Reconstruction of relative sea-level changes during the last millennium in northern West Greenland

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Abstract

Reconstruction of relative sea-level (RSL) changes around Greenland's coasts increases our understanding of Greenland Ice Sheet (GIS) retreat since the last glacial maximum, as well as assisting in constraining models of ice sheet behaviour. Understanding earlier ice sheet responses to climate variation will improve predictions of GIS change under various IPCC climate change scenarios, and therefore of Greenland's likely contribution to global sea level rise from its loss of ice throughout this century. Salt marshes at Upernavik, northern West Greenland were investigated for their elevation range with respect to the tide, diatom assemblages, stratigraphy and sediment organic content (loss on ignition), and samples were dated using ^{210}Pb and AMS ^{14}C. This is further north than this approach has previously been used. Shallow sediment and slow sedimentation rates, related to adverse growing conditions for the halophytic vegetation, limited the precision of results, but RSL rise of 0.3m occurred over the 100 years prior to 2014, with limiting dates showing at least 0.2m rise in the previous 235 years, in agreement with the Huy3 model of GIS evolution. The contrast with recent RSL stability in south- and central West Greenland probably relates to the later deglaciation of the northern GIS and continuing collapse of the North American Ice Complex forebulge. GPS data from Upernavik show 7.81 mm/yr crustal uplift from 2007-2011, probably linked to retreat of Upernaviks Isstrøm 60km east of our field site, but the slow accretion of these marshes is unlikely to be able to demonstrate a change from RSL rise to RSL fall for some time. These marginal northern marshes are positioned mainly above highest astronomical tide (HAT) level, possibly related to sea ice damage below this and low precipitation permitting halophytic vegetation growth further above HAT, but they remain useful sources of RSL data over recent centuries.

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Declaration of Copyright

I confirm that no part of the material presented in this thesis has previously been submitted for a degree at this or any other institution. In all cases, material from the work of others, referred to in the text, has been acknowledged as such.

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This thesis is the product not just of 5 years of fragmented life, and of the wonderful support I have received, but is also the result of many earlier years' forays into the less-tamed parts of the environment. My mother's decision to take me around an English salt marsh while at school strongly encouraged this thread. My wife Helen's tolerance of the seemingly endless split between work, study, and family responsibilities spread across various parts of the country has been more than heroic, and she has not once questioned the need for me to undertake this research; she has also helped me see the obvious on many occasions when I have been looking the other way. The bemused tolerance of my work colleagues when requesting extra leave just to go somewhere cold and barren to do extra work, has both amused and encouraged me, particularly those who have sympathised with my actions and even understood some of what I've said about this research. And again, my mother who has more recently needed greater help than I have been able to provide – but has never been other than supportive herself.

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1. Introduction

Rising sea levels around the world constitute a significant hazard from climate change (IPCC, 2014) with some Pacific islands already having been reduced in area or having disappeared (Albert *et al.*, 2016). Improving predictions of sea level change over forthcoming decades and centuries will help direct mitigation efforts more effectively. As the Greenland Ice Sheet (GIS) is predicted to contribute 0.5 m or more to global sea level rise during the 21st century (Pfeffer *et al.,* 2008), more than all other ice caps and ice sheets combined, improving understanding of its likely response to various climate change scenarios is important. Isostatic adjustment of the Greenland coast elevation, in response to changes in the ice loading, mean that changes in relative sea level (RSL) provide an important constraint on the mass balance of the GIS through the Holocene. Reconstruction of RSL can therefore improve our understanding of the GIS' dynamic response to past changes in climate, the speed and duration of this response, and improve predictions of its melting and future impact on global sea level. This requires an understanding of its retreat after the termination of the last glaciation as well as the more recent fluctuations following the Neoglacial and Little Ice Age (LIA).

Saltmarshes can be an important source of information on recent RSL changes, through their preservation of evidence on former sea levels, incorporated during their formation. Temperate salt marshes have enabled detailed reconstruction of changes over long periods (Allen, 2000). The challenging coastal environment in the Arctic means that saltmarsh development is much more restricted than further south but studies in south and central Greenland have nonetheless provided the most detailed data available on RSL changes there in recent centuries (Woodroffe and Long, 2009, 2010; Long *et al.*, 2010, 2012).

2. Background

2.1 Changes in sea level

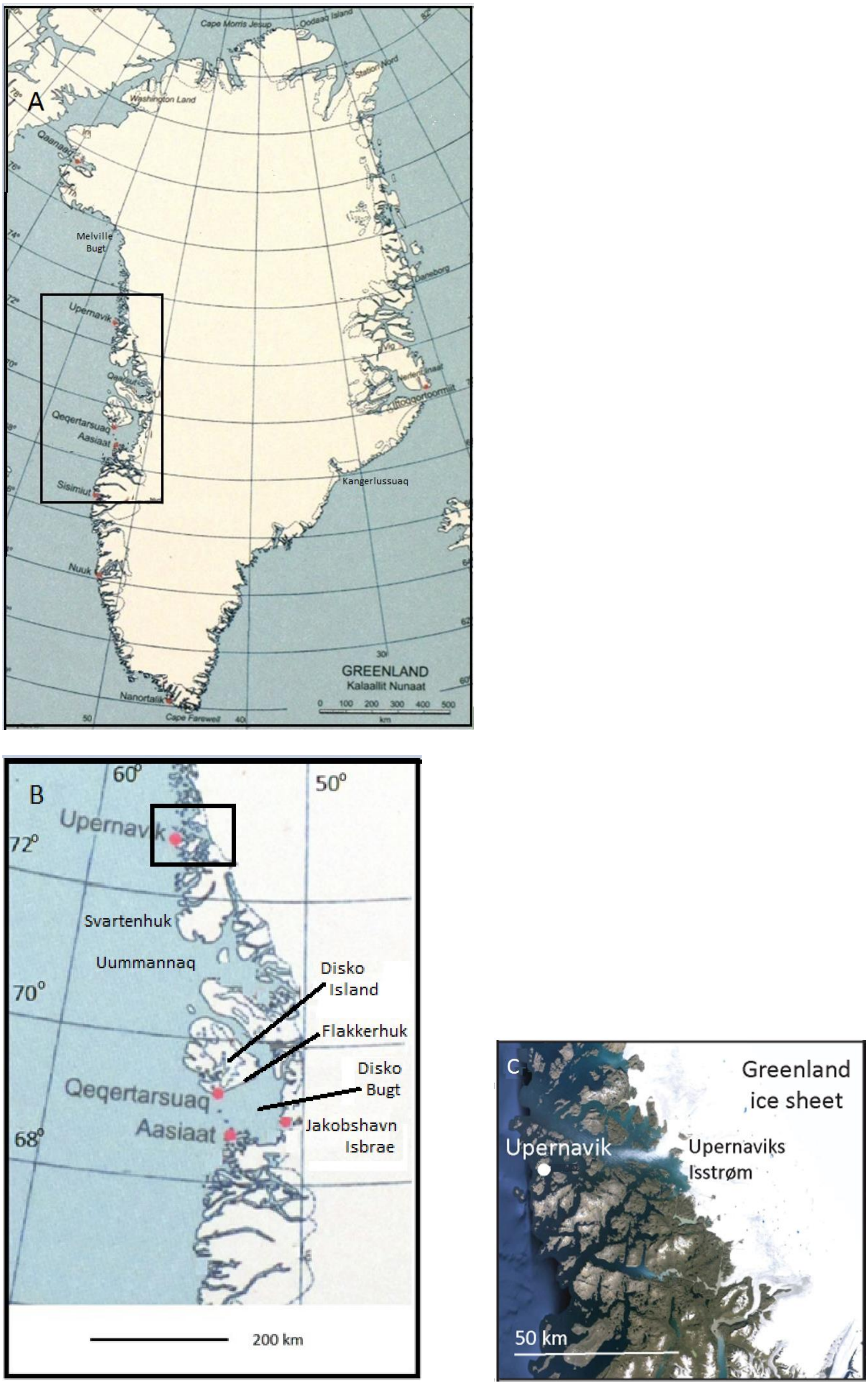
Alternating cycles of rising and falling sea level have taken place throughout the Quaternary, with the transfer of large volumes of water between the oceans and ice caps. This shifting of mass causes vertical movements of the Earth's crust (Milne and Shennan, 2007) especially over land where ice caps can reach several kilometres in depth, but the reduced ocean volume results in a sea level variation between glacials and interglacials of up to 150 m, averaged globally.

Reconstructing former sea levels can be undertaken in various ways. Coastal features which develop within a particular tidal zone but may have moved, can be dated; these include erosional features, coral (Pirazzoli and Suter, 1986), mangrove sediment (Peltier and Fairbanks, 2006) and saltmarsh sediment (for example see Watcham *et al.,* 2013). Tide gauges record detailed variation as well as local trends from the time of their installation, which has been particularly in recent decades (Ezer, 2013), although these data are coastal rather than oceanic and have an uneven global distribution. More recently, satellite altimetry and GPS monitoring can provide rapid and detailed information on changes in both sea-surface and land elevation (Bevis *et al.,* 2012) and have revealed an immediate response in land elevation during large-scale melt events in Greenland (Jiang *et al.,* 2010). RSL changes are not uniform around Greenland, and detailed reconstruction needs repeating at intervals both along a coastline, and at varying distances from the GIS to distinguish near-field from far-field effects, elastic (more pronounced near the ice sheet margin) from viscous glacio-isostatic adjustment (GIA) signals and the varied responses of different sectors of the GIS to climate. Improved, regional RSL constraints for different regions of Greenland have been a major factor recently in decreasing discrepancies between ice sheet modelling of GIS evolution and observations (Lecavalier *et al.*, 2014).

2.2 The Greenland Ice Sheet and changes since the Last Glacial Maximum

The largest ice sheet outside Antarctica, the GIS ranges from 60° to nearly 83° North (2600 Km) (Fig. 1). It covers 80% of Greenland, with a variable width, unglaciated strip of land exposed particularly in the north, east and south-west. The GIS reaches the sea through tidewater glaciers in numerous fjords but the only extensive contemporary marine-based ice frontage stretches for several hundred kilometres in the north-west, in Melville Bugt (Briner *et al.,* 2013). The northern dome reaches 3300 m at 72° north and has an average thickness of 1600 m but a maximum of over 2300 m. Its area is approximately 1.7 million km^2 and it contains 2.9 million km^3 of ice (Bamber *et al.*, 2001). Its mass has depressed the bedrock below sea level in some

Fig. 1 Overview of Greenland and location of this study: A) Overview of Greenland; B) Inset map of West Greenland and places mentioned in the text; C) Field site in regional context.



areas but the smaller, more dynamic southern dome of the GIS is based above sea level. The GIS would contribute to a globally averaged sea-level rise of 7.36 m if it were to melt completely (Bamber *et al.*, 2001). The behaviour of the GIS is not uniform but varies both regionally, depending on the climatic and marine drivers (changes in sea temperature), and on a more local scale where discreet and rapidly moving ice streams transport material from the icecap to the sea whether through meltwater, in land-terminating glaciers, or predominantly as icebergs in marine–terminating ones (Wang *et al.,* 2012). Variations in sub-glacial topography form an important control here.

While GIS mass balance changes dominate GIA, South and West Greenland have seen regional subsidence during the late Holocene from the collapse of the Laurentide ice sheet forebulge (Long *et al.* 2011). Close to the GIS, changes from isostatic adjustment can vary considerably over short distances (Tarasov and Peltier 2002), with the marine limit (ML) - the highest level reached by the sea during the Holocene - in southeast Disko Bugt dropping by 31 m in 8 km, with increasing distance from the ice margin (Long and Roberts, 2002).

The LGM refers to the time of maximal global glaciation, approximately 21 cal ka BP (Anderson *et al.,* 1999, Miller *et al.*, 2010) but in Greenland the maximum ice extent was at 16.5 cal ka BP (Lecavalier *et al.*, 2014), with ice reaching the continental shelf along most of the coast from Svartenhuk (72°N) in the west to Kangerlussuaq (68° N) in the south-east (Funder and Hansen, 1996)(Fig. 2. Retreat towards the modern coastline (Fig. 2) had begun by 14 cal ka BP in southern Greenland, the rising sea level melting and destabilising marine–based areas leading to large-scale iceberg calving. This varied regionally but was largely complete by 11.7 cal ka BP (Lecavalier *et al.*, 2014). However, Jakobshavn Isbrae, the major outlet glacier in Disko Bugt which drains 6% of the entire GIS, briefly re-advanced more than 110 km onto the outer shelf during the Younger Dryas cold phase at around 12.2 cal ka BP, retreating again within about 200 years (Cofaigh *et al.*, 2013). In northern Greenland the main retreat began around the end of the Younger Dryas (Lecavalier *et al.*, 2014). Continuing retreat across the land depended on local topography, but by 7 cal ka BP the GIS was approximately its current size, with the largest ice free area being in West Greenland (Funder *et al.,* 2011). The GIS margin has fluctuated since then, reaching a minimum extent, predicted to be up to 50 km inland of its present position in central West Greenland during the Holocene thermal maximum (HTM) at around 4 cal ka BP

(Lecavalier *et al.,* 2014), later advancing to its largest position during the Holocene during the LIA. Glaciers obliterate direct evidence of their previous smaller extent as they re-advance (Long *et al.*, 2009; Alley *et al.* 2010), but evidence for changes in ice marginal position can be produced or modelled from dating of moraines and rock exposure, lichen growth patterns, RSL data, lake sediments, and climate evidence from ice cores.

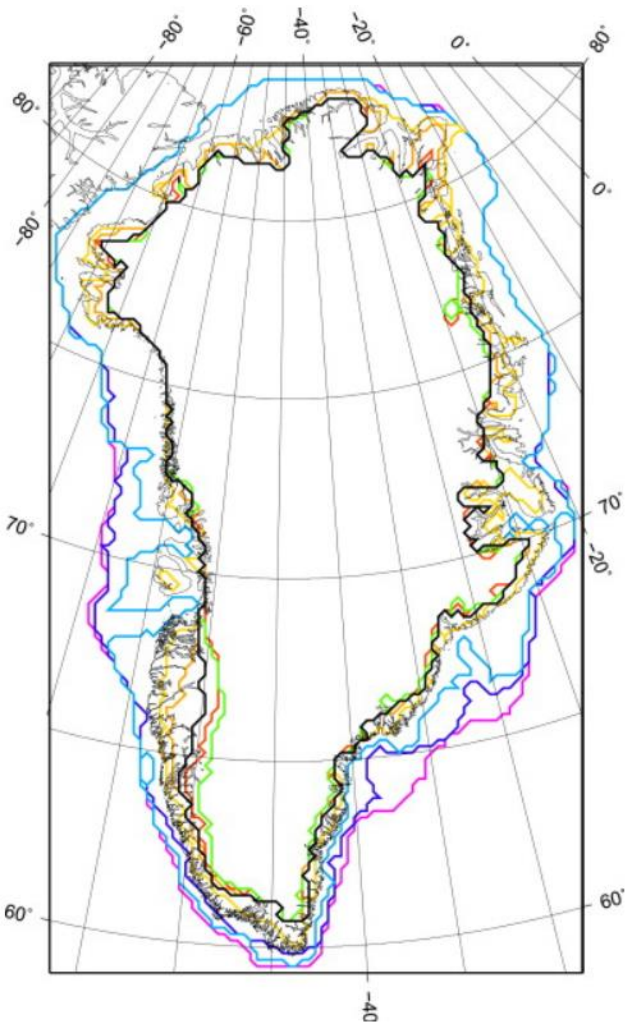


Fig. 2 Successive stages of GIS ice retreat through the Holocene; 16 ka BP –pink; 14 ka BP – dark blue; 12 ka BP – light blue; 10 ka BP – yellow; 9 ka BP – Orange; 6 ka BP - red; 4 ka BP – Green; present day – black. From Lecavalier *et al.*, 2014.

2.3 RSL research in Greenland

The earliest data on RSL change in Greenland relates to the ML and the re-emergence of previously submerged archaeological remains (Rasch and Jensen, 1997). The ML varies considerably around the Greenland coast (**Fig**. 1), in places reaching 120 m above modern sea level (Funder and Hansen, 1996; Long *et al.,* 2011). Its position and age has been determined from marine shells, driftwood and whale bones (Bennike 2008) and elevated former beaches. However, inherent uncertainties with both dating and the position of these observations means they often have an error of c. ±5 m elevation and 1-2 ka in age (Long *et al.,* 2011; Ingölfsson *et al.,* 1990). Coring isolation basins has yielded greater and more precise data. These water-filled hollows, common in many coastal areas, have sills which have transitioned, sometimes repeatedly, between below and above sea-level, thus alternating between being freshwater and marine. Identifying and dating the transition between marine and lacustrine sediments within the basin has yielded data with an error sometimes within 0.5 m of elevation and a century in age (Long *et al.*,1999, 2003, 2006, 2011; Sparrenbom *et al.* 2006a, b).

Fig. 3: Observations of the postglacial marine limit around Greenland, from Funder and Hansen 1996.

More recently saltmarshes, which have given a detailed picture of RSL fluctuations in temperate areas (Nelson and Kashima, 1993; Horton, 1997; Shennan, 2007; Barlow *et al.*, 2013) have been investigated in Greenland (e.g. Woodroffe and Long, 2009). Arctic saltmarshes are often fragmented, with thin sediment, many scattered rock fragments (Lepping and Daniels, 2007) and suffer ice damage in winter. However, the precision of RSL reconstruction based on saltmarshes can be as little as ± 0.1 m and with decadal age precision, this is the most detailed late Holocene RSL reconstruction achieved in Greenland (Woodroffe and Long, 2009, 2010; Long *et al.*, 2010, 2012).

