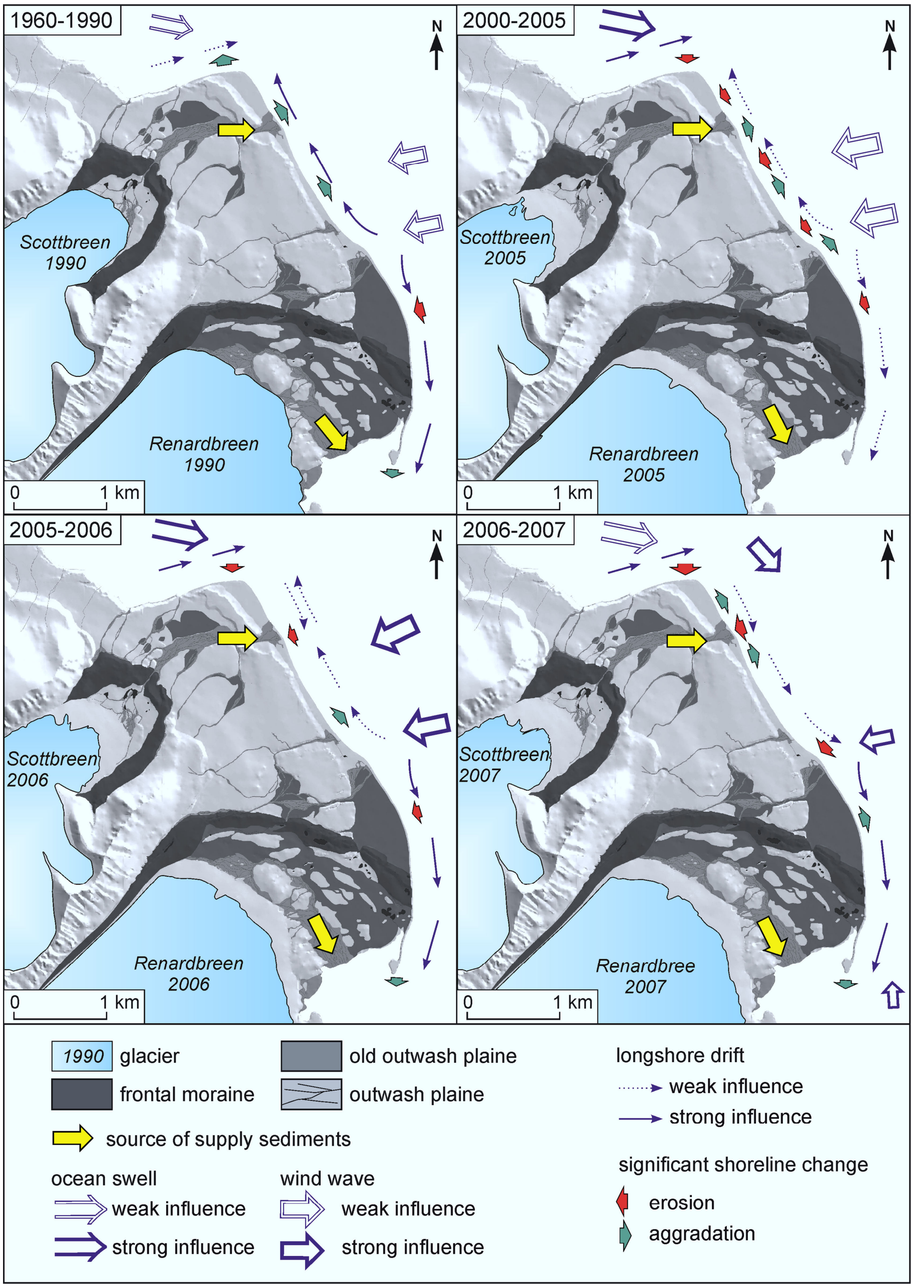

Fig. 5.5.6. The factors and processes influencing the shoreline changes along Calypsostranda between 1960 and 2007 (after: Zagórski 2011). The background based on DEM (Zagórski 2002).

In consequence of the changing wind pattern, the southern Bellsund is characterised by unstable configuration of ocean currents (Jezierski 1992; Harasimiuk 1987). The opposite situation characterise the Recherchefjorden, with stable, clockwise configuration of weak longshore drift induced by small diffraction waves associated with katabatic winds. In such conditions the role of tides comes into prominence. According to Zagórski (2011) local tidal range is 1.7 m. Tidal waves are shaping the surface of tidal flat developed in the mouth of Chamberlindalen (Harasimiuk & Jezierski 1991; Zagórski *et al.* 2012).

Besides the geomorphological effects the tides, particularly during the high tide, reinforce wave activity and longshore drift along the entire studied coast. Tides are responsible for the formation of ebb-currents operating in river mouths and tidal inlets linking lagoons with open sea.

Photo 5.5.7. The storm deposition of gravel and seaweed on the surface of terrace I - Calypsostranda (Photo K. Pękala 1995).

Ice factors and their impact on the development of coastal zone

This group of factors is represented by various forms of ice found within the coastal zone including sea-ice, polygenetic shore ice, icefoot, ice floes and glacial ice (Fig. 5.5.7, Photo 5.5.8A). Ice can act as a direct sculptor of shore zone, reinforce the geomorphological effects of coastal processes as well as protecting coasts from operation of waves, tides and currents (Jezierski 1993; Zagórski 1996; Rodzik & Zagórski 2009).

Due to the influence of warm West Spitsbergen Current and operation of long-fetch waves developed in Greenland Sea the western, open coasts of Spitsbergen are predominantly ice free. For instance, the operation of long-fetch waves along the open coast of southern Bellsund restricts the formation of stable sea-ice cover. The temporary sea ice cover that forms over nearshore waters during the periods of cold and windless weather is quickly broken by waves and winds. In relatively shallow and sheltered by group of skerry islands Dunderbukta sea ice cover last up to couple of weeks.

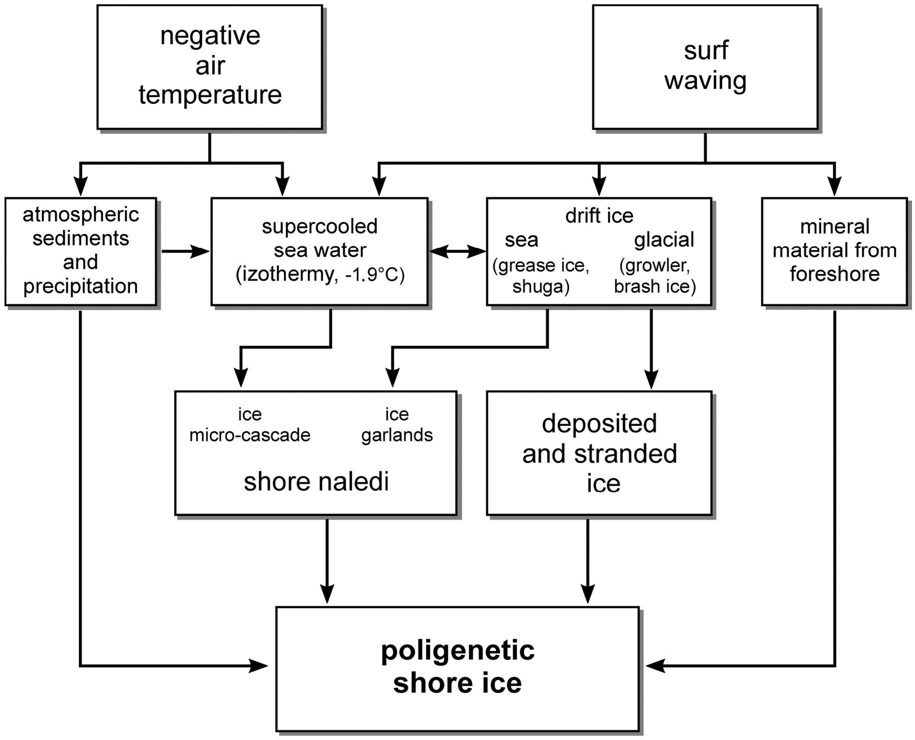

Fig. 5.5.7. Scheme of connections between development conditions and types of shore ice on high energy shores of southwestern Spitsbergen (after: Rodzik & Zagórski 2009).

