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Schmidt hammer tests across a recently deglacierized rocky coastal zone in Spitsbergen – is there a "coastal amplification" of rock weathering in polar climates?

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Abstract: A significant limit to current understanding of cold coast evolution is the paucity of field observations regarding development of rocky coastlines and, in particular, lack of precise recognition of mechanisms controlling rock coast geomorphology in polar climates. Results are presented from a pilot survey of rock resistance using Schmidt Hammer Rock Tests (SHRT) across the recently deglacierized Nordenskioldbreen forefield and coastal zone, in central Spitsbergen, Svalbard. The aim is to improve understanding of the effects of rock weathering on high latitude coasts. SHRT across a field of roches moutonnées of metamorphic rocks, uncovered from ice over the last century and exposed to the operation of littoral processes, demonstrated significant relationships between rock surface resistance and distance from present shoreline, distance from the ice cliff as well as thickness of the snow cover. Sites closest to the present-day shoreline were characterized by lower resistance in comparison with more inland locations. The result support models that advocate intensification of weathering processes in cold region coastal settings.

Key words: Arctic, Svalbard, rocky coasts; SHRT, coastal evolution.

Introduction

One of the most controversial problems of cold region coastal geomorphology is the determining of the relative significance of littoral processes and frost weathering in controlling rocky cliff and shore platform morphology. The classic example of this debate is the origin of strandflats which has been a regular topic for discussion in the geomorphological literature for almost a century (Nansen 1922; Dahl 1946; Werenskiold 1952; Moign 1974; Guilcher *et al.* 1986; Holtedahl 1998). Until the beginning of the 21th century world-leading coastal geomorphologists often claimed that it is impossible to obtain a clear agreement on the efficiency of coastal processes in high latitudes (Trenhaile 1983; Byrne and Dionne 2002).

Recent decades have seen major development in Arctic coastal research due to projects of the Arctic Coastal Dynamics (ACD) Group (Rachold *et al.* 2005; Forbes *et al.* 2011) and the reopening of Russian works to the wider scientific community, especially in the field of thermoabrasion (Aré 1988; Nikiforov *et al.* 2005; Aré *et al.* 2008; Streletskaya *et al.* 2009). However, the major focus in these initiatives has been on understanding and modelling ice-rich permafrost coastlines, particularly in Alaska, western Canada, and the Laptev Sea region, which are characterized by some of the most rapid erosion rates in the world (Lantuit *et al.* 2011). The role of ice, snow and frost action on rocky cliffs and shore platforms, specifically in sheltered fjords of polar archipelagos, remains poorly understood (Trenhaile 1997).

Furthermore, the geomorphology of cold region rocky coasts is marked by significant regional contrasts. On the one hand during the last three decades several geomorphological works along Atlantic Canada's rocky shorelines (*e.g.* Dionne and Brodeur 1988; Dionne 1989; Trenhaile and Mercan 1984; Trenhaile *et al.* 1998; Trenhaile 2001; Trenhaile *et al.* 2006; Porter and Trenhaile 2007; Porter *et al.* 2010) have realized fundamental advances in our understanding of ice and frost action on the morphology of intertidal zones as well as "freezing-thawing & wetting-drying" influence on shore platforms and cliffs relief. Relatively few investigations, however, have tested the efficiency of those processes in polar settings.

In the early 1990's Ødegård and Sollid (1993) and Ødegård *et al.* (1995) investigated rocky cliffs in northern Spitsbergen (Kongsfjorden and Liefdefjorden) to understand the thermal regime in frozen rocks beneath a melting snow cover. Their observations identified four periods of differing thermal impacts on coastal cliff breakdown, and postulated processes of thermal stresses related to subzero temperature oscillations. They argued that the formation of segregation ice in fractured rock is one of the leading mechanisms controlling rock coastal morphology in polar environments. The only ACD project carried out on a high latitude rocky coastal zone was a study by Wagensteen *et al.* (2007) in Kongsfjorden (Spitsbergen). Using detailed photogrammetric survey these authors demonstrated that rockwall retreat rates in polar coastal settings are higher relative to the more inland locations studied by Rapp (1960) and André (1997). Interestingly, similar "coastal amplification" of weathering along polar shorelines was previously postulated by Jahn (1961), but the concept has never been sufficiently tested and clarified.