Saltmarshes are depositional ecosystems which develop on sheltered tidal coastlines, their predominant vegetation being halophytic (salt–tolerant, flowering) plants (Allen, 2000). They accumulate mineral sediment, largely deposited during tidal flooding, and organic material from decaying plant matter. The developing marsh platform also incorporates microfossils such as diatoms (Allen, 2000), microscopic phytoplankton with resistant silica skeletons (Gehrels, 2007). The types of both plants and diatoms living on the marsh surface demonstrate zonation in relation to elevation across the marsh, reflecting the exposure at that position to tidal flooding. Analysis of the relative abundance of each species present in a 1 cm thick layer of sediment will permit comparison with contemporary diatom assemblages from marsh sediments at known elevations in the tidal range (e.g. Zong and Horton, 1999). This will give a tidal elevation for the sample at the time when it was originally deposited, and dating of this sample will give an age for this sea-level index point (SLIP).

2.4 High latitude saltmarsh processes

While sediment accumulation of high latitude saltmarshes is similar to that of temperate saltmarshes, there is a different balance of constructive and destructive influences (Dionne, 1998). On the northern Atlantic seaboard of the US, extensive saltmarshes develop profuse vegetation during the summer, while large mats of plants and surface sediment are ice rafted higher up the platform during winter months (Argow *et al.,* 2011). Saltmarshes on the St Lawrence Estuary show sedimentation rates typical of more southerly areas in summer, but ice rafting can move both boulders and sediment to other positions, leading to confusing stratigraphy (Coulombier *et al.*, 2012). Lack of water-stress may be the cause of the high productivity of saltmarshes (Little, 2000) both on temperate and subarctic coasts such as Labrador (Roberts and Robertson, 1986) and this may also apply to marshes in Greenland.

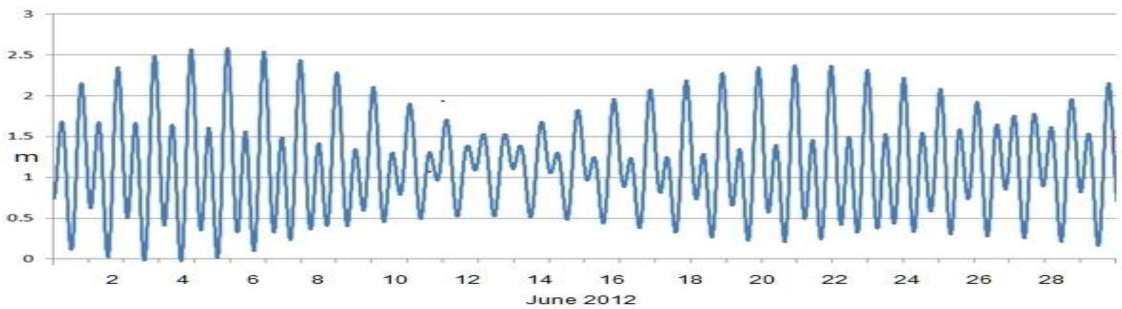
Much of Greenland has a high energy coastline, with deep water and little inter-tidal zone, and saltmarshes are often restricted to small fjord-head areas behind barriers of boulders or sills which protect against the mobile sea ice which can rapidly erode marsh sediment. The growing season is just a few months, between melting of overlying snow in midsummer and renewed onset of low temperatures in September. In addition, changes in permafrost beneath the marsh can distort sediment or underlying glacial till, or displace rocks within the sediment (Forbes and Taylor, 1994). In lower sections of the marsh fissures can develop, and blocks of sediment can be moved laterally across bedrock.

Saltmarshes typically develop within the upper part of the tidal range, but marsh vegetation sometimes grows outside this zone. On high-energy coasts with frequent sea-spray, saltmarsh development can occur well above Highest Astronomical Tide (HAT) level (Cooper and Power, 2003). These patches of 'perched' marsh, common in Greenland, are protected from winter sea ice, but they neither demonstrate zonation of species nor record RSL changes in their sediment.

Lepping and Daniels (2007) investigated West Greenland saltmarsh botanical communities principally in the Uumannaaq area (Fig. 1). Many of these were on river deltas, often very fragmented and with very thin sediment, and displayed low species diversity but up to four elevational zones of halophytic plants. Vestergaard (1978), working on a number of marshes around Disko Island, noted that plant zonation was often more indistinct than in temperate areas. Jensen and colleagues (2006), at Flakkerhuk on Disko Island, found saltmarsh to be the most productive of six vegetation zones along a transect descending from terrestrial areas to the tidal lagoon, in terms of annual carbon accumulation in the soil. This may reflect the lack of water stress experienced by saltmarsh plants, as noted by Little (2000). However, in none of these studies were elevational levels within the salt marsh well constrained to tidal ranges, nor a clear relation described between freshwater and marine water influence.

West Greenland's fjords give it complex tidal dynamics, making tidal prediction more difficult (Richter *et al.*, 2011), in addition to having a 'mixed' tidal pattern where peak tides alternate between a wider and a much narrower range (Fig. 4), and the spring/neap cycle. This pattern means that total flooding duration is less, at higher elevations, than expected in a typical semi-diurnal tidal coastline (Fig. 5) particularly around mean high water neap tide position. This is likely to alter distributions of marsh organisms and the salinity of sediment, and may influence the applicability of training sets developed outside the locality (Woodroffe and Long, 2010; Watcham *et al.*, 2012).

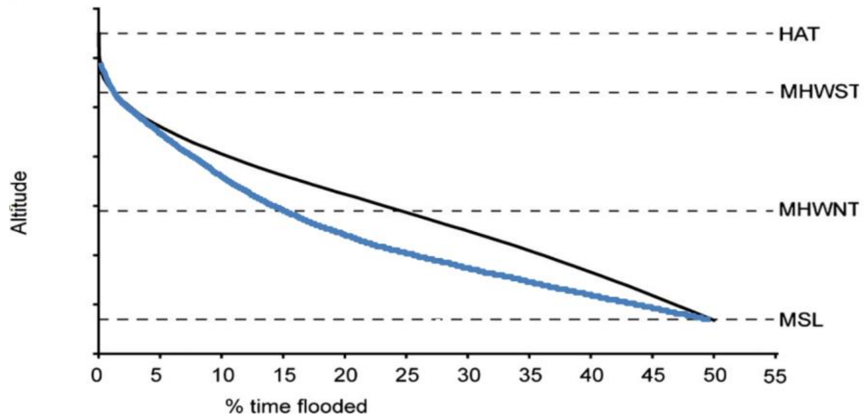
Fig. 4: Mixed tidal range pattern; tidal height predictions (m) for Qequertarsuaq, Disko Bugt, June 2012.



2.5 Existing sea level research on Greenland's saltmarshes

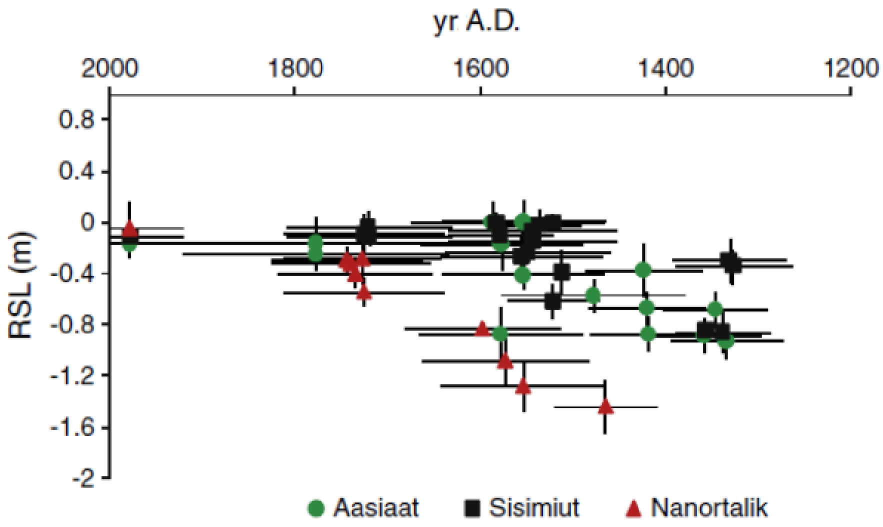
Several studies investigating RSL changes in saltmarshes in south west Greenland (Woodroffe and Long, 2009, 2010; Long *et al.*, 2010, 2012) demonstrated a rising late Holocene RSL over several centuries, with recent slowdown or still-stand (Fig. 6). These records extend back to 700 years because of erosion of the marsh sediment by the marine transgression. (Long *et al.*, 2010). Working on saltmarshes at Sisimiut, 150 km south of Disko Bugt, Woodroffe and Long (2009) and Long *et al.* (2010) concluded that RSL rose from -0.55 m about 1400 AD to -0.05 m at 1600 AD. It has since then remained relatively stable within ± 0.2 m of present. A study from Aasiaat on the margin of Disko Bugt (Long *et al*., 2010) found a similar rise from -0.60 m at 1400 AD to -0.10 m at 1600 AD.

Fig. 5: Inundation duration and elevation on marsh, between an area of semidiurnal tide (black line – Cowpen Marsh, UK- after Brain *et al.*, 2012); and mixed tide (blue line – Qequertarsuaq, Disko Bugt). Key; HAT - highest astronomical tide; MHWST - mean high water spring tides; MHWNT - mean high water neap tides; MSL – mean sea level.



In the very south of Greenland, RSL was rising slightly faster during the last millennium and the rate of RSL slowed later than at the sites to the north. Saltmarsh evidence from Nanortalik shows an RSL rise from c. -1.40 m at around 1450 AD, slowing from about 1750 AD and remaining at current levels since this time, which is c. 150 years later than the slowdown seen at the sites further north (Fig. 6) (Long *et al.*, 2012). The reason for the existence and timing of slowing of RSL rise seen at all three sites on the west coast during the LIA is still debated. It is likely to be due to a combination of factors including the proximity of each site to the ice sheet (and therefore the amount of elastic deformation being experienced) and the interplay of the local Greenland and regional Laurentide ice sheet forebulges which have impacted on RSL along the west coast of Greenland during the late Holocene (Long *et al.*, 2012).

Fig. 6. Relative sea-level index points from Aasiaat, Sisimiut and Nanortalik; (Fig. 1) which show rising RSL until 1600-1800 AD with slowly rising or stable RSL since that time (from Long *et al.*, 2012).



3. Location of this study

Glacial history of Upernavik

No studies of RSL changes in recent centuries in northern Greenland have been published to date, despite the evidence of differing accumulation and deglaciation histories for different sectors of the GIS (Khan *et al.*, 2015). This is therefore important for refining our modelling of Holocene deglaciation history and prediction of future changes. The Upernavik saltmarsh (Fig. 1) is c. 50 km west of the Upernaviks Isstrøm, the major discharge route to the south of Melville Bugt for the northern dome of the GIS. This is a dynamic glacier system, with the Huy 3 model (Lecavalier *et al.*, 2014) predicting GIS retreat having occurred from the continental shelf edge earlier, at 12 cal ka BP, than elsewhere in northern Greenland (Fig. 2). Its glacial trough crosses the continental shelf and remains 900 to 1100 m deep through most of Upernavik Isfjord (Andresen *et al.*, 2014), suggesting the palaeo-Upernaviks Isstrøm front could have been in contact with warming marine currents for a long distance, and vulnerable to rapid retreat as discussed above in relation to Jakobshavn Isbrae. Other studies have supported this conclusion; Corbett *et al.* (2013), working along a transect from Upernavik Island to the modern margin of the GIS, dated paired samples from exposed bedrock and erratic boulders using cosmogenic nucleotides, and found that much of the landscape greatly predates the last glaciation, suggesting the ice sheet was non-erosive, cold-based and possibly largely consisted of snow patches, and that deglaciation across the entire width of the archipelago took place rapidly at about 11.3 ka BP. Briner *et al.* (2013) dated GIS retreat to behind a current lake position close to Upernavik northern ice stream to before 9.6 ± 0.1 ka, and deglaciation of a small island nearby to 9.6 ka ± 0.1 ka, but with a re-advance into the lake at ~1100 to ~700 ka, retreating again within the last decade.

Dynamic change in this area has been evident more recently. Weidick (1958) compiled evidence that 10-15 km of progressive retreat of the Upernaviks Isstrøm had taken place since 1849, from a probable LIA maximum position, the former trunk ice stream outfall now discharging as four separate ice streams. Further retreat has continued since then with both north and south ice stream fronts now ~20 km behind the 1849 position (Andresen *et al.*, 2014). There have been two distinct periods over the past 30 years of rapid retreat of the calving front with increased ice flow speed and lowering of the glacial surface, at different times for the four component ice streams (Khan *et al.*, 2013, Larsen *et al.*, 2016); this timing is attributed to climatic forcing and warmer deep water, variably amplified by the depth and width of the exposure of the calving front to this water. The decreasing ice mass of the Upernaviks Isstrøm is the major factor in the GPS–detected uplift of bedrock near the glacier snout of 17.1 ± 0.6 mm k^{-1} between 2007 and 2011, while at Upernavik Island, 63 km further west, a lower uplift rate of 7.81 ± 0.6 mm k^{-1} is influenced by other ice stream catchments of the GIS. This uplift is largely the elastic response to unloading but includes a proportion of longer term, viscous GIA (Nielsen *et al.* 2012).

4. Research questions

The overarching focus of this study has been to extend detailed reconstruction of late Holocene RSL changes further north along the West Greenland coast, closer to both the extensive northern dome of the GIS and to the extensive marine ice frontage of Melville Bugt, where direct coastal reconstruction of RSL changes is more difficult; and to assess the potential for salt-marsh based RSL reconstruction techniques in an area increasingly marginal for saltmarsh development.

4.1 Research questions

1) To what extent has relative sea-level changed in northern West Greenland in recent centuries?
2) In what way does the morphogenesis of very northerly saltmarshes in Greenland differ from that in saltmarshes further south?

4.2 Aims

a) Reconstruction of late Holocene relative sea-level change at Upernavik.
b) Quantification of the major morphogenetic features of the Upernavik saltmarshes.
c) Reconstruction of the Holocene Marine Limit in the Upernavik area.

4.3 Objectives

i) Establish a series of sea-level index points on the saltmarshes at Upernavik using contemporary and fossil diatom assemblages.
ii) Assess the marsh platform boundaries, saltmarsh sediment organic content, and accretion rates of the Upernavik saltmarshes.
iii) Measure the detailed tidal changes at the saltmarshes studied through several daily cycles to allow comparison with the tidal predictions available.
iv) Measure the elevation of the lowest perched boulders at Upernavik.

5. Summary, and structure of this thesis

The increased mass loss from the GIS in recent decades highlights the place of Greenland and its ice sheet in likely sea-level rise around the world over forthcoming decades, linked to the measured and predicted changes in global climate. The likely response of the GIS to climate changes remain uncertain and will vary locally, but our understanding of its overall evolution since the LGM, and through the Holocene and Neoglacial, to atmospheric and ocean warming is improving. More detailed reconstruction of regional sea-level changes through the late Holocene, particularly recent centuries, will allow improved understanding of the past changes of the GIS, and improve predictions about its likely response to the altered temperature, weather and oceanic changes with predicted global climate change (IPCC, 2014). This will also help constrain likely patterns of sea-level rise around the globe throughout this century.

The remainder of this thesis is a paper concerning the specific research carried out, to be presented for publication, and a final summary, including material relevant to the thesis but not to the paper itself. There are three appendices.

Saltmarsh-based reconstructions of recent relative sea-level changes in northwest Greenland

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1. Introduction

Saltmarshes are excellent archives of relative sea-level (RSL) changes over a range of different timescales. In Greenland they provide accurate relative sea-level data over the past few hundred years which provides evidence of Greenland Ice Sheet mass changes during and after the Little Ice Age (LIA). They are particularly valuable as they provide a longer term context for the evaluation of very short tide gauge and GPS records, which inform on mass changes in Greenland over the past decade or so.

Saltmarshes have been documented around the coast of Greenland although north of 74° N they are increasingly fragmentary and limited by the long annual duration of sea-ice cover and the general lack of sheltered coastal environments (Bay, 1992). This study reports evidence of sea-level changes over the past ~200 years from saltmarshes close to Upernavik in northern west Greenland (72.796°, -56.112°) which is close to the limit of ideal conditions for marsh development (Lepping and Daniëls, 2007)(Fig.1).

The pattern of present day RSL change around the Greenland ice sheet is dominated by bedrock uplift caused by ice sheet mass loss, as recorded by continually monitoring GPS receivers (e.g. Bevis *et al.*, 2012). The GPS record of land motion at Upernavik airport (~1 km from the field site) shows bedrock uplift of 7.81 mm/yr between 2007 and 2011. By comparison the SRMP GPS receiver 60 km east of Upernavik is situated close to the current calving margin of the Upernaviks Isstrøm and records much more rapid uplift of 17.22 mm/yr over the same period (Bevis *et al.*, 2012). These uplift rates are based on very short time series at this point. By contrast the late Holocene pattern of RSL change in the Upernavik region is RSL rise due to collapse of the Laurentide ice sheet forebulge lowering the bedrock elevation, and reloading during the neoglacial (Lecavalier *et al.*, 2014).