Sea ice conditions are much harsher in most of the fjords: Recherchefjorden, Van Keulenfjorden and Van Mijenfjorden. In inner bays of Recherchefjorden: Josephbukta, Vestervågen and Fagerbukta sea ice cover lasts over 6 months (from December to June). Usually the full process of sea surface freezing passes through the following phases: *grease ice*, *shuga*, *ice rind*, *nilas* and *young ice*. Due to the low wave activity the freezing process very rarely passed through the phase of *pancake ice* formation. The thickness of local sea ice reaches up to 1.5 m (Rodzik & Zagórski 2009). During winter the coasts of Bellsund and Greenland Sea are reached by polygenetic shore ice. Shore ice plays an important role in protecting the coasts from the abrasion. On the other hand the reflection of waves from the ice cliff facilitates the erosion and migration of deposits from the nearshore zone. Shore ice forms in November and persist until June. The dominant form of shore ice resulting from deposition of ice floes on the shore is the icefoot. The formation of icefoot starts with the development of garland terraces that evolve from onshore freezing of waves mixed with fragments of grease ice and shuga (Photo 5.5.8B). In the next step the ice cascades are formed by freezing of water splashes. Icefoot may reach couple of meters width and form 1-3 m high ice-cliff. Uneven melting of shore ice leads to the formation of characteristic 'pitted beach' microrelief (Ruszkowska 1985; Rodzik & Zagórski 2009).

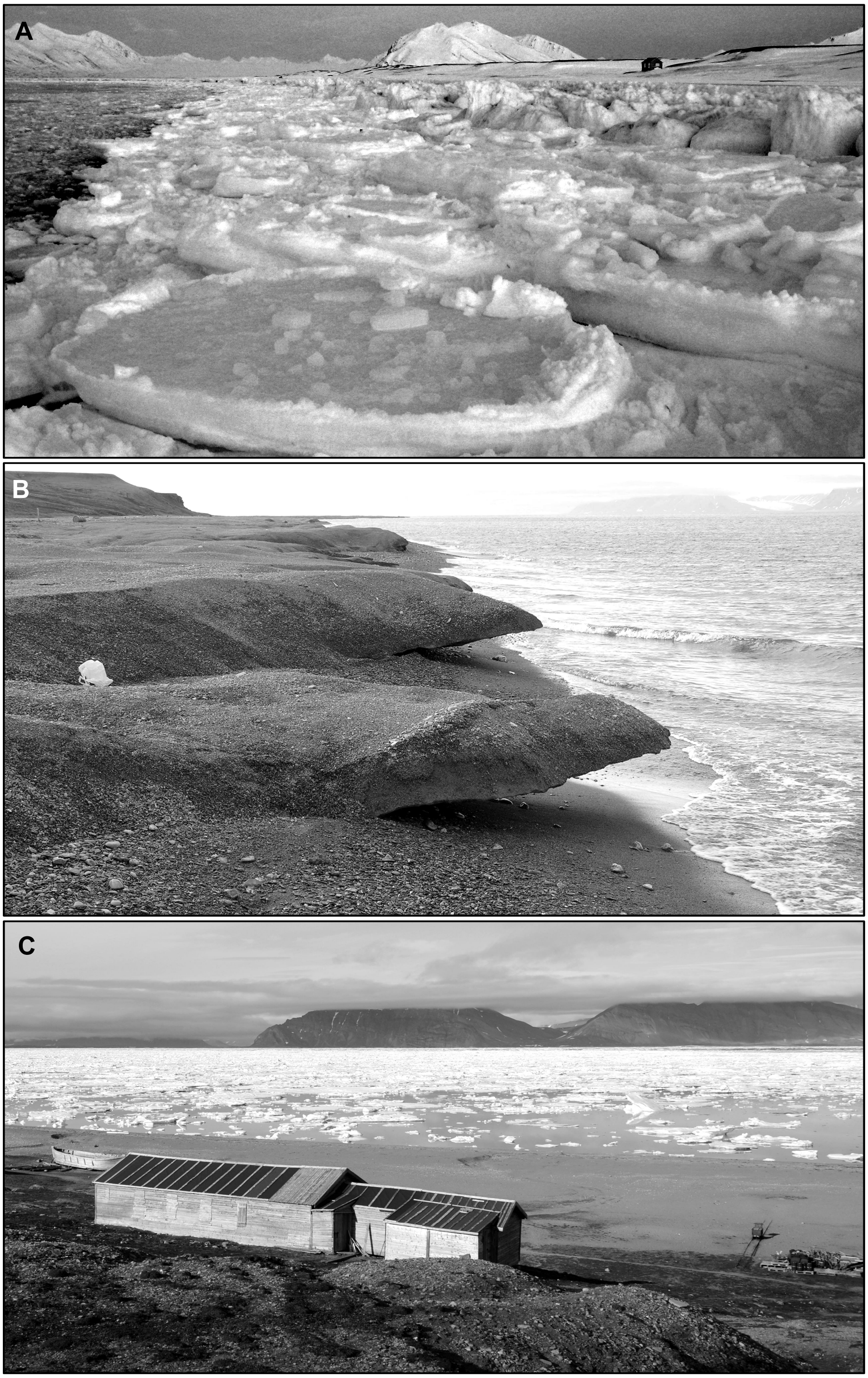

Photo 5.5.8. Types of shore ice and sea ice formed along Calypsostranda: A- poligenetic shore ice formed in spring (Photo G. Gajek, April, 2008), B- poligenetic shore ice forms in summer (Photo P. Zagórski, July, 2005), C- drifting ice in summer (Photo P. Zagórski, July, 2011).

At any time of the year, Bellsund can be filled with drifting ice, transported from the Barents Sea by ocean currents. Ice floes pushed by tidal currents fill even the most distant sectors of Bellsund fjords. The occurrence of drift ice is important in suppressing the operation of wave activity (Photo 5.5.8C).

Glacial factors and their impact on the development of coastal zone

The rapid deglaciation at the turn of Weichselian and Holocene caused the termination of large scale glacial deposits accumulation along the coasts of Bellsund. Currently, only Recherchebreen and Renardbreen form moraines within the coastal zone. The accumulation of pushed moraines is associated with glacier surges during the Little Ice Age (Reder 1996; Zagórski *et al.* 2012).

Three generations of pushed moraines were distinguished in front of Renardbreen (Pękala & Repelewska-Pękalowa 1990; Zagórski *et al.* 2007). The LIA moraine has covered the Early- and Middle- Holocene moraines and previously egzarated and redeposited relict soils from the Viking Period (Pękala & Repelewska-Pękalowa 1990; Dzierżek *et al.* 1990ab). During the post-LIA period the marine terrace (terrace I) with relict storm ridge that forms the base for LIA moraine has significantly prograded (Pękala & Repelewska-Pękalowa 1990) (See: Figs. 2.2.2, 2.2.3 and 2.2.5).

The post-LIA recession of Renardbreen led to the exposure of Josephbukta. During the 1990's the glacier front retreated on land and previously marine-terminated glacier became the land-terminated glacier. In the meantime the deposits from abrasion of Renardbreen frontal moraine started to supply the formation of a spit system that delimits Josephbukta from the east (Harasimiuk 1987; Zagórski 2004a; Zagórski *et al.* 2006, 2012) (Fig. 5.5.8).