In this paper I explore further the hypothesis of "coastal amplification" of weathering rates on the rocky coasts of Spitsbergen. To do so, I select the recently deglaciated coastline adjacent to the Nordenskioldbreen glacier, where I report results of Schmidt Hammer Rock Tests across transects that extend from the present coast inland. The work is interesting since the study site is characterised by a relatively dry polar climate and limited fetch, in contrast to the maritime often stormy climate of western coast where majority of previous rocky coastal studies were carried out (Jahn 1961; Moign 1976; Guilcher *et al.* 1986; Ødegård and Sollid 1993; Ødegård *et al.* 1995; Migoń 1997; Wagensteen *et al.* 2007).

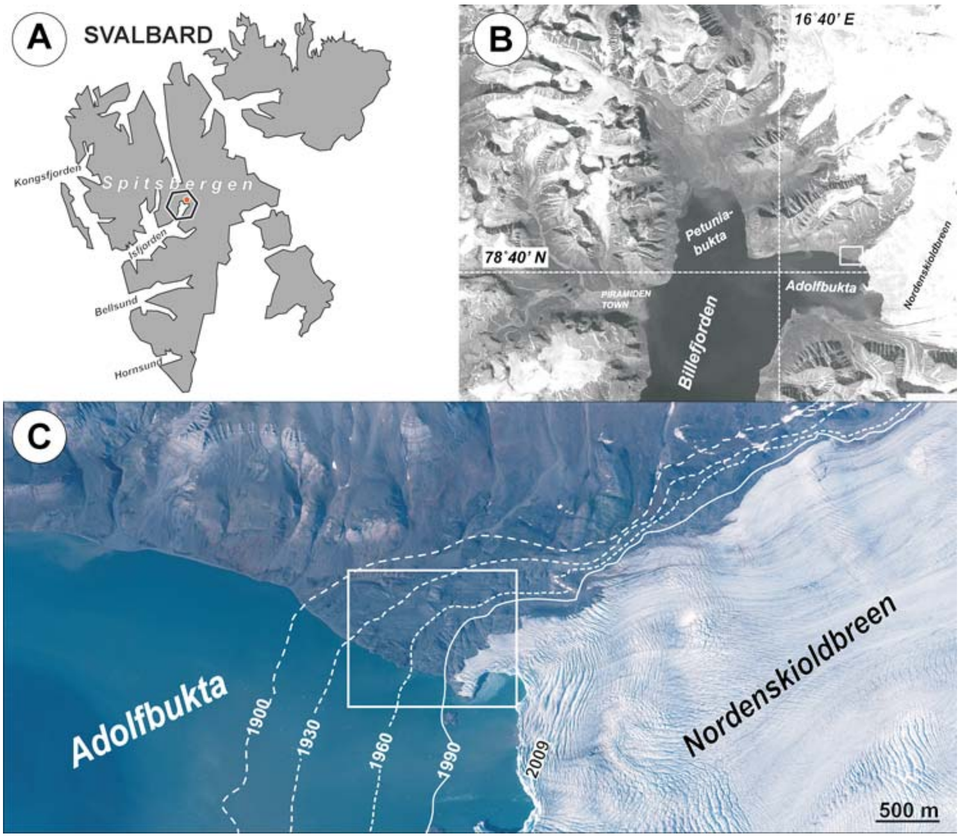

Fig. 1. Location of the study area. **A**. Svalbard Archipelago, map shows main fjords along the western coast of Spitsbergen Island, dot in a polygon marks location of study area. **B**. Main bays of northernmost Billefjorden region – middle branch of Isfjorden largest fjord system of Spitsbergen, white Square indicates section of the rocky coastline selected for study. **C**. Northern Adolfbukta, Central Spitsbergen. Fragment of orthophotomap based on Norwegian Polar Institute aerial photgraphs taken in 2009. Image shows the current front of Nordenskioldbreen: the dashed lines indicate former positions of this tide-water glacier, in the years 1900–1930–1960–1990. White square marks the selected roche moutonée field where SHRTs were carried out in summers 2009–2010 and is zoomed in Fig. 2A.