Resolving the pattern of RSL during the last few centuries, and when the switch occurred from bedrock subsidence to uplift (RSL rise to RSL fall) is therefore critical in improving our understanding of the recent history of the ice sheet in northwest Greenland. The nearest recent saltmarsh-based RSL records to Upernavik are from Aasiaat (Long *et al.*, 2012; Woodroffe and

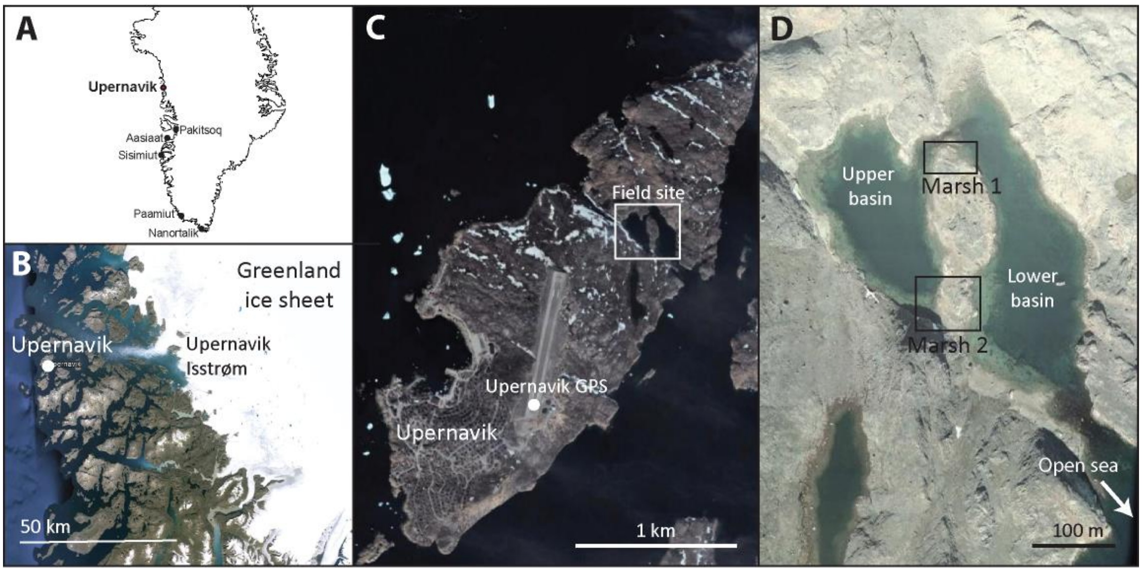
Long, 2009, 2010) and Pakitsoq (Long *et al*., unpublished data) which are ~420 km south of Upernavik in Disko Bugt. The present study therefore provides important new proxy data on the history of this sector of the Greenland Ice Sheet over the past two hundred years or so.

2. Setting and methods

2.1 Field site

The Upernavik area and north-western Greenland more generally comprises many marine-terminating ice margins and island archipelagos. The inhabited island of Upernavik (72.796°, -56.112°), which is the focus of this study is situated at the outer coast, approximately 60 km from the current calving margin of Upernaviks Isstrøm (Fig. 1). The island is situated slightly to the south of the main cross-shelf trough of the isstrøm and relatively close to the reconstructed LGM ice sheet margin location (which is hypothesised to have been on the continental shelf ~25 km to the west of Upernavik (Funder *et al.*, 2011).

Fig. 1. Maps and photographs of the field area. A) Upernavik and other saltmarsh field locations in west Greenland, B) The location of Upernavik township in relation to Upernavik Isstrøm and the northern Greenland Ice Sheet, C) Upernavik Island with the township and field location shown, D) The location of the marshes sheltered between two linked tidal basins on the eastern side of Upernavik Island.



The area immediately outside of the present day ice sheet margin at Upernavik Isstrøm was deglaciated around 9.9 ± 0.1 ka cal BP, which slightly earlier than the timing of first deglaciation of land-based ice in Disko Bugt (Long *et al.*, 2006). Briner *et al.* (2013) also found no evidence of raised marine features above sea level near the terminus of the Upernaviks Isstrøm, suggesting that in this location the ice sheet has not thinned or retreated significantly during the

Holocene. This is supported by evidence that the LGM to present day retreat of the ice sheet in this region is ~ 80 km or less (Funder *et al.*, 2011, Lecavalier *et al.*, 2014).

Evidence from threshold lakes adjacent to the current isstrøm terminus suggests that the ice sheet readvanced to a slightly larger than present neoglacial position in this region between 950-1350 AD (Briner *et al.*, 2013). Direct observations suggest that the Upernaviks Isstrøm itself was close to its maximum neoglacial position in 1849 (Weidick, 1958), but has since retreated 20-30 km, discharging from its four constituent four glacier margins since 1985 (Khan *et al.*, 2013; Larsen *et al.*, 2016; Nielsen *et al.*, 2012).

Elsewhere in west Greenland, studies of recent saltmarsh deposits at outer coast locations (Aasiaat and Sisimiut, 100-180 km from the ice sheet margin) show rising RSL between ~1300 AD and ~1600 AD with RSL stability (± 0.25 m) since that time (Woodroffe and Long, 2009; Long *et al.*, 2012) (Fig. 1). Where saltmarshes are situated closer to the present day ice sheet margin (e.g. Nanortalik ~70 km from the ice sheet margin, Long *et al.*, 2012) rising RSL continues until more recently (~1750-1800 AD) but is also stable since that time. Given that Upernavik Island is ~60 km from the ice sheet margin we might expect to see RSL rise over the earlier part of the record followed by later RSL stability in the last century.

In this region locations for saltmarsh development are limited to sheltered, low relief coastal inlets away from the main fjord margins. The island of Upernavik has a small sheltered inlet system on its eastern coast which is the focus of this study (Fig. 1). The marshes here are snow covered for approximately 8-9 months of the year and therefore have a very short growing season. Despite the difficult conditions, saltmarsh vegetation is established in the upper half of the intertidal zone and into the supratidal zone and has accumulated over the past 200 years or so mainly under conditions of RSL rise. Seasonal sea ice is present for approximately 160 days in the area with spring break up around the end of May/beginning of June (Krause-Jensen *et al.*, 2012; Laidre *et al.*, 2008).

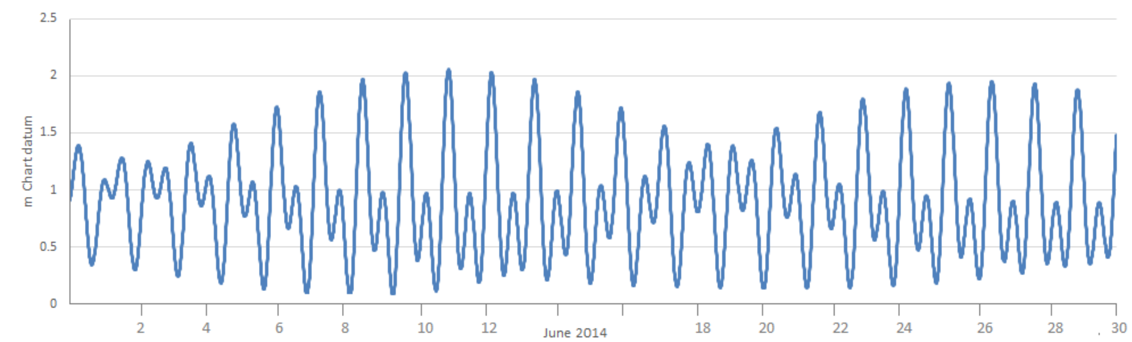
Tidal levels and meteorological data for Upernavik are presented in Table 1 (Cappelen, 2011). The calculated tidal levels for Upernavik are computed from tidal analysis on only one month of data obtained by a tide gauge in July 2002 (pers. comm. Danmarks Meteorologiske Institut (DMI)). Therefore these tidal levels should be treated with caution as the underlying data used to generate them may be affected by the seasonal cycle, interannual variability and meteorological effects on the sea surface (Pugh and Woodworth, 2014). In addition to this, the tidal pattern in West Greenland is a 'mixed' semi-diurnal one, where both high and low peak tides alternate each day between a wider and a much narrower range. This is in addition to the spring/neap cycle which recurs approximately every 29 days. The mixed pattern means that the higher parts of the tidal range are inundated only during alternate high tides, about once per day, even during the spring tide period, and therefore salt marsh plants in this zone have half the exposure to salt water that might be expected. This is shown in the tidal predictions for Upernavik for June 2014 in Fig. 2.

Table 1. Study area data; major tidal parameters, above, and meteorological data, below.

Tidal range (m)	Height of mean high water of spring tides (MHWST) above mean tide level (MTL) (m)	Height of highest astronomical tide (HAT) level above mean tide level (MTL) (m)
1.97	0.48	1.05

Mean January temperature (1961-1980) (°C)	Mean July temperature (1961-1980) (°C)	Months air temperature above zero °C	Annual average temperature (1961-1980) (°C)	Annual precipitation (mm)
-18	5.3	4	-7.5	265

Fig. 2 - Modelled tidal predictions for Upernavik for June 2014. This shows the alternating peaks for higher high and lower high water,. Note that lower high water higher peaks do not correspond with the timing for higher-high water spring (or neap) tides; and a similar pattern applies to low tide**.**



2.2 Methods

RSL changes at Upernavik were reconstructed by studying salt marsh sediment, using both contemporary and fossil diatom distributions, in relation to the tidal range, and the stratigraphy of the sediment itself. We calculated the elevation of samples in relation to m MSL by comparing model-predicted ten minute tidal data for Upernavik harbour (obtained from DMI) to observed tidal variations recorded using a sea-bed pressure transducer during fieldwork in June 2014. Because the predictions and observed tidal fluctuations were very similar we felt comfortable using predicted MSL as our datum. To see whether the upper and lower basins (Fig. 1D) were synchronised with the tidal cycle on the open coast we levelled the tide in the upper basin during the high tide and in the lower basin during the low tide and compared these to tidal predictions for the open coast during the same tidal cycle in 2014. We established that the upper part of the tidal cycle (which impacts on the salt marsh which exists above modelled MHWST) is not affected by the geometry of the basins and there is no evidence of delay in the tide between the basins and the open coast. There is a difference in timing and amplitude of the low tide in the lower basin but this does not directly impact on the saltmarsh.

We established a temporary benchmark on marsh one, which all modern and fossil saltmarsh samples were levelled to. We also levelled tidal elevations before and after high and low tide to this benchmark. In addition, the level of the upper and lower margins of each salt marsh was measured at a number of positions, and on marsh one, the boundary between upper and lower marsh (marsh two was not divided into distinct vegetation zones). Depths of both outer and inner sills were levelled across several cross-sections, as were the heights of a number of perched boulders on slopes above nearby shorelines.

Transects to sample the modern saltmarsh environment were established descending across two salt marshes, from the freshwater upland areas to the lowest point on the salt marshes (e.g. Fig. 3C). On marsh one the transect ended on a rocky bedrock platform by a cliff descending into the lower basin. On marsh two the transect terminated where persistent winter ice abutted the lower edge of the salt marsh (Fig. 3F). Therefore a further short transect was made on an accessible area of tidal mud flat. The vertical range of the marsh was 1.33 m. Contemporary diatom samples were taken from the surface 1 cm of the salt marsh at 5 cm vertical intervals, to allow a modern diatom training set to be constructed for these tidal elevations. We also took seven short blocks from marsh one, one in the upland zone immediately adjacent to the high marsh, four on the high marsh and three on the low marsh to investigate recent sea-level changes (Fig. 3C,D,E). The sediment blocks, of about 7 cm square and up to 12 cm in depth, were taken with a spade, through the entire depth of the marsh to the underlying layer of gravel or till that underlies the entirety of these marshes. Samples were wrapped securely in plastic prior to boxing for transport to the laboratory, and stored at 4 °C once in Durham.

In the laboratory block surfaces were cleaned with a knife to allow stratigraphical analysis and sub-sampling. Microscope slides were prepared for analysis of diatom assemblages both from contemporary samples and at 1 cm intervals through the full depth of the blocks, using standard techniques (Palmer and Abbott, 1986), with 150 to 250 diatom valves identified under high power (x1000 magnification) in each slide where there were sufficient of these present. Identification was carried out using Hartley *et al.* (1996) and Spaulding *et al.* (2010). A few grams

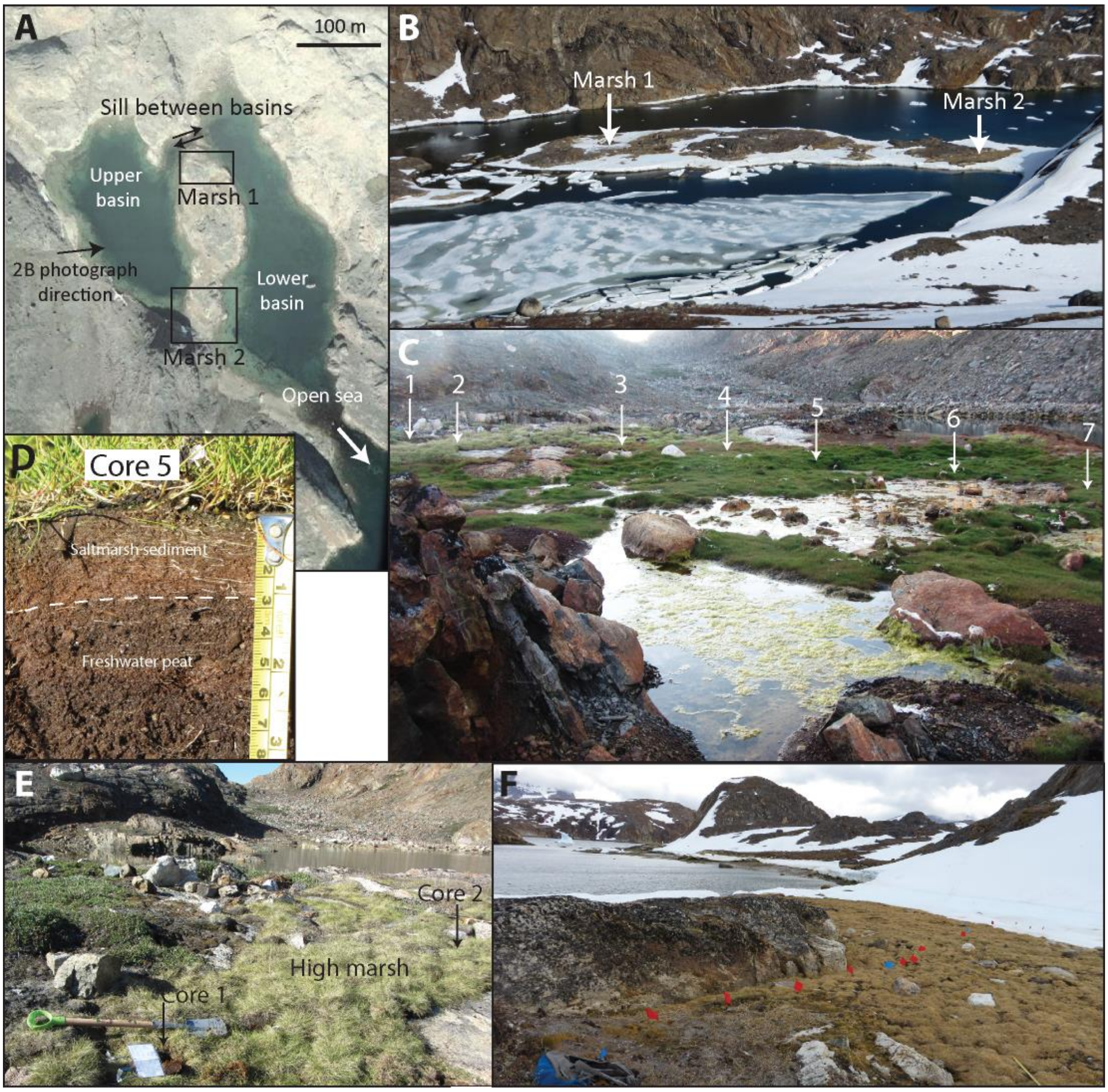


Fig. 3. Details of Upernavik marshes**:** A) location of the marshes at Upernavik, in a sheltered position on a peninsula between the 'upper' and 'lower' basins; B) photograph from late June 2014 of the peninsula and the location of the marshes (note snow-covered terrain and sea ice in the upper basin); C) locations of the seven blocks collected from marsh one; D) a typical short block from marsh one showing a lower, freshwater peat and upper saltmarsh sediment which finishes on marsh vegetation; E) close-up of the high marsh/upland transition on marsh one showing the location of blocks 1 and 2; F) marsh two in late June 2014, having recently become exposed by melting of the winter snow cover. This marsh is made up solely of low marsh plant communities, overwhelmingly P*uccinellia phryganodes*.

of sediment from each level in blocks 1, 3, 5 and 7 were dried at 120° C and burnt at 550°C for four hours to calculate percentage loss on ignition (LOI) at different depths within the marsh platform (Heiri *et al.*, 2001). Samples at 0.5 cm vertical intervals from the top few cm of blocks 1, 3, 5 and 7 were prepared for dating with ^{210}Pb and ^{137}Cs, by freeze-drying and ball milling prior to sealing into tubes for analysis in a gamma well detector after being stored for a minimum of

28 days to allow the excess lead to equilibrate in each sample (Long *et al.*, 2014; Ivanovich and Harmon, 1992).

Basal and upper peat samples from blocks 2, 3, 4, 5, 6 and 7 were dissected under water for selection of plant macrofossils which were reduced to graphite and AMS ^{14}C dated at the NERC Radiocarbon Facility in East Kilbride, Scotland. Three samples were subsequently forwarded to the Keck Carbon Cycle AMS Facility, University of California for dating because of their small size. All AMS ^{14}C dates were calibrated using Oxcal 4.2 (Ramsey, 2009) and IntCal 13, citing a 2 sigma age range (Table 3).