Similar type of changes, although much larger in size, occurred across the forefields of Recherchebreen. During the LIA the glacier covered the entire Fugerbukta – the large bay in the SE part of Recherchefjorden (Fig. 5.5.9A , Photo 5.5.9A). The ice-cliff of Recherchebreen extended from Rubypynten in the SW up to Lægerneset in the NE (Reder 1996; Zagórski *et al.* 2012).

Remnants of moraines scattered around present coast of Recherchefjorden indicated the stages of glacier advance. For instance, the Rubypynten is an abraded left-bank lateral moraine reshaped by coastal processes into a cape. Whereas, the right-bank lateral moraine was deposited along 3 km long section of eastern coast of Recherchefjorden covering the marine terrace I (Zagórski 2002; Zagórski *et al.* 2012) (Fig. 5.5.9A).

During 1980's the front of Recherchebreen was separated from the Fagerbukta by system of two outwash plains accumulated on the deposits of reworked frontal moraine (Photo 5.5.9B). Only a fragment of glacier, in the form of 4-10 m high ice-cliff, terminated in a small lagoon (Harasimiuk & Jezierski 1988). In the next 25 years the front of glacier has significantly retreated and enlarged the area of a lagoon. Presently, the glacier is calving to the lagoon from 3 km long and 15-20 m high ice-cliff. Observations by Zagórski *et al.* (2012) suggest that due to the narrow inlet to the lagoon most of calved icebergs are cut off the fjord and float in the lagoon (Fig. 5.8.9BC, Photo 5.5.9BC).

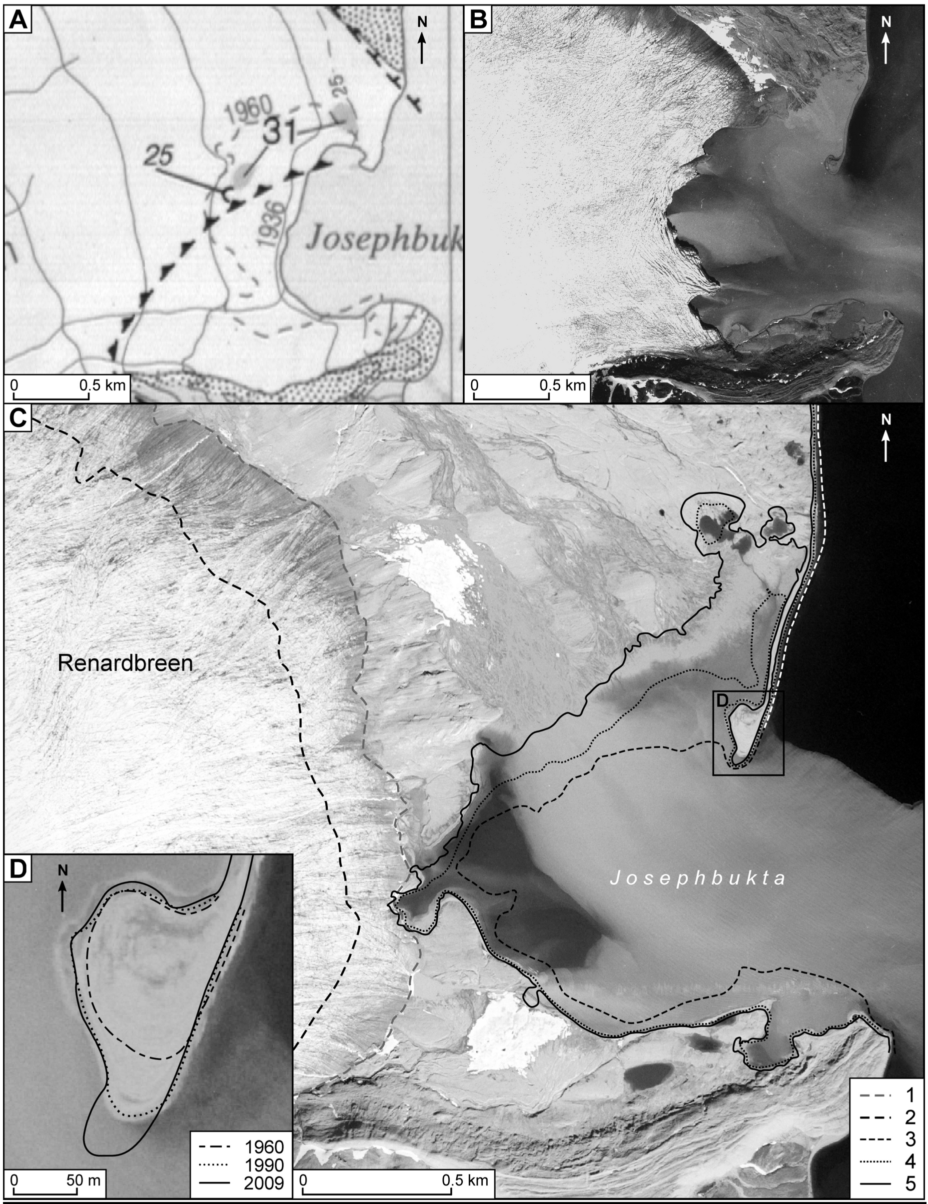

Fig. 5.5.8. Evolution of the coastal zone in front of Renardbreen (after: Zagórski *et al.* 2012): A- shorelines in 1936, based on the geological map Svalbard, 1:100,000: B11 G Van Keulenfjorden (Dallmann *et al.* 1990); B- shorelines in 1960, based on Norwegian Polar Institute aerial images (No. S60 7400); C- shorelines in 1990 based on orthophotomap (Zagórski 2005). The range of high and low spring tides in Josephbukta area indicated on base of GPS measurements in August 2008: 1- glacier front in 1990, 2- glacier front in 2009, 3- lower low water, 4- mean tide level estimated from GPS measurements, 5- higher high water; D- extension of Josephbukta spit between 1960 and 2009.