Study area

Research was undertaken on the recently exposed rocky forefield of Nordenskioldbreen, along the northern shores of Adolfbukta, in the central part of Spitsbergen (Fig. 1). Adolfbukta represents a microtidal environment, with a tide range *ca* 1.5m, and is characterized by lengthy periods of winter sea ice (typically 7–8 months). After spring/summer break-up, floating sea ice is normally rapidly removed from the basin under appropriate wind conditions. During the summer, the coastline is influenced by debris-rich growlers which are sourced by calving from Nordenskioldbreen – the only tidewater glacier in Billefjorden (Szczuciński *et al.* 2009). Wave energy is limited by a shallow fjord sill (less than 50 m) and narrow entrance, so wave action is restricted to the ice-free summer months, mainly at high tides and under rare storm events. Meteorological conditions in the centre of Spitsbergen differ from the western coast in being colder and less maritime (Przybylak *et al*. 2007). Average annual precipitation is typically less than 200 mm yr^{-1}, and mean annual air temperature is *c.* -6.5°C with air temperatures above 0°C occurring between June and the end of September (Rachlewicz and Szczuciński 2008). Frozen ground conditions are extensive and vary from thick and continous permafrost in the mountain ranges to relatively thin and recently developed permafrost in glacial valleys. Discontinuous and thin permafrost (or even non-frozen ground) occurs in the coastal and seabed area of the fjords (Humlum *et al.* 2003). Snow cover is thin (approx. 0.3 m on the ice-bounded fjord, and 0.6–0.9 m in the valleys), although wind action accumulates snowdrifts 1–2 m deep at the bottom of cliffs (based on author's winter survey in 2009).

Several authors (Rachlewicz *et al.* 2007, Małecki 2009) documented the high rate of retreat of all glaciers in the northern part of the Billefjorden region. Since the end of the Little Ice Age (in Svalbard, at the beginning of 20^{th} century) Nordenskioldbreen retreated approximately 3.5 km (Fig. 1) exposing *ca* 17 km^2 of unstable para-periglacial landscape (following the definition of *para-periglacial* by Mercier 2008) – characteristic of the majority of glacier forelands in the vicinity (Rachlewicz 2010). For coastal studies it is also noteworthy that in the Billefjorden region, the highest Late Weichselian marine limit reaches approx. 90 m a.s.l. and the relative sea-level reached close to present in the mid to late Holocene (Salvigsen 1984; Forman *et al.* 2004).

The local geology is one of the most diverse in the Svalbard Archipelago due to disturbance of geological units associated with the Billefjorden Fault Zone (Dallmann *et al.* 2004). The major bedrock units exposed by post-LIA retreat of Nordenskioldbreen consist of hard and resistant Precambrian metamorphic rocks (Smutsbreen Unit), including plagiogneisses, garnet-biotite schists, amphibolites, quartzites and marbles. For this study, an approximately 1 km^2 zone was selected, encompassing plagiogneiss roche moutonnées and plunging cliffs, between the present-day shoreline, ice-cliff and LIA moraine belt (Fig. 1).