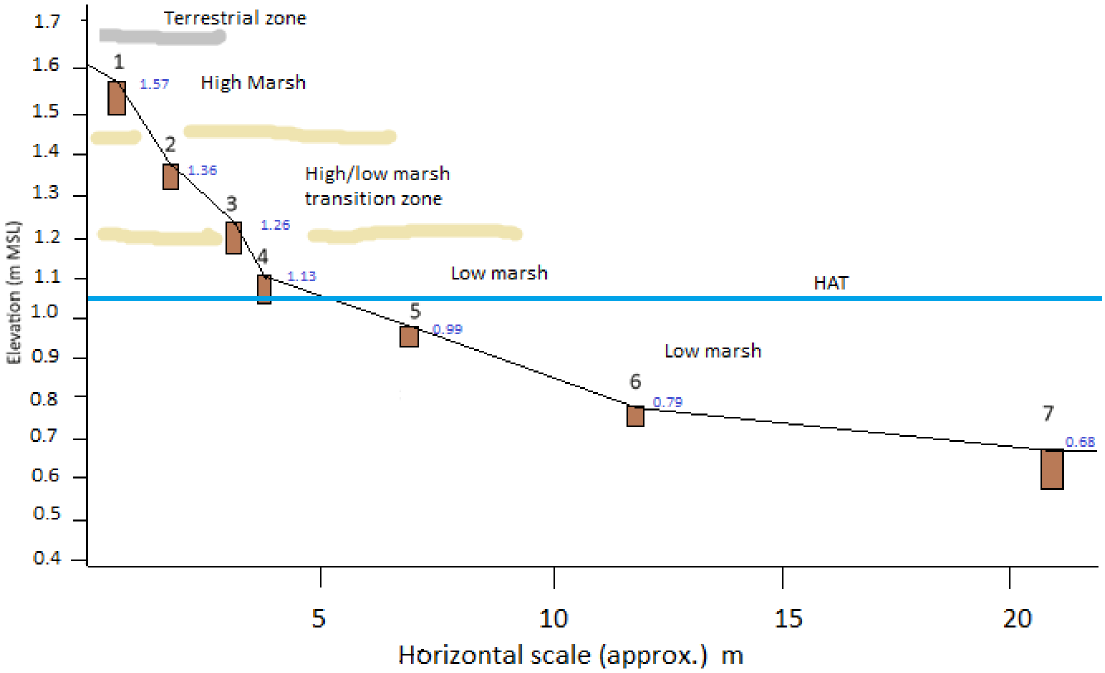
In addition we prepared duplicate samples from four layers within blocks 4 and 5 where we found both leaves and black carbonaceous spores of unknown origin. We were unsure whether these spores were contemporaneous with leaves found in the same 1 cm horizons and whether they might have been affected by post-depositional processes. By dating both leaves (principally from saltmarsh vegetation) and spores in these layers we could test their relative usefulness for dating. The original intention was to develop a transfer function (TF) from the contemporary diatom assemblage counts to reconstruct the tidal elevation at which each sediment sample was originally laid down. However, because of the relatively low number of sediment samples with identifiable valves in the training set (31 in total) and the frequently low total diatom counts obtained, the statistical TF approach was unable to predict realistic elevations for palaeo-marsh surfaces (Woodroffe *et al.*, 2009). Therefore a visual assessment (VA) approach was used (Long *et al.*, 2010) combining three principal elements; the sediment stratigraphy of each block, its LOI, and the distribution of the major high marsh and freshwater diatom taxa. While this method of reconstruction is more subjective its strength is in combining a wider variety of evidence, and its ability to integrate information of varied types despite each being insufficient in its own right.

3. Results

3.1 Modern saltmarsh environments

The Upernavik salt marshes have a total thickness below the soil surface of 10 cm at most, with bedrock or glaciated boulders from the last deglaciation often protruding through the sediment. The marshes are not extensive enough for creek development to occur but there are ponds present in depressions within the low platform of marsh one (Fig. 3C). Marsh one is divided into generally sloping high marsh, uniformly filled by *Carex glareosa* (gravel salt marsh sedge) (Rune, 2011) and flatter low marsh containing *Puccinellia phryganodes* (creeping salt marsh grass) (Rune, 2011), while marsh two is continuously sloping, with no zonation of vegetation, but uniform *Puccinellia phryganodes* growth throughout. Figure 4 shows a stylised cross section of the transect established across the marsh; the presence of stones and boulders displacing the thin sediment laterally prevented this from being a direct line. Table 2 provides data about the levels and zonation of these marshes, both of which have an area of barren soil or rock immediately above them before the onset of terrestrial (halophobic) vegetation. Their lower limits are marked not by thinning of the vegetation onto an area of tidal flat as in more expansive temperate marshes but a more abrupt rocky barrier before an abrupt descent into the tidal pools (marsh one) or erosion of the lower edge of the marsh where the gravel substrate is removed by high spring tides (marsh two).

Fig. 4 – Cross section of transect at Upernavik saltmarsh 1, with elevation of blocks taken, vegetation zonation and HAT.



The vertical range of the marshes at Upernavik is interesting because both marshes extend about 0.5 m above HAT, and their lower edges do not extend as far down as the level of MHWST. This means that the low marsh waterlogged platform of marsh one and sloping low marsh of marsh two (both dominated by *Puccinellia phryganodes)* are covered with seawater only during the higher peak spring tides, which in this mixed tide area is one higher high water every day, for a few days each second and fourth week. The high marsh environment of marsh one (dominated by *Carex glareosa)* is very rarely covered by sea water. While low atmospheric pressure, and storm waves, can carry sea water above HAT, the marshes at Upernavik are extremely well protected from significant wave action, and it is probable that a large part of these marshes is never covered by the tides.

	Mean elevation (m MSL)		Max and Min elevations (m MSL)	
	Marsh One	Marsh Two	Marsh One	Marsh Two
Upland/high marsh boundary	1.54	1.45	1.43 – 1.70	1.33 – 1.57
High marsh/low marsh boundary (Marsh One only)	1.31	No marsh division	1.20 – 1.47	-
Low edge	~ 0.66	0.94	-	0.73– 1.15
Reference elevation data	MHWST= 0.48		HAT = 1.05	

Table 2. Elevations of vegetation zone boundaries on marsh one and marsh 2 at Upernavik.

This extension of high marsh environments above HAT is seen to an extent at other saltmarshes on the west coast of Greenland, such as at Aasiaat where marshes are in more exposed locations, and the presence of high marsh above HAT has been attributed to wind/wave conditions (Woodroffe and Long, 2010).

3.1.1 Modern diatom data

Most of the modern samples had enough intact diatoms valves for a representative count to be possible, particularly on marsh one. In both marshes, the majority of the diatom counts are from above modelled local HAT, and on marsh one, *Pinnularia borealis* and *P. intermedia*, continue into the terrestrial zone above the high marsh (Fig. 5). *Navicula contenta* is also confined almost exclusively to the upper high marsh. Other oligohalobian-indifferent species, especially *Navicula pusilla* and *Nitzschia palaea*, cluster around the low/high marsh transition zone, but diatoms generally allocated to the more saline oligohalobian –halophile, mesohalobian and polyhalobian categories are fairly evenly distributed through all zones from the lower high marsh (which is still above local HAT) downwards (Fig. 5). There is an exception to this with *Navicula mutica* and *Achnanthes delicatula* both of which peak in the central low marsh below HAT.

3.2 Fossil sequences

All of the blocks taken from marsh one are shallow, with an upper layer of unhumified saltmarsh peat overlying more mixed organic and mineral sediment, deposited over gravel or finer till (Fig. 6). The elevation range of these fossil sediment blocks is 0.56 m. They were taken from the freshwater environment just above the high marsh (block 1), from the high marsh environment (blocks 2-4) and the low marsh environment (blocks 5-7). The descriptions below do not discuss the lateral variation within the blocks, but this is often considerable despite their averaging only about 7 x 7 cm. There are frequent small lenses of sand or clay within layers, and larger clasts several cm in each dimension. The blocks show a trend of increasing thickness of organic saltmarsh turfa overlying peat and/or minerogenic substrate as you move down marsh.

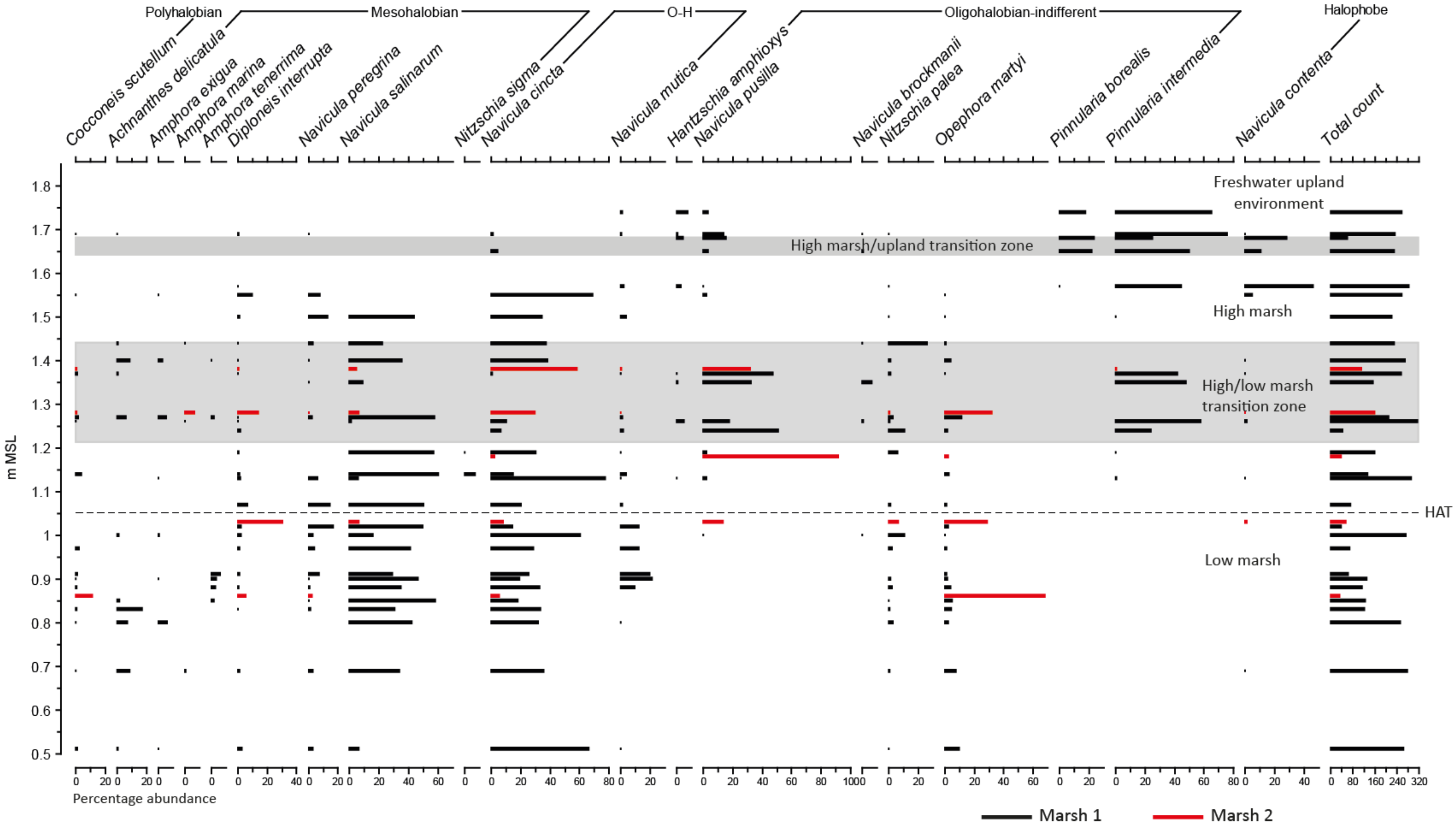


Fig. 5. Modern diatom distributions on Upernavik marshes. Species >5 % are displayed, as a % of total diatom valves. The marsh is between MWHST (0.48 m MSL) and 0.6 m above HAT (1.05 m MSL). Brackish diatoms (e.g. *Navicula cincta*) are found up to the high marsh/upland transition although in some Greenland saltmarshes they do not live far above HAT.

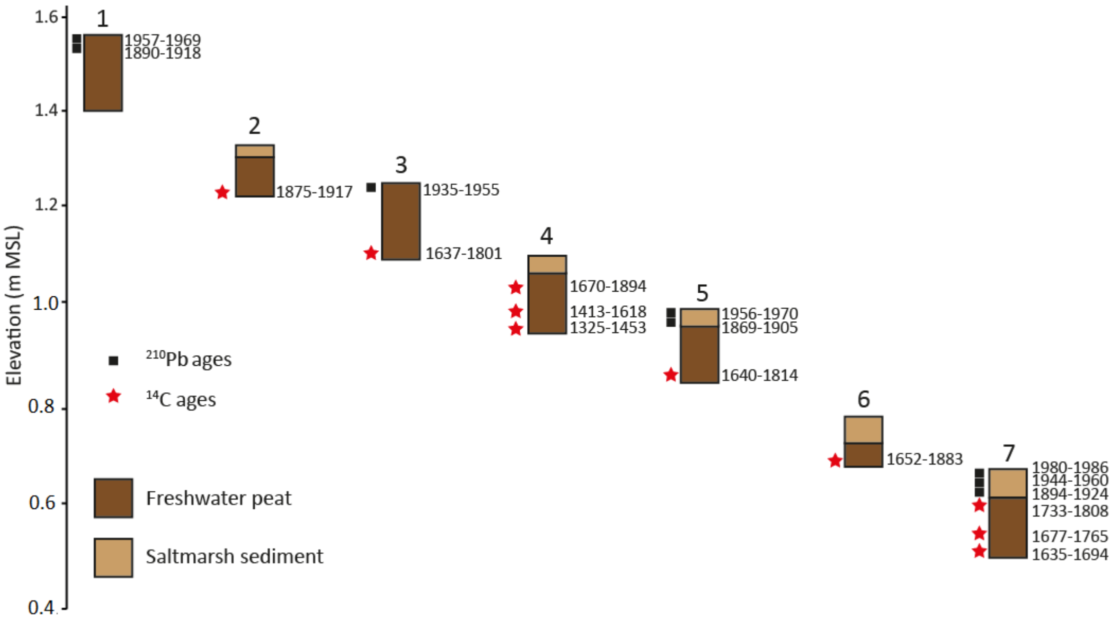


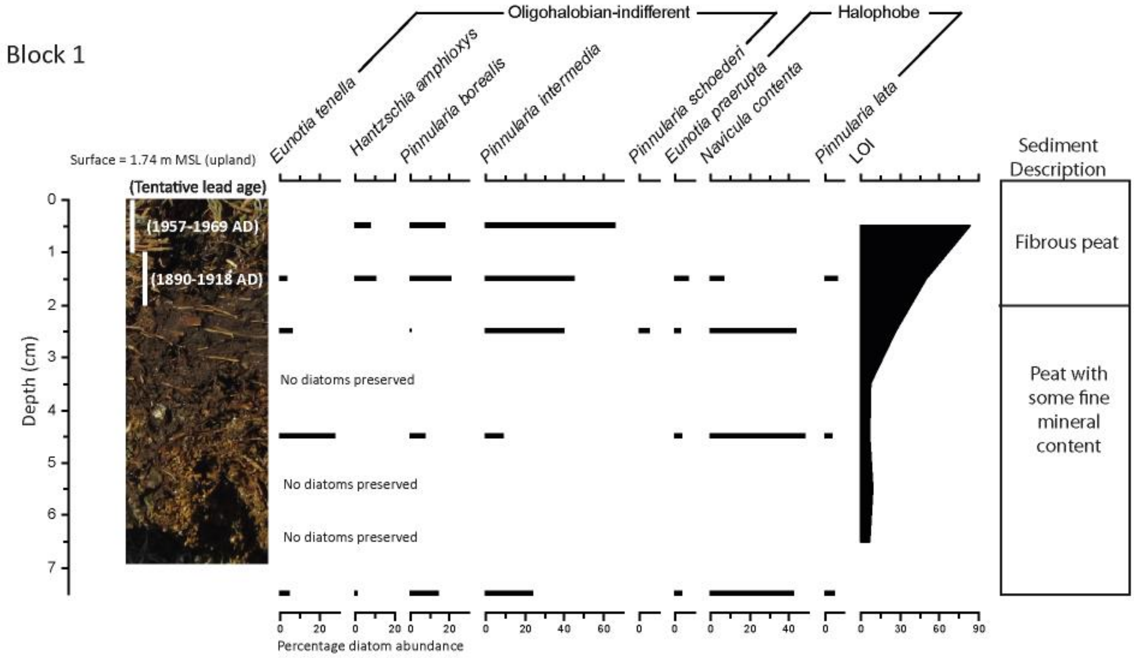
Fig. 6. Sediment blocks taken from marsh one, their surface elevations and ^{210}Pb and ^{14}C dating results (years AD). In this figure vertical extent is exaggerated to illustrate the relationship between the sediment profiles and the dates obtained.

3.2.1 Block 1

This has a depth of 7 cm above the underlying substrate, with a surface growth of *Carex glareosa*, at the very upper boundary of high marsh vegetation (Fig. 7). The lower 4 cm are well- humified peat with a low content of organic material, overlain by 3 cm of relatively fibrous and unhumified peat with a surface LOI of 83% in contrast to 7 % at 3-4 cm. Diatoms were found in most 1 cm sections but not at 3-4 cm, or 5-7 cm. *Navicula contenta*, a halophobic diatom, predominates in the lower and middle of the block but in the upper 2 cm olighalobian-indifferent diatoms, which tolerate a slightly more saline environment, take over. Dating of the 1-2 cm and 0-1 levels with ^{210}Pb gave estimated dates of deposition of 1890-1918 and 1957-1969 AD respectively (Table 3).

3.2.2 Block 2

Block 2 is 6 cm deep, in the upper high marsh (Fig. 7). The lower 4 cm is well humified peat with a high mineral content being replaced in the top 2 cm by unhumified saltmarsh turfa. Diatoms were found in all layers except at 4-5cm. As with block 1, in the lower and middle sections *Navicula contenta* is the commonest species but this declines at 1-2 cm and is absent in the uppermost 1 cm, replaced by olighalobian-indifferent diatoms. AMS ^{14}C dating of leaf fragments from 5-6 cm gave a calibrated date of deposition of 1875-1917 AD (SUERC-58404, 59 % confidence; Table 5).