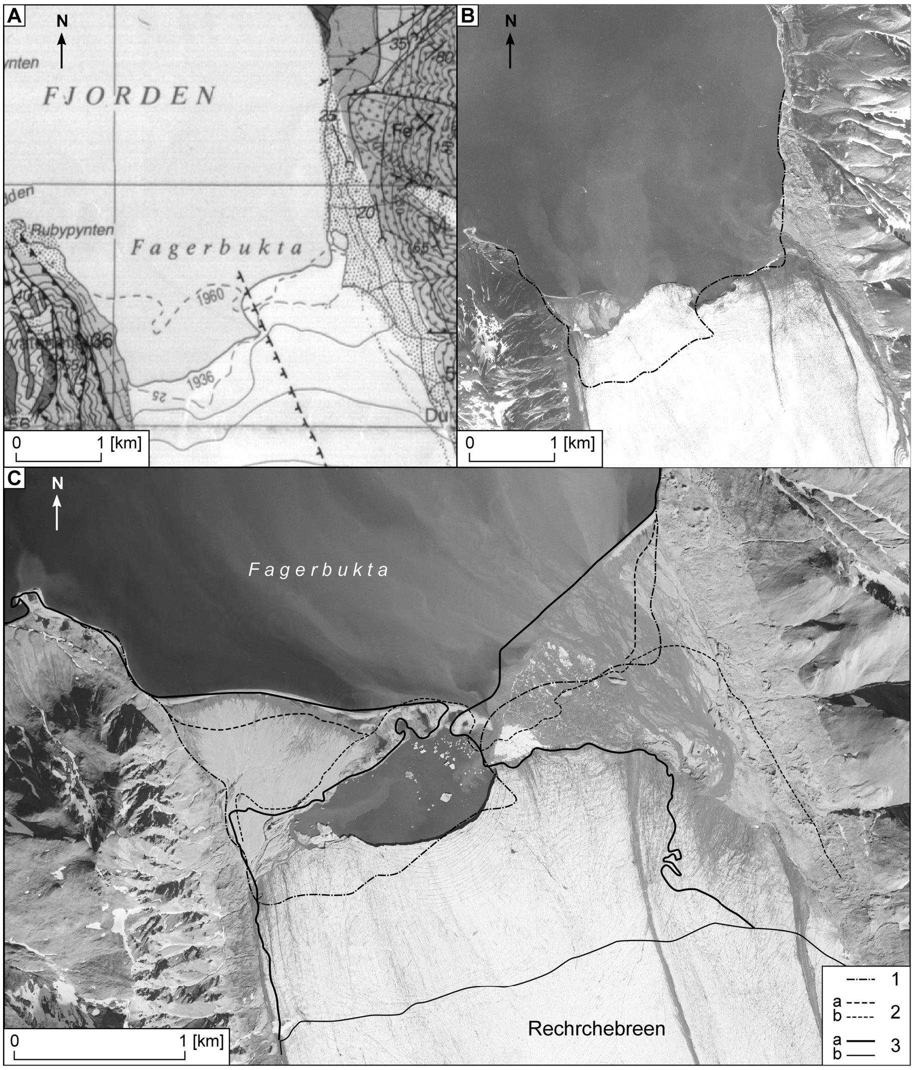

Fig. 5.5.9. Evolution of the coastal zone in front of Recherchebreen (after Zagórski *et al.* 2012): A- shorelines in 1936, based on the geological map Svalbard, 1:100,000: B11 G Van Keulenfjorden (Dallmann *et al.* 1990); B- shorelines in 1960, based on Norwegian Polar Institute aerial images (No. S60 7368); C- shorelines in 1990 based on orthophotomap (Zagórski 2005): 1- glacier front in 1936, 2a- shoreline in 1960, 2b- glacier front in 1960, 3a- shoreline in 2008, 3b- glacier front in 2008.

<u>Fluvial and glaciofluvial factors and their impact on the development of coasts zone</u>

Fluvial and glaciofluvial processes play important role in the transformation of Bellsund coasts. They are exceptionally active along the eastern section of studied coast located to the east of Renardodden. In the western part their influence is limited to the formation of several river and stream deltas. Most of the local rivers have low-gradient, drain only partly-glacierised catchments and are characterised by low rates of sediment transport (Bartoszewski 1998).

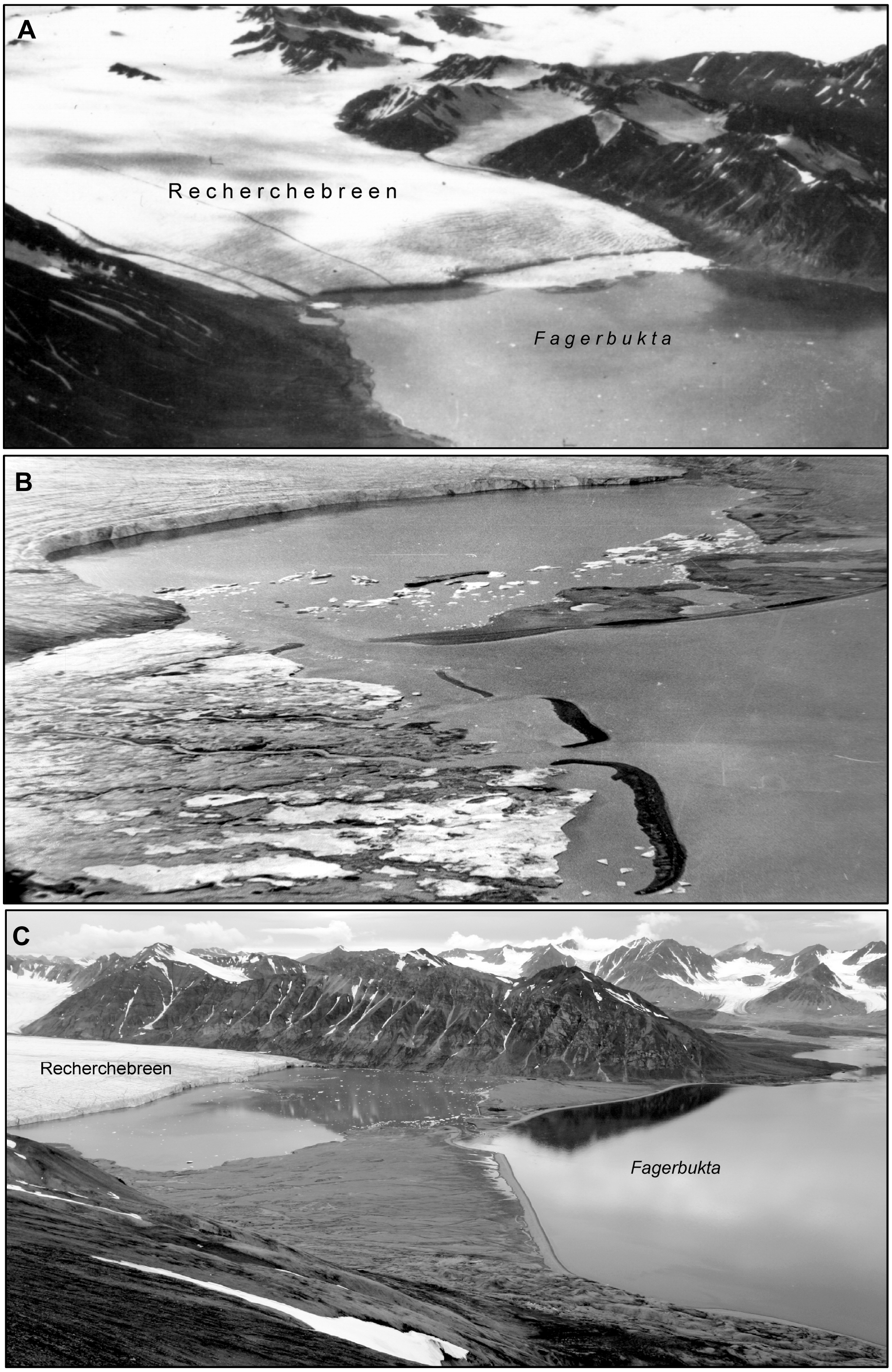

Photo 5.5.9. Development of Recherchebreen forefield: A- an oblique aerial images taken by Norwegian Polar Institute in 1936 (No. S36 94, University of Silesia) showing the position of Recherchebreen's front and icing (naledi) surfaces; B- the formation of the outwash plain and lagoon in 1987 (Photo K. Pękala); C- forefield of Recherchebreen in August 2009, inner lagoon and inactive outwash plains, currently shaped by coastal processes (Photo M. Łodziński).

The mouth sections of Blomlielva, Tjørnelva and Dyrstadelva are deeply incised in raised marine terraces and cliffs and form canyons. The impact of those small streams and rivers on the operation of coastal processes is limited to spring-melt breaching through the wide, gravel-dominated storm ridges formed during autumn-winter storms. The largest river in the study area – the Dunderelva has a strong impact on the coastal zone. River with discharges reaching dozen of cubic meters per second forms ca. 100 m wide estuary penetrated by tidal waves up to 1.5 km upstream (Harasimiuk & Król 1993; Bartoszewski 1998; Zagórski 2002).