Methods

Schmidt hammer tests have been used in weathering and dating investigations of glacier forelands and mountainous areas since the 1960's (Goudie 2006), although more recently this inexpensive tool has thrown new light on hard rock coastal geomorphology (*e.g.* Trenhaile *et al.* 1998; Stephenson and Kirk 2000a, b; Dickson *et al*. 2004; Thornton and Stephenson 2006; Cruslock *et al.* 2010; Chelli *et al.* 2010; Kennedy *et al.* 2010). In this pilot study I took 725 Schmidt hammer readings at 29

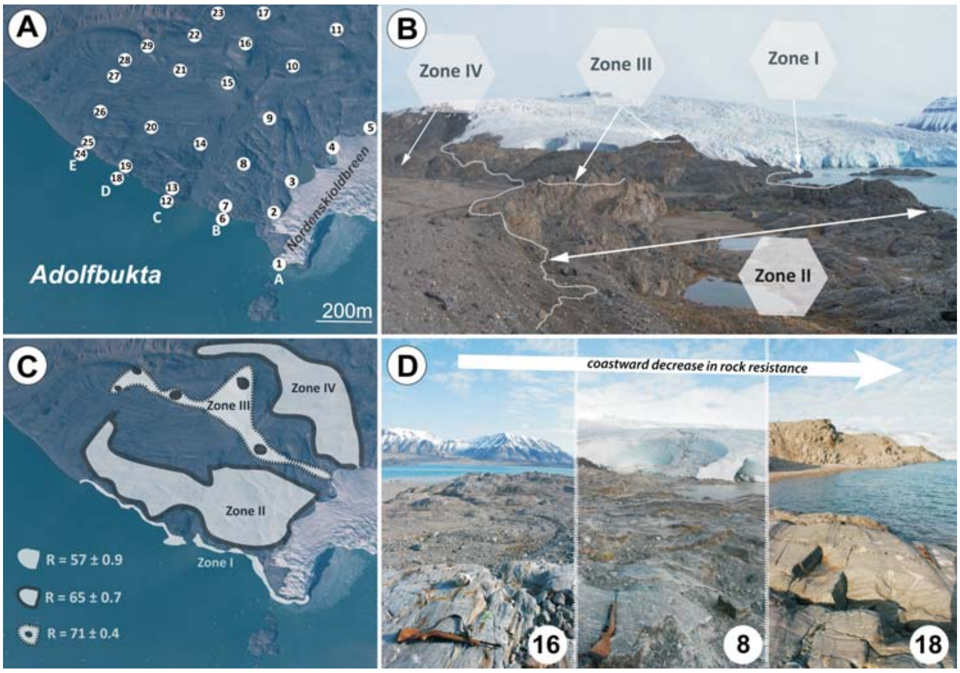

Fig. 2. Location and key findings of SHRT in northern Adolfbukta. **A**. SHRT sites and profiles – white dots with numbers 1–29 indicate locations of rock surfaces hit during tests whereas letters A–E along the coast point the starting point of each of the test profiles. **B**. Oblique image showing the spatial distribution of characteristic zonality in rock resistance along tested rock surfaces. **C** Map of rock resistance variability: Zone I – coastal zone of lowest rock resistance, Zone II and IV – interior forefield of medium rock resistance, and Zone III – peaks of roches moutonées of highest rock resistance. **D**. Examples of rock surfaces from different resistance zones, riffle indicates the direction of ice flow, white arrow indicates the general trend of lowering rock resistance. Left image: example from Zone III – peaks of roches moutonées – highest rock resistance, smooth surfaces, no snow cover; Middle image: example from Zone II & IV – forefield interior – medium rock resistance, debris cover, thick snow cover in winter; Right image: example from Zone I – coastal strip – lowest rock resistance, wandering snowdrifts, wave & tide action. Numbers in white dots (bottom right corner) indicate location of given SHRT site shown on Fig. 2A.

sites (Fig. 2A) following the methodology of Day and Goudie (1977) and Selby (1980), using a classic Proceq N-type tool which provides an arbitrary measure of rock resistance shown on a scale from 10–100 (rebound values – R).

During measurements 25 hits were made at points randomly selected from each of the 29 sites. According to Niedzielski *et al.* (2009) this number of readings provides accurate mean Schmidt hammer test values in the majority of lithologies. Only on several inaccessible surfaces located on the higher parts of cliffs the number of hits was reduced to 10. Each site consisted of *ca* 10×10 cm area of gneissic surface.