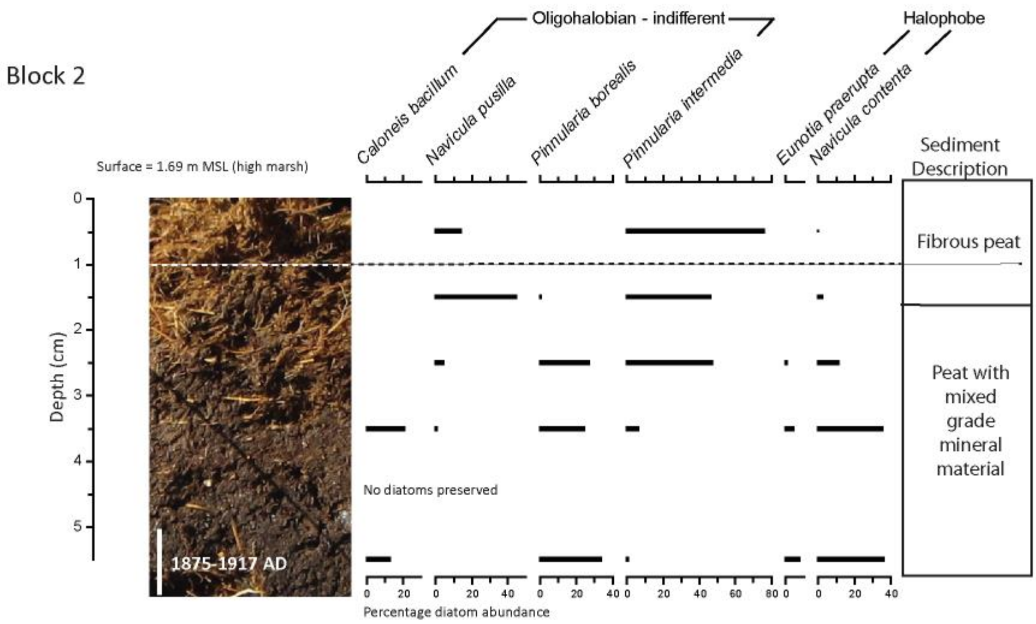


Fig. **7**. Diatom profiles from blocks 1 and 2 in marsh one. Data are expressed as a % of total diatom valves. Only species >5 % are shown. Also shown is % Loss on Ignition (none available for block 2), and ^{210}Pb and ^{14}C ages for these blocks.

Block and depth (cm)	Cesium (mBq/g-1)	Unsupported ^{210}Pb (mBq/g-1)	Simple model age before 2014	Simple model age error (yrs)	Simple model age (yrs AD)	CRS model age before 2014	CRS model age error (yrs)	CRS model age (yrs AD)
Block 1 0-1	121.11	279.84	48.15	5.93	1963.85	103.94	57.70	1908.06
Block 1 1-2	14.18	7.40	107.61	13.26	1904.39	155.40	72.43	1856.60
Block 1 2-3	0.24	1.00	218.61	26.93	1793.39			
Block 3 0-1	67.01	170.15	66.30		1945.70	110.37	74.51	1901.63
Block 3 1-2	11.76	2.86	197.55		1814.45			
Block 5 0-1	17.18	211.70	48.21	7.09	1963.79	40.00	5.41	1972.00
Block 5 1-2	9.77	52.78	124.49	18.30	1887.51	160.01	181.08	1851.99
Block 5 2-3	3.92	1.00	222.73	32.75	1789.27			
Block 7 0-1	3.50	113.45	28.30	47.83	1983.70	22.55	2.11	1989.45
Block 7 1-2	5.44	53.90	60.00	101.42	1952.00	47.64	4.85	1964.36
Block 7 2-3	6.56	31.53	102.63	173.46	1909.37	133.68	65.53	1878.32
Block 7 3-4	0.45	2.85	137.39	232.21	1874.61			

Table 3. Results of ^{210}Pb and ^{137}Cs dating of sub-samples from fossil blocks from marsh one.

3.2.3 Block 3

This 7 cm block comes from the high marsh just above the junction of the high and low parts of marsh one. It has a base of 7 cm of minerogenic sediment with 1.5 cm of unhumified fibrous peat below the surface. The LOI profile increases sharply upwards, from 13 % at 3-4 cm to 57 % at the surface (Fig. 8). The upper 3 cm and the lowest level (6-7 cm) contain diatom assemblages which are fairly similar, predominantly olighalobian-indifferent but with some halophobic *Navicula contenta,* but with no clear pattern of change in diatoms between the base and surface of the block. There is a ^{210}Pb date for the uppermost cm of sediment of 1935-1955 years, and a calibrated AMS ^{14}C date at 6-7cm of 1637-1801 AD (UCIAMS-154538, 89 % confidence; Table 5). Because of the small size of this sample of leaf fragments it required sending to the Keck Carbon Cycle AMS Facility at the University of California for analysis.

3.2.4 Block 4

This block also came from just above the high marsh/low marsh boundary on marsh one, and has 9 cm of sediment, the lower 7 cm of the block being humified peat with some minerogenic matter and the upper 2 cm being unhumified saltmarsh turfa. Diatoms were present in most layers of the block, predominantly *Navicula contenta* below 3-4 cm depth (Fig. 8). Above this, olighalobian and then mesohalobian diatoms form the majority of the assemblages found. We AMS ^{14}C dated leaf fragments from 8-9, 6-7, 3-4 and 1-2 cm with calibrated AMS dates of 1325-1453, 1413-1618, 1670-1894 and 1670-1940 AD respectively (samples UCIAMS-154539, SUERC-58405, SUERC-58407, and SUERC-58412, with 95 %, 80 %, 95 % and 95 % confidence respectively; Table 5); the uppermost sample was small and was analysed at the Keck Carbon Cycle AMS Facility.

3.2.5 Block 5

Block 5 is 7 cm deep, with a basal 2cm basal very sandy layer, overlain by 6 cm of humified peat with some minerogenic sediment and then 2 cm of very organic unhumified saltmarsh turfa to the surface (Fig. 9). The LOI increases upwards from 28% in the basal layer but dips to 12 % in the mid-section and rises again to 60 % at the surface. This pattern of changes in LOI up-block is also seen in block 7. The diatoms show a change from almost entirely halophobian, *Navicula contenta* and *Eunotia arcus* at the base, to halophobe and olighalobian-indifferent at 4-5cm, and olighalobian-indifferent with meso/polyhalobian above 3cm, with a predominance of *N. peregrina* and *N. cincta* (Fig. 7). Three dates were obtained for this block; an AMS ^{14}C date of 1640-1814 AD at 6-7 cm (SUERC-58414, 76 % confidence; Fig. 9 and Table 5) and two ^{210}Pb dates near the surface; 1869-1905 AD at 2-3 cm and 1956 – 1970 at 1-2 cm (Table 3).

3.2.6 Block 6

This is 5 cm deep, a light-coloured layer of organic course sand overlain by 3 cm of waterlogged fairly unhumified saltmarsh turfa (Fig. 9). Diatom assemblages were found in all layers, progressing from strongly freshwater halophobian at the base, especially *N. contenta*, through mainly oligohalobian in the middle layers to predominantly mesohalobian at the surface. An AMS ^{14}C date of 1652-1883 AD for the basal 4-5cm layer was obtained (SUERC-58416; 77 % confidence; Table 5).

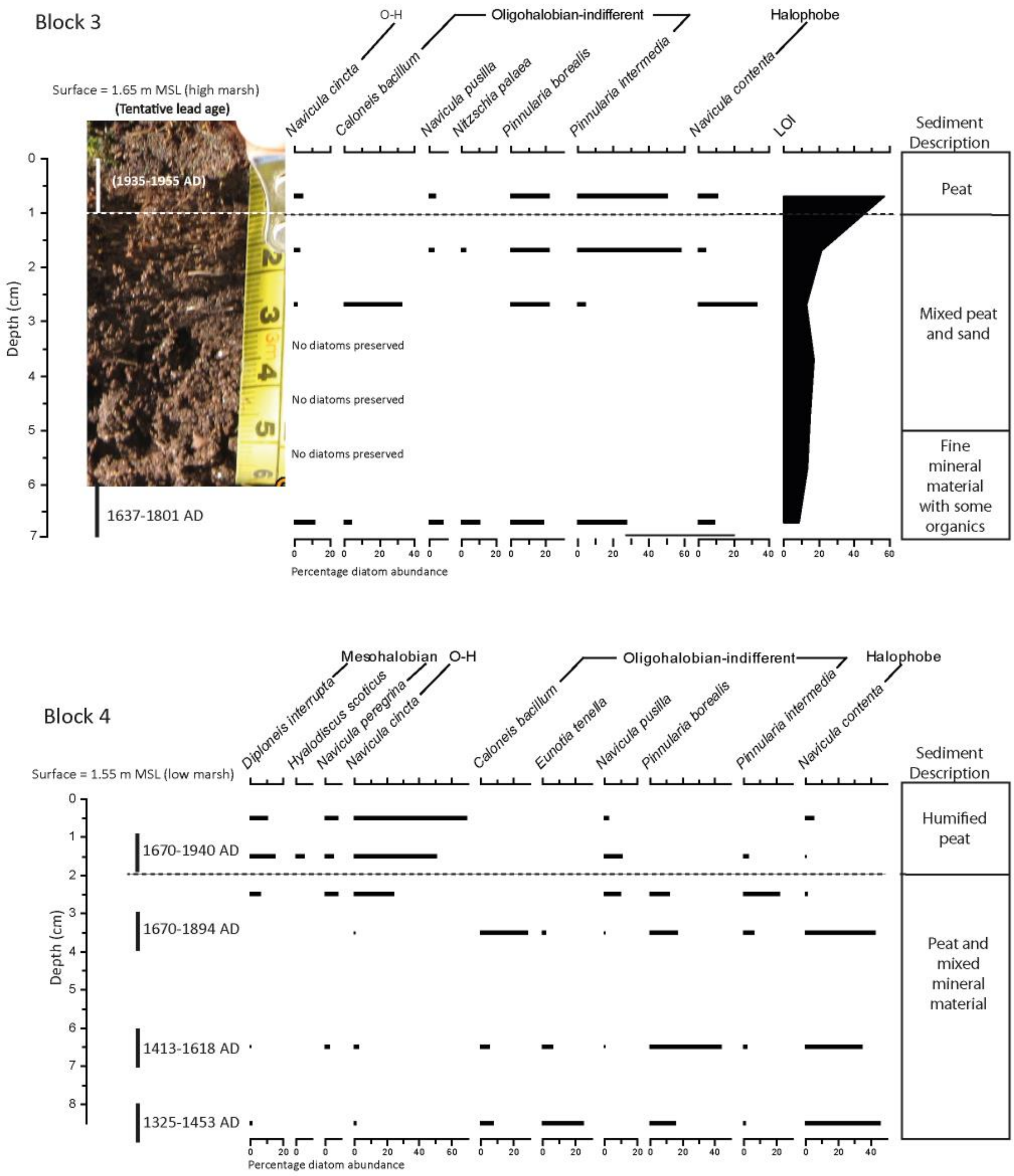


Fig. 8. Diatom profiles from blocks 3 and 4, marsh one. Data are given as % of total valves. Only species >5 % are shown. Also shown is % LOI (block 4), and ^{210}Pb and ^{14}C ages.

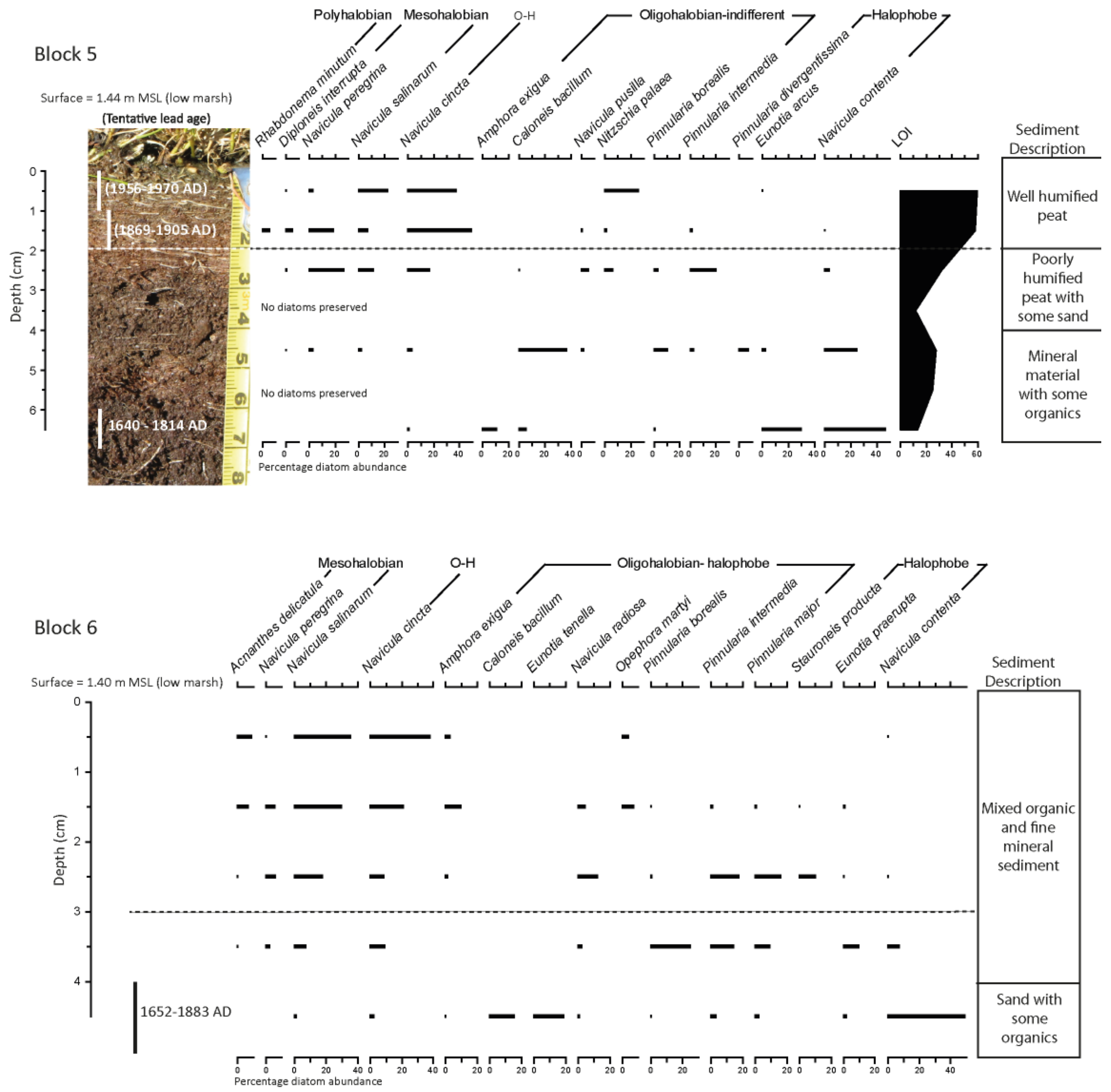


Fig. 9. Diatom profiles from Blocks 5 and 6 in marsh one. Data are expressed as a % of total diatom valves. Only species >5 % are shown. Also shown is % Loss on Ignition (none available for block 6), and ^{210}Pb and ^{14}C ages for these blocks.

3.2.7 Block 7

Block 7 was the lowest block as the salt marsh sediment below this was extremely thin but also appeared to have moved from its original position. Block 7 is 10 cm deep with an organic silt/clay at the base, overlain by a lighter 6 cm layer of silty peat, and a 3 cm upper layer of poorly humified silty saltmarsh turfa (Fig. 10). The LOI profile is high near the base, reaching 69 % at 5-6 cm, dropping to 29 % at 3-4 cm and rising near the surface towards 50 %. There are diatom assemblages found at all but one level. As with most of the other blocks, the strongest freshwater assemblage is the lowest layer, at 28 % *N. contenta* having its only significant presence at 9-10 cm, with an increase in olighalobian-indifferent diatoms, *P. intermedia and P. major*, before becoming predominantly oligo-halophile and mesohalobian the upper 3 cm with the constant presence of some polyhalobian *Cocconeis scutellum* valves (<5 % so not included in Fig. 9). There are some mesohalobian diatoms present at all levels however, especially *N. peregrina* which is seen alongside *N. contenta* in the theoretically freshwater deposit at the base. Six dates were obtained, the three lower AMS ^{14}C dates were on *Carex* seeds, from 1635-1694 at 7-8 cm, 1677-1765 at 5-6 cm, and 1733-1808 at 3-4 cm (SUERC-58417, UCIAMS-154542 and SUERC-58418, with 31 %, 35 % and 36 % confidence; Table 5); the uppermost 3cm gave ^{210}Pb ages of 1894-1924 at 2-3cm, 1944-1960 at 1-2 cm and 1980- 1986 at 0-1 cm (Table 3).