The majority of east coast catchments is highly glacierised. Glacier rivers transport significant amounts of glacial deposits and form extensive outwash plains whose margins are to the different degree reshaped by waves, currents and tides. A good example of described process is the surroundings of Pocockodden where, at the end of the LIA, rivers draining Renardbreen accumulated an outer outwash plain (Zagórski 2004a, 2011)). At the end of the 20th century an intensive accumulation of outwash plains occurred along the coasts of Fagerbukta, in front of Recherchebreen (Reder 1996) (Fig. 5.5.9, Photo 5.5.9ABC). Recently, the accumulation of outwash plains and deltas reinforced by the operation of tides leads to the development of coasts around Josephbukta. By contrast, in Vestervågen the Chamberlinelva and several pro-glacial streams draining Crammerbreane accumulate a complex delta system that trans-form into extensive tidal flat sheltered from the operation of high waves by Reinholmen island (Photo 5.5.6C). In case of Scottelva draining Scottbreen the material delivered to the coast is immediately reworked by waves and entrained into longshore drift (Zagór-ski 2011). The mouth of Scottelva is often blocked by wide storm ridge, what leads to the formation of small coastal pond and later on during the summer season reopening of the river outlet in the form of crevasse (Fig. 5.5.10). The outlet of neighbouring Tyvjobekken is often blocked by storm ridge throughout entire summer season and the outflow occurs via seepage through a gravel barrier (Harasimiuk & Król 1992; Zagórski 2004a; Superson & Zagórski 2007).

Recent evolution of south Bellsund coastal zone

The wide (over 20 km) opening of Bellsund to the Greenland Sea exposes the local coasts to the operation of long-fetch high energy waves. Therefore, the dominant type of coasts formed around Bellsund is an abrasive coast (Fig. 5.5.4). In contrast to open coasts of Bellsund the sheltered coasts of Recherchefjorden are intensively sup-plied in glacial and glaciofluvial deposits and dominated by accumulation. The direct influence of glacial systems on the evolution of coastal zone allows to classify coast of Bellsund as *'paraglacial coasts'* (*sensu* Forbes & Syvitski 1994). The coasts of NW part of Wedel Jarlsberg Land have been divided in four characteristic sections by Harasimi-uk & Jezierski (1992) taking into account their genetic and lithological variability as well as sediment supply, wave activity and longshore dryft dynamics (Fig. 5.5.4).

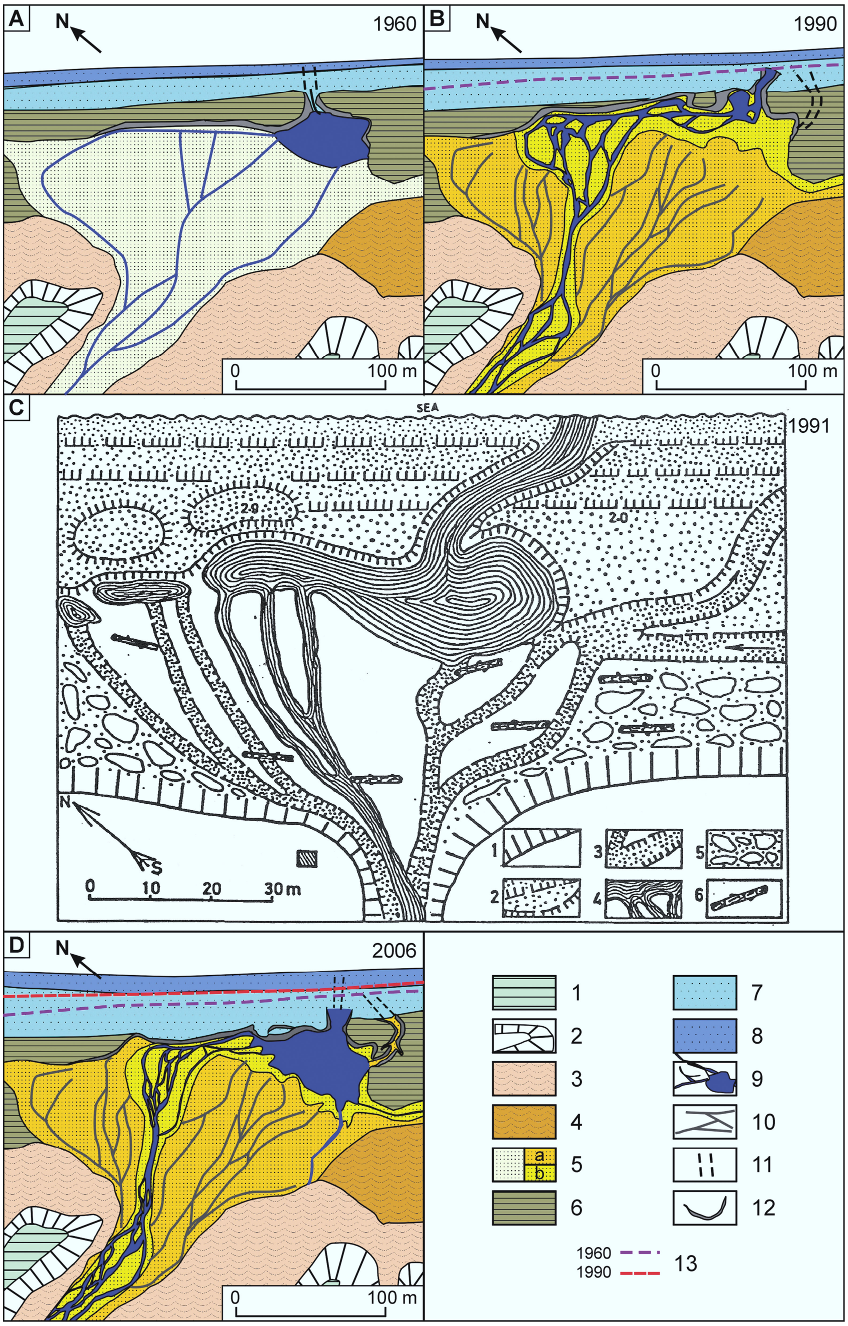

Fig. 5.5.10. Morphological changes of the Scottelva mouth between 1960 and 2006 (after: Superson & Zagórski 2007): A- morphology of alluvial fan in 1960 (after: Szczęsny *et al.* 1989); B- morphology of alluvial fan in 1990 (Zagórski 2005); C- morphology of alluvial fan in 1991 (after: Harasimiuk & Król 1992): 1- dead cliff, 2- edge of the ridge, 3- dead river channels, 4- changes of location of the lake, 5- active channels, 6- bottoms of dead channels covered with mud, 7- beach terrace at 3.5-4.0 m a.s.l., 8- driftwood; D- morphology of alluvial fan in 2006: 1- raised marine terraces, 2- edge of marine terraces, 3-solifluction slopes, 4- alluvial fan: a- dead, b- active, 5- terrace I (2-6 m a.s.l.), 6- modern storm ridge, 7- intertidal zone, 8- active river channel, 9- dead river channels, 10- crevasses, 11-micro-cliffs, 12- micro-delta, 13- position shoreline in 1960 and 1990.

Section 1 includes stripe of coast from Dunderbukta to Tomtvika dominated by flat abrasive-accumulative coast with up to 70 m wide beach. Coastal section has developed on one of the sites of Dunderdalen syncline, in poorly developed Precambrian rocks (Harasimiuk & Król 1993) (Photo 5.5.5A). This section is exposed to the operation of long-fetch waves developing in Greenland Sea. However, the coast is sheltered behind an over 1 km wide belt of skerries what limits the impact of waves on the shore to the storms occurring during high tides. Surface of skerry islands is intensively sculpted by ice floes. Only 2 km section of the northern coast of Dunderbukta is cliffed (Jezierski 1989).