The sampling strategy took into consideration distance of the rock surface from the present-day shoreline, and from the current glacier front position (Fig. 2A). The starting point of each of five profile lines was a rock surface at mean sea-level, approximately 0.5 meters (Profile A: S1–S5), 200 meters (Profile B: S6–S11), 400 meters (Profile C: S12–S17), 600 meters (Profile D: S18–S23) and 800 meters (Profile E: S24–S29) from the present ice cliff position. From each of the starting points the profiles continued inland every 150 meters in line with the Nordenskioldbreen front. To test if there is a vertical difference in rock resistance up the cliff wall, additional SHRT were taken on the top of the cliffs above the starting points (5–15 meters above mean sea-level) in Profiles B–E.

Prior to statistical analysis all anomalous R-values were removed on the basis of Chauvenet's criterion recommended in the interpretation of SHRT by Göktan and Ayday (1993). To test the significance of differences between R-values measured along coastal and more inland roche moutonnée surfaces, a Cochran and Cox test was applied. Kruskal-Wallis and Dunn's tests were run to compare the R-values variations between zones I, II and III.

Rock surface resistance

Table 1 summarizes the SHRT results and presents the mean R-values calculated for each tested rock surface. The following zones of rock resistance can be clearly distinguished (Fig. 2):

Zone I – the coastal: strip covering the lower part of plunging cliffs affected by sea ice movement, wave action and sea spray (Sites: S1, S6, S12, S18 and S24), with mean R-values of 57±0.89.

Zone II – area of intermediate rock resistance – strip of roches moutonnées between the top of the cliffs and Zone III (Sites: S2, S3, S7, S8, S13, S14, S19, S20, S25, S26, S27), with mean R-values of 66 ± 0.83.

Zone III – summits of roches moutonnées – characterized by the highest rock resistance, with mean R-values of 71±0.42.

Zone IV – area of intermediate rock resistance – strip of roches moutonnées adjacent to Nordenskioldbreen lateral moraines (Sites: S5, S11, S17, S23), with mean R-values equal 64 ±0.65.

Discussion

In general, all results of SHRT taken along the present-day shoreline were about 5 units lower compared to R-values on the upper parts of the plunging cliffs, and often over 10 units lower than those from summits of roches moutonnées and more inland sites. In all cases Cochran and Cox tests confirmed differences in R-values between coastal (lower resistance) and inland sites (higher resistance). The analysis of regression proved that R-values from rocks located along the coast were significantly lower than those obtained along inland roches moutonnées (Fig. 3A). No trends exist across profiles perpendicular to glacier front (Fig. 3B–D). In-

Table 1

Schmidt Hammer Rock Tests summary. Statistical parameters for each of the test sites and topographical information regarding their distance from ice front, present shoreline and approximate time of the post-Little Ice Age deglaciation. Sites in grey shading were the starting points of each of five profiles.