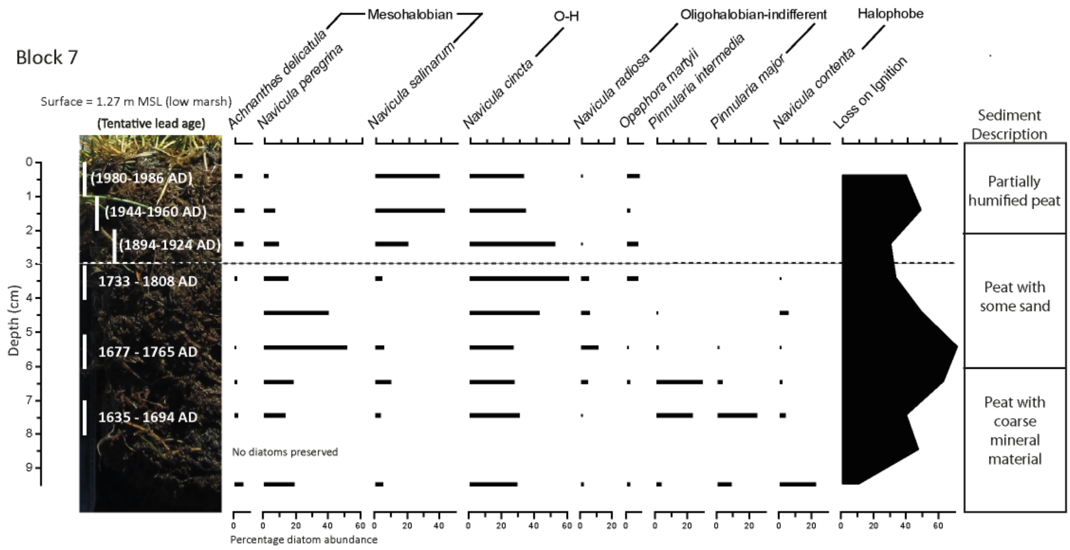


Fig. **10.** Diatom profile from block 7 in marsh one. Data are expressed as a % of total diatom valves. Only species >5 % are shown. Also shown is % Loss on Ignition, ^{210}Pb and ^{14}C ages and the sea level interpretation for this block.

3.3 Comparison of dating leaf fragments and fungal sclerotia

Four duplicate organic samples were sent for AMS ^{14}C dating, from layers of sediment from which standard macrofossil leaf or seed samples were also sent (Table 5). These were small matt black hollow spheres, thought to be sclerotia, fungal 'survival' bodies that can persist in viable form for some years before growing if they are in suitable conditions. These are probably from *Cenococcum geophilum*, which grows on woody material, and has been found in material in Sisimiut, and used to date vegetation changes that took place there during the late Holocene (Leng *et al.*, 2012). However, this saprophytic fungus grows on carbon compounds from existing plants, particularly woody material which may itself have died some time before being colonised by the fungus. The dates on these sclerotia are all significantly older than the dates from the leaf fragments found within the same 1 cm thick horizon. The largest age difference is c. 1000 years between the leaf fragment age (1413-1618 AD) and the fungal sclerotia age (260-535 AD) at 6-7 cm depth in block four (Table 5). The ages of the leaf fragments are in stratigraphic order, whilst the ages on the fungal sclerotia vary widely within the same sediment profile (Table 5). We assume that the leaf material was incorporated into the sediment surface usually within a few years of its initial formation, while the sclerotia were derived from fungal growth on dwarf willow or birch whether in the vicinity of the saltmarsh or possibly some kilometres from the site, and were transported either by wind or by animals or birds. Therefore dating these fungal sclerotia is not useful in determining the ages of saltmarsh sediments. These four samples provide limiting dates for deglaciation at their unknown site of origin, rather than probable sediment deposition dates, and have not been considered when reconstructing RSL.

3.4 Sediment accretion rates

All of the dates, with the exception of the fungal sclerotia which are not considered to be contemporaneous with the sediment horizon they were found in, are in chronological order by depth, although there are some marked changes in the rate of sedimentation with depth (Table 4). The rates of sedimentation are much lower than those found in temperate areas, where several mm of accretion or more per year is general (Cahoon and Reed, 2011). Accretion rates in the upper few cm of saltmarsh turfa are lower than in the deeper terrestrial peat layers. Block 2 apparently shows the most rapid accretion, based on a single date, and it may be that this is the result of bioturbation or mass sediment movement giving a misleading age, although being on the steepest section of the marsh this block may have consistently gained material from higher up the slope. In contrast, block 4 has shown slower accretion throughout its deposition history with the apparent exception of the section from 2 to 4 cm. If the uppermost age of 210 years is disregarded and the next age is averaged to the surface giving a rate of 0.15 mm/yr, this is in keeping with the slow general rate for this block. The lowest block, block 7, generally shows faster accretion than the others, which could relate to lack of water stress in this moist lower platform allowing faster plant growth which also permitted more efficient mineral sedimentation when this area was covered by the tide. However, there is a single narrow band at 3 cm of 0.07 mm/yr, coinciding with lowest LOI in this block – in contrast to the general pattern of slightly faster accretion with lower LOI elsewhere in the marsh. While this could relate to a change in marsh processes such as the transition from freshwater to saltwater conditions, it is possible that it relates to sediment loss through ice rafting or frost heaving.

Sediment layer boundary depth cm	Block 1		Block 2		Block 3		Block 4		Block 5		Block 6		Block 7	
	(^{210}Pb dates)	mm^{-1}	(^{14}C dates)	mm^{-1}	(both dates)	mm^{-1}	(^{14}C dates)	mm^{-1}	(both dates)	mm^{-1}	(^{14}C dates)	mm^{-1}	(both dates)	mm^{-1}
0														
	48				66			(0.07)	48				28	
1		0.17								0.13				0.31
	108						210		124				60	
2				0.46								0.18		0.23
								(0.87)					103	
3						0.26								0.07
							233						245	
4										0.30				
											248			0.41
5								0.11						
			119										294	
6														
					296		500		288					0.36
7														
								0.16					350	
8														
							626							
9														

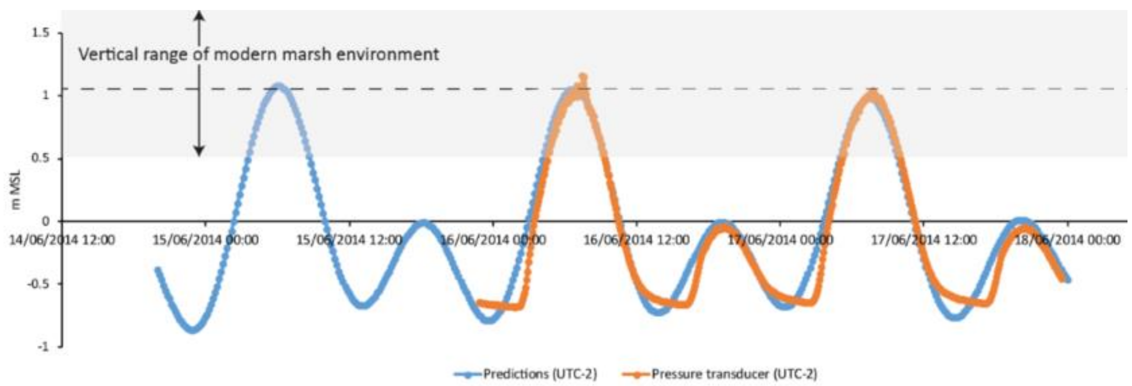
Table 4. Sediment ages and inferred accretion rates. ^{210}Pb ages of dated 1 cm thick sediment layers are in red, and ^{14}C ages in green. Both are reported as years before 2014 (mid-point of age range); rates of accretion (mm/yr) within the block, between adjacent dates; or the uppermost date and the surface, in black. For discussion of rates in brackets (block 4) see text.

3.5 Tidal range

Reconstruction of tidal elevations, using the pressure transducer measurements taken from the upper basin over a 2-day period immediately following the peak spring tide for the year, showed very close correspondence to the modelled predictions for the open coast (fig. 11) for the majority of the tidal cycle, and especially the higher-high water hemi-cycle when the salt marshes are reached by the tide. The alternating high and low peaks demonstrated reflect the mixed tide regime that occurs along the majority of the West Greenland coast (fig. 2), with lower high water peaks barely reaching mean tide level at this stage in the spring/neap cycle. The main difference demonstrated from the predicted pattern is a delayed final emptying to low tide, this slowing starting several hours after the water level has dropped below the low edge of the marshes. This delay reflects the placing of the pressure transducer in the upper basin, separated from the open sea by two bedrock sills which were also partially blocked by ice floes during the final stages of emptying before actual low tide. Both sills remained under water at low tide at this point in the tidal cycle, with still water across them for a period before the return flow of the flood tide began. This gives us confidence that the sills do not materially influence the tidal pattern within the basins or the duration of exposure of the salt marshes to sea water.

Direct levelling of both high and low tide adjacent to marsh 1, carried out during the 24 hours just following the peak spring tide, corresponded well with the pressure transducer data (see **figure** ?2); the rise to high water matching modelled predictions closely, but the final stages of the drop to low tide showing a lag. These measurements were taken close to the outflow of the upper sill (being the only accessible area of tidal flat) where faster discharge continued for a while after low water in the open sea; this delay additionally supported by the lower basin also demonstrating a slight lag in its emptying.

Fig. 11. Modelled tidal predictions for Upernavik Harbour (blue) and pressure transducer measurements for mid-June 2014. The dotted line shows HAT.



Sample code and depth below surface	Laboratory code	Material dated (grey/bold; see table caption)	Sample elevation (m MSL)	$\Delta^{13}C_{VPDB}$ ‰ ± 0.1	Conventional radiocarbon age (yr AD ± 1σ)	Age ranges, cal yr AD (whole range = 2σ)	Preferred age range, cal yr AD (% in brackets)
Block 2 5-6 cm	SUERC-58404	Leaf fragments	1.635	-26.8	Modern ($F^{14}C$ 100.01 ± 0.44)	1695-1725, 1813-1837, 1842-1852, 1868-1873, 1875-1917, 1954-1956	1875-1917 (59 %)
Block 3 6-7 cm	UCIAMS-154538*	Leaf fragments	1.595	-24.0 $^{\Delta}$	235 ± 25	1637-1680, 1763-1801, 1938-1950	1637-1801 (89 %)
Block 4 1-2 cm	UCIAMS-154539*	Leaf fragments	1.535	-25.8 $^{\Delta}$	130 ± 25	1677-1765, 1773-1777, 1800-1893, 1907-1940	1670-1940 (95 %)
Block 4 3-4 cm (L)	SUERC-58405	Leaves	1.515	-27.4	132 ± 35	1670-1780, 1798-1894, 1905-1944	1670-1894 (80 %)
Block 4 3-4 cm	SUERC-58406	sclerotia	1.515	-31.2	725 ± 37	1221-1304, 1365-1384	1221-1384 (95 %)
Block 4 6-7 cm (L)	SUERC-58407	Leaves	1.485	-27.1	437 ± 37	1413-1515, 1598-1618	1413-1618 (95 %)
Block 4 6-7 cm	SUERC-58409	sclerotia	1.485	-30.1	1650 ± 37	260-279, 326-475, 485-535	260-535 (95 %)
Block 4 8-9 cm (L)	SUERC-58412	Leaves	1.465	-27.0 $^{\Delta}$	498 ± 37	1325-1345, 1393-1453	1325-1453 (95 %)
Block 4 8-9 cm	SUERC-58413	sclerotia	1.465	-30.4	1598 ± 35	392-545	392-545 (95 %)
Block 5 6-7 cm (L)	SUERC-58414	Leaves	1.375	-27.5	207 ± 37	1640-1695, 1726-1814, 1837-1843, 1852-1868, 1917-1950	1640-1814 (76 %)
Block 5 6-7 cm	SUERC-58415	sclerotia	1.375	-30.6	982 ± 37	992-1155	992-1155 (95 %)
Block 6 4-5 cm	SUERC-58416	Carex seeds	1.355	-28.8	174 ± 37	1652-1707, 1719-1820, 1832-1883, 1914-1950	1652-1883 (77 %)
Block 7 3-4 cm	SUERC-58417	Carex seeds	1.235	-28.3	235 ± 35	1524-1559, 1631-1685, 1733-1808, 1929-1950	1733-1808 (36 %)
Block 7 5-6 cm	UCIAMS-154542*	Carex seeds	1.215	-29.4 $^{\Delta}$	130 ± 25	1677-1765, 1773-1777, 1800-1893, 1907-1940	1677-1765 (35 %)
Block 7 7-8 cm	SUERC-58418	Carex seeds and leaves	1.195	-29.1	214 ± 37	1530-1540, 1635-1694, 1727-1813, 1918-1950	1635-1694 (31 %)

Table 5. Radiocarbon dates from Upernavik. Starred samples were small (260µg to 470 µg carbon), analysed at low current at the Keck Carbon Cycle AMS Facility, University of California, Irvine, USA. Samples highlighted in grey are on fungal sclerotia from blocks 4 and 5, the same depths as leaf samples for comparison. $^{\Delta}\delta^{13}C$ values were calculated from $\delta^{13}C/^{12}C$ ratios measured during AMS ^{14}C determination and compared to Craig (1957) $\delta^{13}C/^{12}C$ values for PDB. These may not be representative of $\delta^{13}C$ in the original sample.

3.6 Relative sea-level reconstructions

The sediments from Upernavik yield a mixture of direct SLIPs and limiting ages which we use to reconstruct RSL (Fig. 12A). At Upernavik, unlike at several other saltmarshes studied in west Greenland (Long *et al.*, 2012), oligohalobian-indifferent and halophobian diatoms such as *P. borealis, P. intermedia* and *N. contenta* are present above the highest limit of high marsh vegetation (Fig. 3). We assign limiting ages when we cannot tell whether the horizon being dated is in the highest high marsh or the adjacent upland environment. The diatom assemblages in these environments (dominated by *P. borealis, P. intermedia* and *N. contenta*) are very similar. Only where there is a stronger marine signal in the top few centimetres of the sediments are we confident that they have a direct relationship to sea level, and we assign these as sea-level index points (e.g. blocks 5-7, Fig. 8, 9, 10). The SLIP and limiting point data is summarised in table 6.

The indicative meaning of the majority of the dated saltmarsh samples in this study is estimated as within the modern day high marsh (1.6 m MSL ± 0.15 m, Fig**.** 3) which is where there is a transition in the modern diatoms from an assemblage dominated by *N. contenta, P. intermedia* and *P. borealis* to a more diverse and marine assemblage which includes small but increasing percentages of *N. pusilla, N. cincta* and *N. salinarum*. For the uppermost three dated samples in block seven which are from low marsh environments below 1.27 m MSL (the surface elevation of the lowest block) we estimate their indicative meaning as 1.4 m MSL ± 0.15 m, but assign the top 0-1 cm dated horizon in block 7 as 1.3 m MSL ± 0.15 m because this is close to the surface elevation of this block.

Block 1 shows a change environment in its upper section at 2 to 3 cm with the increase in LOI and decrease in minerogenic content (Fig**.** 5). This transition is weakly supported by a change in diatom type, as although the proportion of the strongly halophobian *N. contenta* declines, *P. intermedia* and *P. borealis*, both fairly halophobian, remains quite abundant. This change happens below the ^{210}Pb date of 1890 – 1918, for the 1-2 cm level. We hypothesise that this increasing LOI, decrease in *N. contenta* and increase in *P. intermedia* up block suggests increased waterlogging as sea-level rises means the block is approaching the high marsh environment for the first time. It is worth noting that the surface environment at this elevation today is just above the highest occurrence of marsh plants and therefore this block does not yet directly record sea-level changes. As this environment does not have a direct quantifiable relationship to RSL we assign the lead ages from this block as limiting ages.

The directly dated horizons in block 2 and at the base of block 3 are also from freshwater environments so we also assign these as limiting ages (Fig. 7 and 8). The ^{210}Pb age in the top 1 cm of block 3 is accompanied by an increase in LOI and a decline in *N. contenta* above 2 cm. We suggest this is evidence of the first marine influence (the surface of this block is in the modern high marsh) and with a ^{210}Pb age of 1935 - 1955 suggests increased marine influence in the past c. 70 years. The dated horizons in block 4 are old (Fig. 8) and the lowest three have high occurrences of *N. contenta*. These are assigned as limiting ages. The uppermost ^{14}C dated horizon in block 4 is likely to be from an upper marsh environment but has a wide probability distribution on its age (1670-1940 AD) and therefore is not a useful sea-level index point. Blocks 5 to 7 yield the most useful sea-level index points, with the top 2-3 cm of each block indicating a high or low marsh environment because of the increased occurrence of meso- and oligohalobian-halophile diatoms.

Block 5 is from the flatter platform of the low marsh which nowadays has standing pools of water and has probably been waterlogged during the growing season whether as terrestrial vegetation or now as salt marsh, giving higher organic productivity with either type of vegetation because of the lack of water stress (Little, 2000). The deeper ^{210}Pb date of 1896 to 1905 at 1-2 cm, just above the stratigraphic change, suggests the transition to salt marsh began here more than 110 years ago.

Block 6 has an initial decline in *N. contenta* 2 cm above the base, with a subsequent decline in other halophobian and oligohalobian-indifferent diatoms and an increase in oligohalobian-halophobian ones. Together with the stratigraphical change at 3 cm this is the approximate point when salt marsh replaced freshwater marsh. The only date of this block is 1652 to 1883 AD at 4-5 cm (3 cm lower than the transition) and is therefore a limiting date, but averaging the surface peat sedimentation rates of approximately 0.132 mm/yr in Block 5, above and 0.132 mm/yr in Block 7, the transition to saltmarsh at 3 cm may have occurred roughly 129 years ago.

Block 7 shows a decline in *N. contenta* just above its base at 9 cm suggesting earlier onset of marine conditions than in higher blocks, with *P. borealis* and *P. intermedia* continuing upwards for another 3 cm (Fig. 10). This low zone has a high LOI again suggests productive vegetation, probably freshwater marsh. There is considerable discrepancy between the calibrated AMS carbon date immediately below the upland/high marsh transition at 3-4 cm (1733-1808 AD) and the ^{210}Pb date immediately above it at 2-3 cm (1894-1924 AD). The mean date for this transition is 1840 AD, 170 years ago.

Table 6 - Sea-level reconstruction points data. HM – high marsh; LM – Low marsh.