Section II extends from Tomtvika to Skilvika and is formed in Precambrian tillits and quartzites (Kapp Lyell Fm., Birkenmajer 2004) covered with 2 m thick layer of marine gravels laying perpendicularly to the tectonic structures (Fig. 5.5.4). The cliffed coast up to dozen meters high has a discordant shape associated with different resistance of rocks to the abrasion. Cliffed headlands are eroded during strong storms. Bays are surrounded by mixed gravel-pebble beaches. Rocky headlands, that separate small bays, are extended by accumulations of skerries that stick out into the sea several dozen of meters and disturb the longshore drift (Photo 5.5.4A). Section II is influenced by both long-fetch waves from Greenland Sea and local short-fetch waves from N and NE that interfere with each other.

Section III includes coast between Skilvika and Pocockodden and is located in the zone of convergence of longshore drift (around Renardodden) between two zones of current's divergence (Fig. 5.5.4, Photo 5.5.6B). The end of this section is characterised by intensive coastal erosion. In the NW part, along the eastern coast of Skilvika, the cliffed coasts formed in Palaeogene sandstones with coal insertions and covered with glacial deposits are 20-25 m high (Pękala & Repelewska-Pękalowa 1990; Landvik *et al.* 1992) (Photo 5.5.3C). In the SE part of the section the erosion affects the margin of old outwash plain formed by proglacial streams of Renardbreen. The middle part of Section III is occupied by a 3 km long and several dozen of meters wide accumulative coast (Harasimiuk 1987). The characteristic elements of coastal relief are series of wide storm ridges and a dead-cliff transformed by solifluction and eroded by pronival creeks. The dead-cliff delimits the Calypsostranda marine terrace and is incised by two gorges formed by Scottelva and Tyvjobekken. The coast is influenced by the operation of various factors including glacial, ice, fluvial and glaciofluvial changing in time and in intensity (Fig. 5.5.11A).

Zagórski (2011) studied the changes of the extent of Calypsostranda between 1936-2007 using the collection of aerial images, archival maps and DGPS measurements (Fig. 5.5.11A). His study distinguished three periods of negative area balance (coastal erosion): 1936-1960, 1990-2000, 2005-2006) three periods of positive area balance (coastal progradation): 1960-1990, 2000-2005 and 2006-2007. Since the intensification of storms in the 1990's the role of marine processes is dominant in shaping the modern shoreline. For instance, in 1994, the mean erosion of Calypsostranda lower terrace observed during autumn storms was 6.5 m and locally reached 12 m. Zagórski (2011) associated the change of geometry of shoreline particularly in the surroundings of Calypsobyen, that occurred between 2000-2005 with the operation of swell waves with concomitant net positive area balance (2,060 m^2).

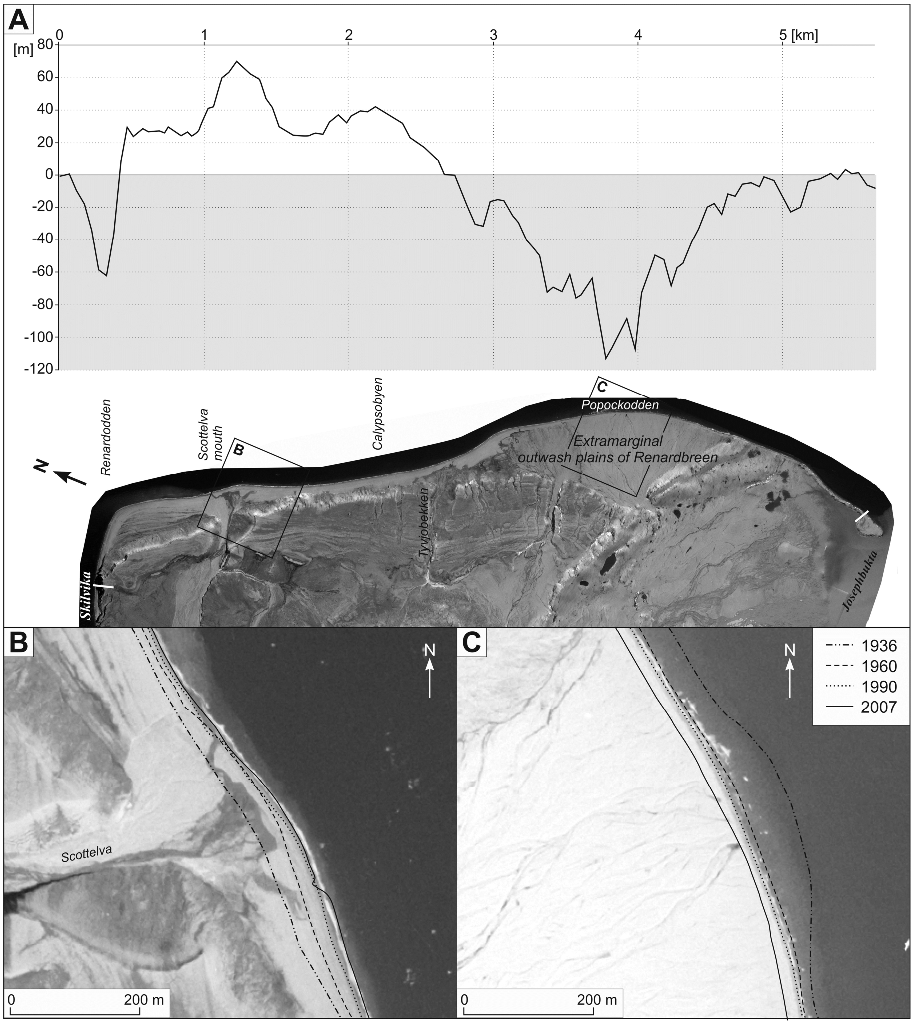

Fig. 5.5.11. A- Shoreline changes between Skilvika and Josephbukta from 1936 to 2007; B- the Scottelva mouth – shoreline progradation; C- extramarginal outwash plain of Renardbreen – shoreline erosion (after: Zagórski 2011, modified).

The sediment supply from proglacial rivers of Scottbreen and Renardbreen were of great importance for the formation of shore zone during the last century. The intensified sediment supply from Scottbreen catchment and material eroded from Skilvika cliffs resulted in over 60 m progradation of coast around the mouth of Scottelva (Fig. 5.5.11B). On the contrary, the disappearance of sediment supply to extramarginal outwash plain of Renardbreen together with operation of storms led to over 100 m erosion of shoreline around Pocockodden (Fig. 5.5.11C, Photo 5.5.10). In general, the part of Section III between Skilvika and Josephbukta is dominated by abrasion. Between 1963 and 2009 the area of terrace I decreased by 32,700 m^2, what corresponds with ca. 5.7 m (0.08 $m \cdot a^{-1}$) coastal erosion (Zagórski 2011).

Photo 5.5.10. Shoreline along Pocockodden formed as a result of the erosion of the extra-marginal outwash plains of Renardbreen (Photo K. Pękala 1992).

Section IV includes coasts of Recherchefjorden which due to the sheltered location are shaped by low-energy waves (Photo 5.5.11). The dominant role in coastal morphodynamics is played by sediment fluxes from fluvial, glaciofluvial and glacial sources (Harasimiuk 1987; Harasimiuk & Jezierski 1991; Zagórski *et al.* 2012).