Site	Mean R-value	Margin of error (95%CI)	Median	Mode	Min	Max	Skewness	Distance from the shoreline (m)	Distance from the glacier front (m)	Height above mean sea-level (m)	Age of exposure from beneath glacier ice
S1	51	1.17	51	multimodal	45	57	-0.19	0	0.5	0	2008–2009
S2	68	0.58	68	68	65	70	-0.01	150	0.5	23	2008–2009
S3	67	0.68	67.5	69	64.5	69	-0.58	300	0.5	42	2008–2009
S4	68	0.5	68	69	66	70	-0.12	450	0.5	37	2008–2009
S5	68	0.79	69	70	64	70	-0.59	600	0.5	72	2008–2009
S6	57	0.83	57	57	54	61	0.65	0	200	0	1960–1990
S7	65	0.87	66	66	62	68	-0.20	1	200	28	1960–1990
S8	69	0.58	69	70	66.5	71	-0.03	150	200	37	1960–1990
S9	72	0.28	72	73	71	73	-0.62	300	200	33	1960–1990
S10	65	0.47	65	65	63	67	-0.29	450	200	63	1930–1960
S11	62	0.67	62	63	59	64	-0.35	600	200	96	1930–1960
S12	62	0.48	62	61	61	64	0.83	0	400	0	1930–1960
S13	69	0.74	69	70	66	72	-0.20	1	400	13	1930–1960
S14	68	0.79	69	70	64	70	-0.59	150	400	20	1930–1960
S15	68	0.74	68	70	64	70	-0.46	300	400	52	1930–1960
S16	73	0.35	73	73	71	74	-0.68	450	400	78	1900–1930
S17	60	0.88	60	58	55	63	-0.37	600	400	81	1900–1930
S18	59	1.05	59	multimodal	54	64	0.24	0	600	0	1930–1960
S19	63	1.04	63	multimodal	60	68	0.26	1	600	14	1930–1960
S20	68	0.82	69	70	64	70	-0.91	150	600	20	1930–1960
S21	73	0.4	73	73	71	74	-0.45	300	600	40	1930–1960
S22	65	0.56	65	65	62	67	-0.48	450	600	90	1900–1930
S23	63	0.55	63	63	60	65	-0.59	600	600	164	1900–1930
S24	58	0.91	58	58	54	62	-0.08	0	800	0	1900–1930
S25	59	1.16	59	multimodal	54	65	0.14	1	800	14	1900–1930
S26	65	0.73	65	63	62	68	0.19	150	800	17	1900–1930
S27	65	0.7	66	66	62	68	-0.60	300	800	14	1900–1930
S28	70	0.38	70	70	68	71	-0.24	450	800	27	1900–1930
S29	73	0.26	73	73	72	74	-0.30	600	800	40	1900–1930

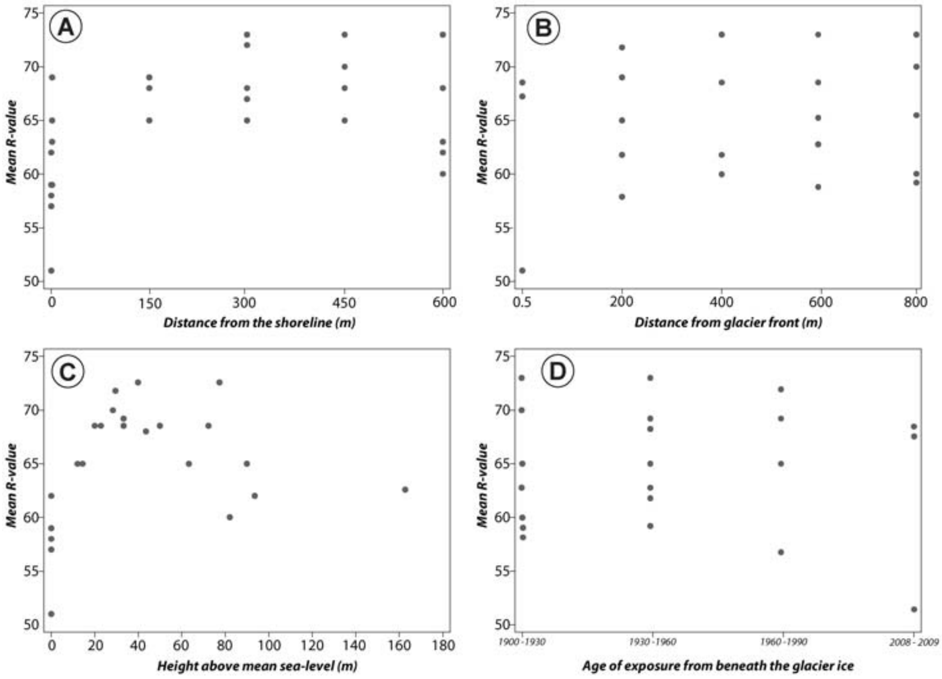

Fig. 3. Mean R-values obtained during SHRT. **A**. Along the coast and more inland locations with a significant trend of seaward rock resistance weakening. **B**. Along lines perpendicular to glacier front – no significant relationship found. **C**. Across roches moutonées of different height above mean sea-level – no significant relationship found. **D**. Across zones exposed by retreating Nordenskioldbreen since the end of LIA – no significant relationship found.