SLIPS	Depth	Age	Error	Elevation	IM	IM error	RSL	Palaeo-tidal position
Block 3	0-1	1945	10	1.645	1.68	0.15	-0.035	Upland sample
Block 5	0-1	1962	8	1.435	1.6	0.15	-0.165	HM/LM
Block 5	1-2	1890	20	1.425	1.68	0.15	-0.255	HM
Block 7	0-1	1983	3	1.265	1.3	0.15	-0.035	HM/LM
Block 7	1-2	1952	8	1.255	1.4	0.15	-0.145	HM/LM
Block 7	2-3	1900	20	1.245	1.4	0.15	-0.155	HM

Limiting points								
	Depth	Age	Error	Elevation	IM	IM error	RSL	Palaeo-tidal position
Block 1	0-1	1963	6	1.735	1.68	0.15	0.055	Upland sample
Block 1	1-2	1904	14	1.725	1.68	0.15	0.045	Upland sample
Block 2	5-6	1896	21	1.635	1.68	0.15	-0.045	Upland sample
Block 3	6-7	1719	82	1.595	1.68	0.15	-0.085	Upland sample
Block 4	3-4	1782	112	1.515	1.68	0.15	-0.165	Upland sample
Block 4	6-7	1516	103	1.485	1.68	0.15	-0.195	Upland sample
Block 4	8-9	1389	64	1.465	1.68	0.15	-0.215	Upland sample
Block 5	6-7	1727	87	1.375	1.68	0.15	-0.305	Upland sample
Block 6	4-5	1768	116	1.355	1.68	0.15	-0.325	Upland sample
Block 7	3-4	1771	37.5	1.235	1.68	0.15	-0.445	Upland sample
Block 7	5-6	1721	44	1.215	1.68	0.15	-0.465	Upland sample
Block 7	7-8	1665	29.5	1.195	1.68	0.15	-0.485	Upland sample

3.7 Vertical error of the sea-level reconstruction

The root mean square error of prediction (RMSEP) of the components of error for the vertical reconstruction of RSL at Upernavik salt marsh is 12.45, and therefore a conservative estimate of 15 cm has been adopted for error. The components of vertical error are shown in Table XYZ .

Table 7. Components of vertical error of the RSL reconstruction at Upernavik saltmarsh

	Component of error	**Estimated error** (cm)
a	Levelling of higher high water to TBM; the deviation of measured values from the predictions of tide levels at the open coast (appendix 2)	2
b	Correspondence of pressure transducer measurements to tidal predictions (Fig. 11)	5
c	Levelling error for surface elevation of sediment blocks to TBM (as of tide error, above)	2
d	Depth of each SLIP within its block	2
e	Variation in level of high marsh/upland boundary – 2 σ value (*see below)	10.866

*Marsh 1 high marsh/upland boundary varies in elevation by 27 cm with a mean of 69.5cm TBM. 1 SD is 5.433 therefore 2 σ = 10.866.

4. Discussion

4.1 Late Holocene and recent RSL changes in the Upernavik area

The Holocene RSL history of the Upernavik area is modelled to consist of early Holocene RSL fall from a marine limit close to present to a very deep low-stand (-15 to -20 m between 8-4 ka BP) and rapid RSL since then (Figure 9C, Lecavalier *et al.*, 2014). The profusion of perched boulders on slopes at all elevations starting from the upper edge of the wave splashed rocks, demonstrates agreement with this RSL curve and that the deglacial marine limit is at current sea level +2 m or more likely below present day sea level. This is the situation for much of the coastline from Upernavik north towards Thule and compares to a marine limit of c. +60 m in Disko Bugt (Long *et al.*, 2006), and close to +130 m in the Sisimiut area (Long *et al.*, 2009). The Upernavik region is close to the centre of the biggest modelled area of RSL rise on the west coast of Greenland during the late Holocene, caused by the collapse of the Laurentide forebulge along with eustatic sea-level rise (Fig. 12C, Lecavalier *et al.*, 2014). However the situation of rapid regional late Holocene RSL rise (c. 15m in 4000 years – c. 3.75 mm/yr) until recently is in contrast to the last decade or so when there has been significant crustal uplift at Upernavik recorded by GPS (7.81 mm/yr of uplift between 2007-2011, Bevis *et al.*, 2012). This is linked to the rapid deglaciation at the nearby Upernavik Isstrøm, superimposed on the continuing (but slower) collapse of the NAIC forebulge. This is likely to now be causing rapid RSL fall at Upernavik although this has not been recorded in the saltmarshes. However, because of global eustatic sea level change (Engelhart *et al.* 2009**,**) and gravitational changes related to ice cap shrinkage (Gehrels and Long, 2008) the RSL drop demonstrated would probably be less than the recorded uplift rate.

Sea level index points developed from saltmarshes close to present day sea level in this study demonstrate a rise in RSL of c. 0.3 m over 100 years prior to 2014 AD (at a rate of 3 mm/yr), and limiting dates showing a minimum of a further 0.2 m rise in the preceding 235 years (Fig. 9A). This rapid RSL rise agrees with rapid rise modelled to have occurred during the last millennium (crudely shown as a linear rate of rise by Lecavalier *et al.* (2014)) (Fig. 12B). The saltmarshes at Upernavik have very slow organic accumulation rates and under conditions of persistent and rapid RSL rise during the majority of the 20th century they have not had time to develop very thick sediment profiles.

To compare the new saltmarsh-based RSL record from Upernavik to other locations in west Greenland, Upernavik is the only studied location where we see persistent RSL rise throughout the last few centuries. In Disko Bugt, and in central west and southern Greenland we see a 1-3 m RSL rise over several centuries, but with little or no change in the past 200-400 years (Long *et al.*, 2012; Long *et al.*, 2010; Woodroffe and Long, 2009, 2010). The lack of RSL stability in the last couple of centuries at Upernavik as compared to other west coast locations is due to the timing of Greenland ice sheet retreat in this region and the overwhelming and continuing influence of the collapsing North American Ice sheet Complex (NAIC) forebulge in recent times. Deglaciation occurred somewhat later around of the northern dome of the GIS (Funder and Hansen, 1996), at a time when global sea level had already risen considerably from its minimum at the LGM. To consider the components of the NAIC and its impact on RSL, the Upernavik region is more severely impacted by the collapse of the Innuitian ice sheet (IIS) than locations further south. The IIS reached its maximum extent at about 8 ka BP, after the majority of the more southerly and rather larger Laurentide Ice sheet component of the NAIC had collapsed (England *et al.* 2006). In south-west Greenland the slight re-advance of the GIS during the late Holocene neoglacial and subsequent retreat since the end of the Little Ice Age has been important in late Holocene RSL changes but this is not thought to be a significant factor in the north-west where the margin remained largely stable during this period (Briner *et al.*, 2013).

Pinpointing when the reversal from rapid RSL rise (as shown by our new saltmarsh data) to RSL fall (suggested by current uplift from GPS data) occurred during the last century is still difficult. Because of low productivity and a very short growing season the marshes at Upernavik have very low sedimentation rates. We would normally expect to see the highest sedimentation rates in the high marsh (due to enhanced biological productivity) but even here a 1 cm thick section can represent 60-70 years of vertical saltmarsh accumulation. However we can say that for the majority of the 20th century it appears that the marshes have undergone rapid RSL rise (Fig. 12A), and therefore the crustal uplift (and RSL fall) currently being experienced must be a very recent (post 1980s at least) phenomenon. Based on these results we would only expect to register a change from a transgressive to regressive sequence in the diatoms and sediments (e.g. through LOI values) of the Upernavik saltmarshes over the next 50 years or so, that is assuming that RSL rise continues at the rate recorded between 2007-2011 (7.81 mm/yr, Bevis *et al.*, 2012).

The retreat of the Upernaviks Isstrøm since 1849 was relatively slow until ~1931 when it accelerated to nearly 1km/yr for around a decade before slowing somewhat (Briner *et al.*, 2013), but the calving front also widened progressively in this period, splitting into four arms which have continued to retreat at different rates. In the late 1980's there was over 100 m of thinning of one of the arms and acceleration of another (Andresen *et al.*, 2014). Although the downwasting of Upernaviks Isstrøm is episodic, there has been considerable ongoing decrease in mass for the past 80 or so years. The uplift this has triggered is a combination of immediate elastic rebound as well as more viscous post-glacial rebound which takes place over much longer time period (Alley 2010)

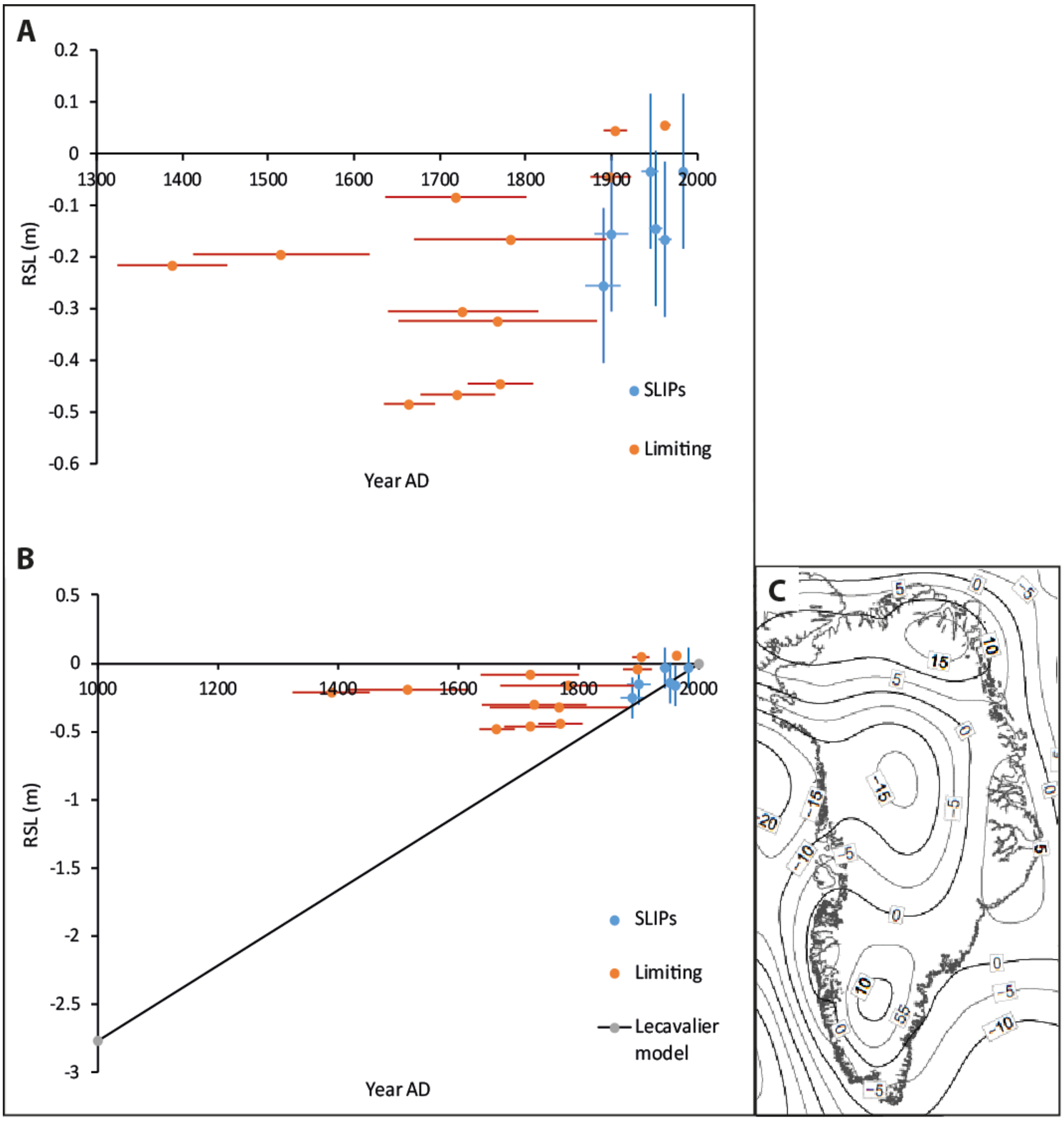


Fig. 12. A) RSL reconstructions from Upernavik saltmarshes. Blue crosses are sea-level index points (SLIPs), orange lines give limiting information (RSL was below these values), B) RSL data with model-predicted RSL for the last 1000 years from Lecavalier (pers comm) using the optimal earth model from Lecavalier *et al.*, (2014) including an alternate North American Ice Complex (NAIC) chronology which is the best fitting solution from Tarasov *et al.*, (2012), C) Spatial plot of RSL predictions (in metres) at 4ka BP from Lecavalier *et al.* (2014) which does not include an alternative NAIC chronology to that given in ICE-5G.

and it seems likely that the transition, from RSL rise seen at Upernavik salt marsh to RSL fall recorded by GPS monitoring (Bevis *et al.*, 2012), took place during the latter part of the 20th Century and certainly prior to 2007.

4.2 Vertical range of saltmarshes in west Greenland

One challenging aspect of using saltmarshes to reconstruct RSL at Upernavik is the height range of the modern marsh which extends from just above MHWST to c. 0.5 m above HAT **(Fig. 3**). This means that the brackish diatoms seen in the high marsh are surviving in an environment which is exceedingly rarely flooded by saline water. Comparison of our study to others which examine saltmarshes from further south in west Greenland suggests that the elevation of the entire saltmarsh at Upernavik is higher in relation to the tidal frame than in marshes further south, and that there is an increasing proportion of the marsh above HAT moving north in west Greenland (**Fig. 10**) (Long *et al.*, 2012; Long *et al.*, 2010; Woodroffe and Long, 2009, 2010). The most likely reason for the lower limit of the marsh being higher in the tidal frame as we move north is because marshes are more vulnerable to erosion by sea ice which forms within the adjacent tidal ponds on the water surface each winter (**Fig. 2B**). This is likely a major factor in preventing marsh vegetation developing below about the MHWST level, where greater water depth as well as more prolonged inundation greatly increases impacts from ice floes (**Fig. 11A**), and when spring tides combine with the early summer break up of the frozen sea. In addition, further north there is a progressively shorter growing season during which the low marsh can develop and extend down towards MTL. This can usefully be compared using 'degree days'; the number of months of the year above 0^{O}C, multiplied by the mean temperature each month (Fig. 10). This growth rate is in part the cause of the very low sediment accretion rates, which in Upernavik are currently from 18.5 to 140 years per millimetre of accretion, while further south it is often several millimetres per year (Cahoon and Reed, 2011). For data on a range of West Greenland saltmarshes see Appendix 3.

The cause of the extension of more northerly marshes above HAT (Fig. 14B) is not clear. Some authors have attributed marsh extension above HAT to storm and wave splash (Woodroffe and Long 2010). However these processes are less likely to impact the marshes at Upernavik than in other locations farther south, because the shortened summer season reduces the number of storms when the sea surface is free (Lantuit *et al.*, 2012) and the strong mixed tide pattern means that there are only half as many peak spring tides per cycle, which is when surges or abnormally large waves are most able to reach the supra-tidal zone.

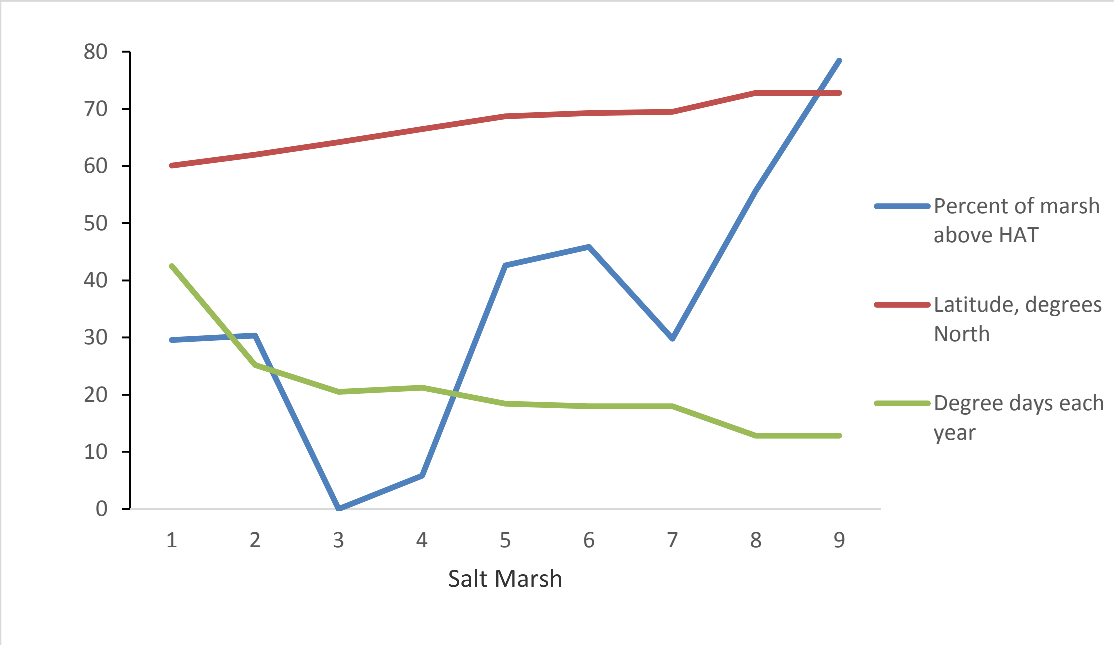


Fig. 13. Data on saltmarshes in West Greenland. The sites are in order from most southerly (60°N) to most northerly (72°N). Site Key: 1 – Nanortalik; 2 – Paamiut ; 3 – Nuuk; 4 – Sisimiut; 5- Aasiaat; 6 – Fortune Bay; 7 – Pakitsoq; 8 – Upernavik marsh 1; 9 – Upernavik marsh 2.