The most significant changes concerned the areas in close vicinity of the fronts of the glaciers (Figs. 5.5.8 and 5.5.9). The direct influence of the glacier system and proximity of the channels of proglacial waters facilitated intensive aggradation of the coastal zones where glacial, fluvioglacial and marine processes interacted. Additionally, the intensiveness at which the coast was moulded was enhanced by the advancement of glaciers of the 'surge' type (Renardbreen and Recherchebreen). Approximately 30 km of the coast was under direct influence of glacier systems. The recession of the glaciers during the 20th century led to the formation of more than 20 km of new shoreline, especially in the forefield of the Renardbreen and Recherchebreen, including 3 km of ice cliff (Fig. 5.5.4, Photo 5.5.4C). At the same time deglaciation contributed to the transformation of some areas of the coast from proglacial to paraglacial ones: extramarginal outwash plains of the Renardbreen and outwash plains of the Recherchebreen (Photo 5.5.9ABC). In the case of the Renardbreen this was caused by a change in the direction of the discharge of proglacial waters to Josephbukta (Fig. 5.5.8). In the second case, it was the development of the internal lagoon to which all proglacial waters flowing out of the Recherchebreen disgorge. In the case of other surveyed areas of the coastal zone of the Recherchefjorden, which were indirectly shaped by the glacier systems, the changes were not so extensive.

Photo 5.5.11. View of the Recherchefjorden coast from Maria Theresiatoppen – section IV (Photo M. Dwornik 2009).

Conclusions

High Arctic coasts have received relatively little attention compared to their better studied mid and low latitude counterparts. This position needs rectifying given the rapid pace of change in the impacts on the coastal zones of the High Arctic in response to global warming.

Over 25 years of geomorphological investigations of Bellsund coasts supported by long series of hydrological, meteorological and glaciological observations make them one of the best studied coastal environments in Svalbard. The coasts of Bellsund provides a superb opportunity to quantify how High Arctic coasts responded to the Holocene sea-level and climate changes and to monitor their adjustment to the ongoing environmental change.

Acknowledgements
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Streszczenie

Geomorfologia wybrzeży

Strefa ukształtowana przez procesy morskie w północno-zachodniej części Wedel Jarlsberg Land osiąga miejscami znaczną szerokość, gdyż obejmuje zarówno podbrzeże, brzeg, jak i przyległy pas równin nadmorskich, wchodząc na znaczną odległość w głąb niezlodowaconych dolin. W obrębie omawianych wybrzeży wyróżniają się dwie substrefy: dawnej i współczesnej rzeźby litoralnej. Substrefa dawnej rzeźby litoralnej obejmuje: podniesione morskie terasy akumulacyjne i skalno-osadowe, tworzące w wielu miejscach rozległe, nieco nachylone powierzchnie, urozmaicone starymi wałami sztormowymi, zagłębieniami dawnych lagun i skalnymi ostańcami abrazyjnymi (paleoszkierami). Główne rysy rzeźby zostały ukształtowane przy udziale procesów endogenicznych, jak: izostazja, a zwłaszcza glacjoizostazja i mogą być przekształcane przez procesy egzogeniczne (Zagórski 2002) (Appendix 2).

Podniesione terasy morskie tworzą system plejstoceńskich i holoceńskich stopni abrazyjno-akumulacyjnych, nadbudowanych niekiedy miąższą serią osadów różnej genezy i zwykle rozdzielonych stromymi załomami w formie paleoklifów. Szerokość tej strefy jest zróżnicowana: od kilku kilometrów w osiach dolin do kilkudziesięciu metrów na przedłużeniu grzbietów górskich. Wyróżniono tu kilka poziomów teras morskich, ukształtowanych głównie na przełomie Weichselianu i holocenu, położonych na odpowiednich wysokościach n.p.m. (ryc. 5.5.1, fot. 5.5.2): I – 2-8, II – 10-20 m (lokalnie 7-12 m), III – 22-30 m (lokalnie 17-25 m), IV – 30-40 m n.p.m. (lokalnie 27-35 m), V – 40-50 m (lokalnie 37-50 m), VI – 50-65 m n.p.m. (lokalnie 55-65 m), VII – 70-85 m (lokalnie do 95 m), VIII – 105-120 m n.p.m. (Reinsletta) (Zagórski 2002) (Appendix 2).

Na obszarze badań można wyróżnić kilka stref glacjoizostatycznych, związanych z etapami ewolucji wybrzeży w późnym plejstocenie i holocenie (ryc. 5.5.1): 1) dolny odcinek Dunderdalen z terasami niskimi i ujściem estuariowym Dunderelvy, 2) Lognedalen i Lognedalsflya – system niskich teras morskich z abrazyjnym wybrzeżem szkierowym, 3) Dyrstadflya i Lyellstranda z dolnymi odcinkami przyległych dolin – stosunkowo wąska strefa podniesionych teras morskich, ograniczona wysokim klifem, 4) Calypsostranda – strefa podniesionych teras morskich, z dużym udziałem osadów glacjalnych, ograniczona martwym klifem, 5) południowe wybrzeże Recherchefjorden (Vestervågen) oraz dolny i środkowy odcinek Chamberlindalen – system głównie niskich teras morskich z wybrzeżem akumulacyjnym, 6) Reinsletta – system podniesionych teras morskich o lokalnych przedziałach wysokościowych (Harasimiuk 1987; Harasimiuk, Jezierski 1991; Zagórski 2002).

Współcześnie kształtowana linia brzegowa, licząca ok. 60 km długości, charakteryzuje się przewagą odcinków abrazyjnych z nielicznymi fragmentami akumulacyjnymi, położonymi w rejonach dostawy materiału terygenicznego – brzeg Calypsostrandy oraz zachodnie i południowe brzegi Recherchefjorden(ryc. 5.5.4). Wyróżniono brzegi abrazyjne (klify), rozwijające się w: metamorficznych skałach formacji Hecla Hoek, osadowych skałach paleozoiku/mezozoiku, piaskowcach paleogenu, plejstoceńskich i holoceńskich osadach żwirowych, plejstoceńskich i holoceńskich morenach oraz klify lodowe (Harasimiuk 1987; Zagórski 2004, 2011; Zagórski i in. 2006). Brzegi płaskie, abrazyjno-akumulacyjne, rozwijają się między innymi w metamorficznych skałach proterozoiku i w osadach czwartorzędowych. Współcześnie wybrzeże NW części Ziemi Wedela Jarlsberga jest kształtowane przez różne czynniki morfogenetyczne: morskie (falowanie, pływy, prądy wzdłużbrzegowe), lodowe (lód brzegowy, stały lód morski, pak lodowy, pływający lód lodowcowy), glacjalne (lodowce) oraz czynniki fluwialne i fluwioglacjalne (dopływ wody i dostawa materiału terygenicznego). Skomplikowany układ fiordów oraz zróżnicowana ekspozycja różnych typów brzegu sprawia, że czynniki te oddziałują na nie w różnym stopniu (Rodzik, Zagórski 2009; Zagórski i in. 2012).

Obecnie najbardziej stabilne jest wysokoenergetyczne wybrzeże otwartego morza, zbudowane z odpornych na abrazję, prekambryjskich skał metamorficznych i chronione w znacznym stopniu przez pas szkierów (ryc. 5.5.4). Z kolei klifowy brzeg Bellsundu jest podcinany abrazyjnie przez falowanie z różnych kierunków. Najniższą terasę wybrzeża Calypsostrandy, która może być na przemian akumulowana i abradowana, kształtują: zmienne falowanie i zmienne prądy wzdłużbrzegowe. Najszybciej zachodzi transformacja niskoenergetycznego wybrzeża Recherchefjorden, związana z dynamiką współczesnych procesów glacjalno-morskich: recesją lodowców i odsłanianiem strefy paraglacjalnej, kształtowanej przez dostawę wody i materiału mineralnego z lodowców oraz przez: pływy, falowanie i prądy wzdłużbrzegowe.