terestingly the rock surfaces on plunging cliffs do not contain any cracks or signs of ice movement, whereas the roches moutonnées are covered with glacial striations and cracks. However, none of those surficial modifications reduced rock resistance of inland roches moutonnées. On the contrary, it seems that glacial erosion of roche moutonnée surfaces exposed fresh, non-weathered rock, which was hardly modified by para-periglacial processes, whereas rock surfaces deglaciated in the same period, but located in a zone of coastal influence, had been subjected to intensified weathering. Low waves and a lack of beach sediments which could be used in quarrying and polishing the cliff walls appears to have led to the formation of the weak rock layer in the intertidal zone. The lower resistance of coastal rock surfaces in relation to inland outcrops may relate to the low-energy fjord environment. Weak wave activity in such a sheltered fjord as Adolfbukta is unable to erode and remove rock weakened by intertidal wetting-drying and frost shattering. This may be responsible for preservation of a weathered layer in the coastal zone. Moreover, the continuous and intensive operation of para-periglacial processes since the end of the LIA has led to the removal of unstable and weak rock surfaces from the Nordenskioldbreen foreland, exhuming hard resistant outcrops. Similar relation has been discovered by Blanco-Chao et al. (2007) during the study on shore platform evolution in para-periglacial environment of northern Galicia, Spain. In their survey SHRT indicated lower rock strength along platforms which were continuously influenced by tidally-induced weathering, whereas in areas where weathered material was removed by abrasion exposing fresh outcrops – rocks were more resistant. Galician example highlighted the significance of inherited factors such as glacial deposits and former shoreline configuration which may have a direct influence on the rocky shoreline evolution after deglaciation and during warmer periods associated with intensified sediment removal, abrupt relative sea-level changes and prolonged open water conditions.

Another factor that affects the degree of rock weathering is the effect of snow cover on rock thermal regime (*e.g.* Ødegård and Sollid 1993). Winter observations revealed that the lower parts of the coastal cliffs in the study area are protected by up to 2 meter thick snowdrifts, and an even deeper snow cover could be filling hollows between roches moutonnées in Zones II and IV. However the snow cover along the cliffs is typically uneven, dotted with snow-free rock surfaces and rock bulges. The coastal cliff in Adolfbukta is south-facing and therefore the protruding rock surfaces warm up strongly during polar spring/summer, and the snow cover rapidly melts or sublimates. After sunset or during the polar day when the rockwall is in shadow, the surface temperature cools rapidly, what can lead to freezing of water in rock cracks or crevices: indeed, the surface is always subject to very strong thermal stresses leading to rock disintegration. The results of Hall (1993) on Livingstone Island (Antarctica) emphasized that prolonged wetting of a rock surface by melting snowpatches enhances bedrock weathering, especially on leeward slopes, which appears to be the case on a cliff speckled with snow patches. Differences in snow cover thickness and duration might entail the reduction of rock resistance also in roches moutonnées located far from the coast but affected by late-lying snow cover. The only zones devoid of snow cover or glaciofluvial action were the summits of roches moutonnées and the tops of plunging cliffs, which may imply more stable moisture conditions, and less effective chemical weathering in those zones (*e.g.* Ballantyne *et al.* 1989). The upper parts of the cliffs, however, were often covered with bird guano (a layer up to 2 cm thick), undoubtedly enhancing rock chemical weathering and resulting in slightly weaker resistance (mean R-values for sites 7, 13, 19, 25 are 64 ± 0.95) than more inland sites such as 9,15, 21, 27 (mean R = 67 ± 0.53).

Rock surfaces in Zones II and IV were also subject to lichen colonization and there evidence of meltwater overwashing (old stream channels and accumulations of glaciofluvial gravels, which are already covered by tundra). Generally, even though the variety of subaerial processes which may affect the degree of rock fragmentation appeared to be greater in more inland sites, the results of SHRT indicated that rock surfaces there are more resistant than rockwalls near the sea. This suggests the operation of processes, or the existence of specific conditions, responsible for the weakening of rock strength in the lower parts of cliffs. This may be associated with a "coastal amplification" of rock weathering (*e.g.* tidal wetting and drying, rock saturation level, salt weathering, wave action or sea ice action). However the influence of topographic factors (slope height, slope angle, slope aspect), and differences in rock stress release following deglacial debuttressing, cannot be excluded.

The design of the survey also allowed testing of the potential usefulness of SHRT in relative-dating of the Nordenskioldbreen rocky forefield. While the zonation in rock resistance between coastal and inland sites was quite clear, a similar relation between sites proximal to and distant from the glacier was less apparent. For instance, profile A (S1–S5) across outcrops exposed from Nordenskioldbreen during 2008–2009, and seemed to represent the area most sensitive to non-glacial conditions, theoretically more prone to weathering processes, demonstrated only slightly lower resistance than bedrock exposed during earlier stages of post-LIA deglaciation (Fig. 3D). However regression analysis did not show any significant differences in R-values for results from sites close to the glacier front in comparison with more distant sites. This suggest that SHRT-dating of Nordenskioldbreen foreland should be carried out only in conjunction with other dating methods, and it is not clear that any reliable age correlations are to be found.

Conclusions

This work highlighted the need for a greater understanding of the controls of polar rocky coastal zones. The most important finding in the Adolfbukta pilot study is the clear reduction in rock resistance with decreasing distance from the present-day shoreline. The study suggests two contrasting explanations for reduced rock resistance in the coastal zone:

- coastal processes (tidal wetting and drying, salt weathering, wave action, sea ice action) weaken the rock surfaces more efficiently than other subaerial agents operating on rocky landforms in more inland locations, and allow deeper and more efficient rock weathering;
- the low efficiency of coastal processes in sheltered fjord environments leads to preservation of a weathered rock layer along the coast, whereas high intensity of para-periglacial processes across more inland areas removed the weathered material left after post-LIA glacier retreat.

However SHRT should be treated only as a preliminary reconnaissance and the study on influence of coastal processes on rock breakdown in polar climates should be supported by application of more advanced methods (*e.g.* Equotip, MEM, Terrestrial Laser Scanning, digital photogrammetry, GIS modelling) to reduce the risk of misinterpretation (Lim *et al.* 2005, 2010; Aoki and Matsukura 2007; Viles *et al.* 2011). The major weakness of this study is above all the lack of information regarding the spatial distribution of permafrost and the difference in development of the active layer between coastal and inland outcrops, which could have a significant impact on rock stability and degree of weathering. Schmidt hammer measurements also did not detect any significant differences in bedrock exposure ages, what implies that the method should be combined with either lichenometry (Matthews and Shakesby 1984; Evans *et al.* 1999), ^{14}C dating (Shakesby *et al.* 2006) or terrestrial cosmogenic nuclide dating (Winkler 2009) for the proper deciphering of Nordenskioldbreen's deglacial history.

Looking ahead, for further progress in cold region coastal geomorphology, a natural step should be the intensification of research efforts on evolution of rocky coastlines formed in the various lithologies encountered along the coasts of Svalbard, Franz Joseph Land, the Canadian Arctic Archipelago and Greenland. Of particular interest are quantitative studies of typical polar climate-driven factors controlling rocky shoreline landforms and microrelief, and studies of the adjustment of this type of coastal environment to the rapid rate of post-glacial isostatic recovery and to the recent para-periglacial landscape transition, characteristic of many Arctic settings.

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