Objaśnienia

Ryciny

Ryc. 5.5.1. Zestawienie wysokościowe i profile geologiczne podniesionych teras morskich uformowanych wzdłuż południowego wybrzeża Bellsundu i Recherchefjorden (Zagórski 2004b, zmienione).

Ryc. 5.5.2. Rozwój Calypsostrandy w późnym Weichselianie (Zagórski 2007d): a- obszar przykryty przez strumienie lodowe w czasie ostatniego maksimum glacjalnego (ok. 20 ka BP), b- linia brzegowa 12 ka BP (rozwój terasy V), c- linia brzegowa 11-10 ka BP (rozwój terasy IV), d- linia brzegowa 10-9 ka BP (rozwój terasy III), e- linia brzegowa 8 ka BP (rozwój terasy II); B- krzywa zmian linii brzegowej dla NW Wedel Jarlsberg Land (Lognedalen) (Salvigsen i in. 1991).

Ryc. 5.5.3. Datowanie osadów glacjalno-morskich na przedpolu Scottbreen (Mangerud, Landvik 2007): A- profil podłużny przedpola Scottbreen na podstawie mapy topograficznej 1:100 000: B11 G Van Keulenfjorden (1952): B- zależność stratygraficzna między datowaniem linii brzegowej a morenami z okresu Małej Epoki Lodowej. Lokalizacja profilu patrz: ryc. 5.5.2.

Ryc. 5.5.4. Klasyfikacja geomorfologiczne środowiska brzegowego NW części Wedel Jarlsberg Land i lokalizacja stref nadmorskich (strefy I-V) wybranych do szczegółowych badań (Harasimiuk, Jezierski 1991; Zagórski 2002; Zagórski i in. 2006, poprawione i uzupełnione): 1- aktywne klify w skałach metamorficznych Hecla Hoek, 2- aktywne klify w skałach osadowych paleozoiczno/mezozoicznych, 3- aktywne klify w piaskowcach paleogeńskich, 4- aktywne klify w plejstoceńskich i holoceńskich osadach żwirowych, 5- aktywne klify w plejstoceńskich i holoceńskich osadach morenowych, 6- klify lodowe, 7 – platformy abrazyjne, 8- szkiery, 9- wybrzeża abrazyjno-akumulacyjne rozwinięte na proterozoicznych skałach metamorficznych, 10- wybrzeża abrazyjno-akumulacyjne rozwinięte w osadach czwartorzędowych, 11- wybrzeża akumulacyjne, 12- równie pływowe i delty, 13- grzbiety górskie, 14- rzeki, 15- moreny, 16- lodowce, 17- zasięg czół lodowców (Renardbreen i Recherchebreen) w 2009 roku.

Ryc. 5.5.5. Kierunki fal docierających do NW części Wedel Jarlsberg Land (podkład: Topo Svalbard, Norwegian Polar Institute): 1- martwe fale oceaniczne i oceaniczne fale sztormowe, 2- dyfrakcja martwych fal oceanicznych, 3- krótkie fale wiatrowe.

Ryc. 5.5.6. Czynniki i procesy wpływające na zmiany linii brzegowej wzdłuż Calypsostrandy w latach 1960-2007 (Zagórski 2011). Podkład – DEM (Zagórski 2002).

Ryc. 5.5.7. Schemat połączeń pomiędzy warunkami rozwoju i typami lodu brzegowego w obrębie wysoko-energetycznych brzegów południowego Spitsbergen (Rodzik, Zagórski 2009).

Ryc. 5.5.8. Rozwój strefy brzegowej przed czołem Renardbreen (Zagórski i in. 2012): A- linia brzegowa w 1936 r., na podstawie mapy geologicznej Svalbardu, 1:100 000: B11 G Van Keulenfjorden (Dallmann i in. 1990); B- linia brzegowa w 1960 r., na podstawie zdjęcia lotniczego Norweskiego Instytutu Polarnego (nr S60 7400); C- linia brzegowa w 1990 r., na podstawie ortofotomapy (Zagórski 2005). Zasięgi wysokich i niskich pływów syzygijnych na obszarze Josephbukty wyznaczone na podstawie pomiarów GPS w sierpniu 2008 r.: 1- zasięg czoła lodowca w 1990 r., 2- zasięg czoła lodowca w 2009 r., 3- najniższa niska woda, 4- średni poziom morza wyznaczony na podstawie pomiarów GPS, 5- najwyższa wysoka woda; D- zmiany geometrii mierzei Josephbukty w okresie 1960-2009.

Ryc. 5.5.9. Rozwój strefy brzegowej przed czołem Recherchebreen (Zagórski i in. 2012): A- linia brzegowa w 1936 r., na podstawie mapy geologicznej Svalbardu, 1:100 000: B11 G Van Keulenfjorden (Dallmann i in. 1990), B- linia brzegowa w 1960 r., na podstawie zdjęcia lotniczego Norweskiego Instytutu Polarnego (nr S60 7368, Uniwersytet Śląski); C- linia brzegowa w 1990 r., na podstawie ortofotomapy (Zagórski 2005): 1- zasięg czoła lodowca w 1936 r., 2a- linia brzegowa w 1960 r., 2b- zasięg czoła lodowca w 1960 r. , 3a- linia brzegowa w 2008 r., 3b- zasięg czoła lodowca w 2008 r.

Ryc. 5.5.10. Zmiany morfologiczne ujścia Scottelvy w latach 1960-2006 (Superson i Zagórski 2007): A- morfologia stożka aluwialnego w 1960 r. (Szczęsny i in. 1989); B- morfologia stożka aluwialnego w 1990 r. (Zagórski 2005); C- morfologia stożka aluwialnego w 1991 r. (Harasimiuk i Król 1992): 1- martwy klif, 2- krawędzie i wały, 3- martwe koryta rzeczne, 4- zmiany położenia jeziora, 5- aktywne koryta, 6- dna martwych koryt wypełniowe mułkami, 7- terasa plażowa 3,5-4,0 m n.p.m., 8- drewno dryftowe; D- morfologia stożka aluwialnego w 2006 r.: 1- podniesione terasy morskie, 2- krawędzie teras morskich, 3- stoki soliflukcyjne, 4- stożek aluwialny: a- martwy, b- aktywny, 5- terasa I (2-6 m n.p.m.), 6- współczesny wał sztormowy, 7- strefa pływowa, 8- aktywne koryta rzeczne, 9- martwe koryta rzeczne, 10- krewasy, 11- mikroklify, 12- mikrodelta, 13- położenie linii brzegowej w latach 1960 i 1990.

Ryc. 5.5.11. A- zmiany linii brzegowej między Skilviką a Josephbuktą w latach 1936-2007: B- ujście Scottelvy – przyrost wybrzeża; C- ekstra-marginalne stożki sandrowe Renardbreen – abrazja morska (Zagórski 2011, zmienione).

Fotografie

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Fot. 5.5.3. A- aktywne klify rozwinięte w skałach metamorficznych Hecla Hoek w Dunderdalen (fot. P. Zagórski 2012), B- aktywne klify rozwinięte w paleozoiczno-mezozoicznych skałach osadowych w rejonie Reinsletty (fot. P. Zagórski 2011), C- aktywne klify rozwinięte w piaskowcach paleogeńskich w Skilvice (fot. P. Zagórski 2011),

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Fot. 5.5.5. A- wybrzeże abrazyjno-akumulacyjne w Dunderbukcie (fot. P. Zagórski 2012), B- wybrzeże abrazyjno-akumulacyjne rozwinięte w osadach czwartorzędowych - fale wiatrowe nachodzące na żwirową barierę rozwiniętą wzdłuż mierzei Josephbukty (fot. P. Zagórski 2011), C- nieaktywne sandry Recherchebreen niszczone w wyniku termoabrazji (fot. P. Zagórski 2008).

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