However an alternative hypothesis is that sea water soaks up from the tidal peak level through the marsh sediment, supplying enough moisture to allow halophytic plant growth and higher marsh development. In saltmarshes at Aasiaat and Upernavik marsh one, there is ~0.5m vertical continuation of high marsh above HAT, and there are standing pools in the low marsh platform which re-fill tidally and may provide additional water (Woodroffe and Long, 2010). The marshes at Fortune Bay (Disko Bugt) and Upernavik marsh two have no pools and these marsh reach a lower elevation, ~ 0.4 m above HAT. This lower maximum elevation of marsh 2 at Upernavik is despite this being the marsh facing the outlet to the open sea across the outer sill, potentially receiving more storm waves.

A further factor that may assist this extension of saltmarsh in to the terrestrial zone is the low precipitation in very northern areas, often around 25 mm per month in the summer period (see Appendix 3 for climatic and marsh range data). Much of the precipitation, including some in summer is as blown snow and does not accumulate evenly, and the very thin soil can retain little runoff from the spring melt. Therefore halophytic vegetation that can tolerate salt water is at an advantage, and may result in the marsh/terrestrial interface developing at a greater elevation above HAT, whereas in temperate areas the volume of rainfall percolating through plants and soil often prevents much saline influence above HAT. In contrast, many Greenland saltmarshes, already ending well above this level, have an additional dry zone just above them, with very little vegetation, possibly through this being too saline for most upland plants but too dry for halophytic

Fig. 14. Ice and tidal conditions for saltmarshes at Upernavik. A) Ice floes in the lower intertidal zone in the lower basin, breaking up during spring melt (June 2014), B) The highest tide of the year at Upernavik in June 2014. Note the upper part of the marsh is still exposed although this tide is predicted to be within 2 cm of modelled HAT. The still seawater on the right, abutting the marsh, demonstrates the degree of sheltering of this part of the marsh.

vegetation. Vestergaard (1978) noted that sediment salinity peaked about halfway up the saltmarshes in and near Disko Island. This position is variable in relation to the local tidal range in question but might well be above HAT, but this was not addressed in the paper, and many of these marshes were also subject to greater riverine influence than here. He also noted considerable variability in the elevation boundary between vegetation zones, noting that *Puccinellia* was probably more tolerant than *Carex.* This is in keeping with findings both at Upernavik and elsewhere. Local topographical features may influence freshwater runoff above the marsh and hence the height of the upper boundary and the presence of this dry zone.

5. Conclusions

1. Saltmarshes at Upernavik in northwest Greenland (72°N) provide the first reconstructions of sea-level changes during the past few hundred years in this region.
2. The early Holocene marine limit in this area is at about, or below, current mean sea level.
3. Sea level index points developed from these saltmarshes demonstrate a rise in RSL of c. 0.3 m over 100 years prior to 2014 AD (at a rate of 3 mm/yr), and limiting dates showing a minimum of a further 0.2 m rise in the preceding 235 years. This agrees with rapid late-Holocene RSL rise predicted by a geophysical model of Greenland ice sheet deglaciation.
4. GPS data covering a four year period from 2007-2011 at a location less than 1 km from the field site indicate a current rate of crustal uplift of 7.81 mm/yr. This is likely due to deglaciation at the Upernaviks Isstrom, c. 60 km to the east of the field site.
5. Upernavik Island is likely currently undergoing RSL fall but there is no evidence of this in the saltmarsh record there. This is not surprising as the sedimentation rates on the saltmarsh are very slow (average 0.16mm/yr for the upper 3 cm) and therefore will probably only record current RSL fall during the next century. This data therefore cannot confirm when the current rate of uplift began in the 20^{th} – 21^{st} Century.
6. Comparing the new RSL record from Upernavik to locations in south west and west Greenland, Upernavik is the only studied location where there is persistent RSL rise throughout the last few centuries. The lack of recent RSL stability at Upernavik as compared to other west coast locations is probably due to the timing of Greenland ice sheet retreat in this region and the overwhelming and continuing influence of the collapsing North American Ice sheet Complex (NAIC) forebulge in recent times.
7. The marshes at Upernavik extend from just above MHWST to c. 0.5 m above HAT which is unusual compared to those in temperate locations. This may be due to ice damage to the lower edge and low precipitation favouring halophytic vegetation over freshwater above HAT.
8. The distinctive nature of the very northerly saltmarshes at Upernavik with very shallow sediment, slow accretion related to adverse conditions, and a majority of the present-day marsh above HAT means that reconstructing RSL here is challenging. However reconstructing recent RSL in locations such as Upernavik is key for understanding the longer term behaviour of large ice streams such as the Upernaviks Isstrom which drains a significant proportion of the GIS and is currently in rapid retreat.

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6. Overview of this study and its results

This is the first reconstruction performed of relative sea level changes at this latitude and the furthest north that saltmarshes have been used for this purpose. Despite the thin sediment and unusual nature of these marshes this work has demonstrated rapid, ongoing sea level rise of several mm/yr over the past few centuries, in keeping with current understanding of rapid deglaciation from the continental shelf following the Younger Dryas cold phase to a position close to today's, with the early Holocene marine limit very close to current MTL, initial lowering of RSL below present but rapid elevation of sea level again from that point. This confirms the Huy3 modelling predictions for this region of West Greenland, although the rapid land uplift at Upernavik in the past decade or more shown by GPS data cannot yet be confirmed from saltmarsh evidence.

6.1 Other aspects of work on high latitude saltmarshes

A number of factors make work on the Upernavik saltmarshes difficult, including the shortness and unpredictability of the field season during which marshes are free from ice, and the frequent presence within the thin sediment of stones and of very variable layers of sand. Ideally samples would be taken from sediment directly overlying bedrock to reduce the risk of it having been disturbed by freeze-thaw processes, but all areas of saltmarsh found at Upernavik were deposited over glacial till. No frost-heaving of stones was seen as is clearly evident in marshes further south, possibly the result of thinner sediment and reduced precipitation reducing vulnerability to this. Autocompaction of sediment through ongoing degradation of the organic material within them can reduce apparent deposition elevations in reconstruction studies in temperate marshes, but is negligible in marshes with very shallow deposits (Brain *et al.*, 2012) and has not been considered here.

Ice-rafting of debris, both allochthonous (seaweed, mineral material of a wide range of sizes) and layers of marsh platform with or without vegetation as discussed by Argow *et al.* (2011) on the Atlantic coast of the US in winter, also takes place on Greenland marshes, particularly on larger and deeper marshes than at Upernavik. However, there was no evidence of distortion of the marsh platform by rafted material in the area investigated, and very little seaweed or other material on the ice overlying the marsh surface, and with the majority of the marsh being above HAT only the lowest area was in fact vulnerable to this.

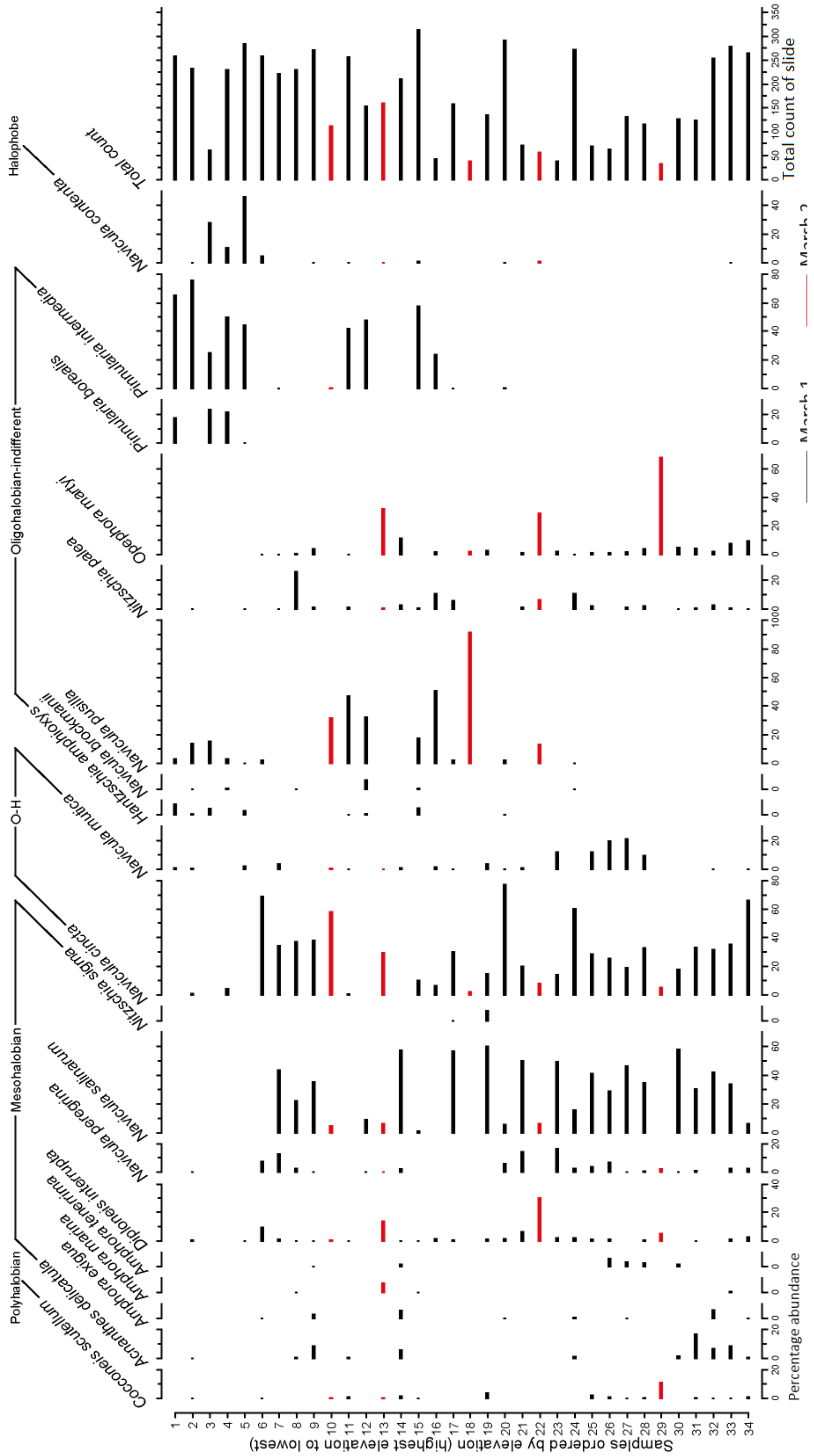
6.2 Areas for future work

This work confirms that these northern saltmarshes remain usable as unique archives RSL change over recent centuries even in the high Arctic where climatic conditions markedly compromise marsh development. These RSL data are important for constraining geophysical modelling of GIA and GIS and two types of further work would be particularly useful. The majority of the coastline of Greenland, with the exception of the sector from Disko Bugt to Cape Farewell, has not had detailed reconstructions undertaken. Saltmarsh vegetation has been recorded north of Upernavik as far north as Qaanaaq (77.468^{O} N) and while less frequent and with thinner sediment it is probable that useful data could be obtained from very northern areas of marsh, to give improved detail of RSL changes in the recent period, over the sea level limiting data that is available (summarised in Lecavalier *et al.*, 2014). This is particularly important close to areas undergoing rapid uplift or ice-stream retreat, including much of the north west sector of Greenland, as well as the south east (Khan *et al.,* 2015). Additionally, in regions where the GIS post-glacial retreat continued some distance from the outer coast and there is an extensive archipelago, as in the Upernavik area, or land area with lengthy fjords between the ice sheet and the open coastline, performing studies at inner and outer sides of this exposed land strip would improve understanding both of sectoral growth and shrinkage of the GIS, and of overall GIS evolution. RSL reconstruction carried out on these marginal salt marshes, where they are present in non-Greenland island groups elsewhere in the Arctic, could also help detailed reconstruction of smaller and former ice sheets elsewhere, refine the global sea level budget and improve models of Earth structure and responses to changes in ice and sediment load.

In addition, improved understanding of the morphogenesis of high Arctic saltmarshes is needed. Two areas stand out within this as important for improved understanding. The increasing elevation of these marshes with respect to the tidal frame, moving further north, may relate to the factors suggested here but has not been investigated extensively. However, given the key importance of elevation for RSL reconstruction, this warrants clarification if possible. Investigating sediment salinity across the range of these marshes, and into terrestrial zones, could help with this. Additionally, mass movement of material, whether ice-rafting or related to underlying freeze-thaw, influences sediment, organic content and diatom assemblages present, frequently moving material to different elevations from where it was originally deposited. This can lead to errors in reconstruction but a greater understanding of when these processes occur and how to avoid sampling these areas or compensate for movement would be valuable.

Appendix 1 – Diatom valve counts; modern and fossil assemblages

a) Modern diatom distributions; as figure 5 but spaced equally



Results of counts

b) Modern diatom assemblage counts. Species in bold are included in fig.5 – Modern diatom distributions

Elevation (m MSL)	**1.74**	**1.70**	**1.68**	**1.65**	**1.57**	**1.55**	**1.50**	**1.44**	**1.40**	**1.38**	**1.37**
Total slide count	**260**	**234**	**63**	**232**	**286**	**260**	**223**	**232**	**272**	**114**	**258**
Acnanthes delicatula		1						2	24		3
Amphora coffeiformis											
Amphora delicatissima											
Amphora exigua						1			9		
Amphora graeffiana											
Amphora holsatica											
Amphora marina								1			
Amphora tenerrima									2		
Caloneis alpestris	7					4					
Cocconeis scutellum		1				1				1	4
Cymbella citrus											
Cymbella norwegica								1			
Diploneis interrupta		2			1	27	4	1	2	1	2
Diploneis stroemii								1			
Eunotia praerupta	1										
Hantzschia amphioxys	21	3	3		9						1
Navicula brockmanii		1		3				1			
Navicula cincta		4		11		181	78	87	105	67	3
Navicula cocconeiformis											
Navicula contenta		1	18	26	133	14			1		1
Navicula mutica	4	2			8		9			1	2
Navicula peregrina		1				21	30	7	2		
Navicula pusilla	10	34	10	8	2	7				37	123
Navicula radiosa						1		10			
Navicula salinarum							99	53	98	6	
Navicula tripunctata											
Nitzschia debilis		2		1							
Nitzschia palaea		1			2		1	61	4		4
Nitzschia sigma											
Opephora martyi				1		1	1	2	11		1
Paralia sulcata						1					
Pinnularia appendiculata											
Pinnularia borealis	46		15	51	2						
Pinnularia intermedia	171	178	16	117	129		1			1	109
Pinnularia major			1	6							
Pinnularia subcapitata		3		8							
Pinnularia subcapitata											
Plagiogramma staurophorum											
Plagiotropus lepidoptera									2		
Rhabdonema minutum						1					3
Rhopalodia musculus								5	9		
Synedra acus									2		2
Tabellaria flocculosa									1		

Modern diatom assemblage counts (cont.)

Elevation (m MSL)	**1.35**	**1.28**	**1.27**	**1.26**	**1.24**	**1.19**	**1.18**	**1.14**	**1.13**	**1.07**	**1.03**
Total slide count	**155**	**161**	**313**	**316**	**45**	**160**	**39**	**136**	**294**	**73**	**58**
Acnanthes delicatula			13								
Amphora coffeiformis											
Amphora delicatissima											
Amphora exigua			12						1		
Amphora graeffiana		5									
Amphora holsatica		2									
Amphora marina		11		1							
Amphora tenerrima			4								
Caloneis alpestris									1		
Cocconeis scutellum		2	4	1				6			
Cymbella citrus											
Cymbella norwegica									1		
Diploneis interrupta		23	1	1	1	2		2	7	5	18
Diploneis stroemii											
Eunotia praerupta											
Hantzschia amphioxys	2			16					2		
Navicula brockmanii	11			3							
Navicula cincta		49	103	34	3	49	1	21	229	15	5
Navicula cocconeiformis											
Navicula contenta		1		5					2		1
Navicula mutica		1	3		1	1		6	1	1	
Navicula peregrina	1	1	6						19	11	
Navicula pusilla	51			57	23	4	36		7		8
Navicula radiosa			1								
Navicula salinarum	15	11	123	5		92	0	82	19	37	4
Navicula tripunctata											
Nitzschia debilis				3							
Nitzschia palaea		2	7	3	5	10				1	4
Nitzschia sigma						1		10			
Opephora martyi		52	25		1		1	4		1	17
Paralia sulcata			4						1		
Pinnularia appendiculata											
Pinnularia borealis											
Pinnularia intermedia	75			184	11	1			3		
Pinnularia major											
Pinnularia subcapitata				3							
Pinnularia subcapitata											
Plagiogramma staurophorum		1					1	5			
Plagiotropus lepidoptera											
Rhabdonema minutum									1	2	
Rhopalodia musculus			4								
Synedra acus			2								1
Tabellaria flocculosa			1								

Modern diatom assemblage counts (cont.)

Elevation (m MSL)	**1.02**	**1.00**	**0.97**	**0.91**	**0.90**	**0.88**	**0.86**	**0.85**	**0.83**	**0.80**	**0.69**	**0.51**
Total slide count	**40**	**274**	**72**	**65**	**134**	**117**	**35**	**128**	**126**	**255**	**280**	**267**
Acnanthes delicatula		5						3	22	19	25	3
Amphora coffeiformis					1			4	1			
Amphora delicatissima									1			
Amphora exigua		3			1					16		2
Amphora graeffiana				1								
Amphora holsatica										2	2	
Amphora marina											3	
Amphora tenerrima				4	5	4		3				
Caloneis alpestris										1		
Cocconeis scutellum			2	1	1	1	4		1	2	1	4
Cymbella citrus						2		1	2			
Cymbella norwegica										2		
Diploneis interrupta	1	7	1	1		1	2		1		5	9
Diploneis stroemii												2
Eunotia praerupta											1	
Hantzschia amphioxys												
Navicula brockmanii		2										
Navicula cincta	6	167	21	17	26	39	2	24	43	82	101	178
Navicula cocconeiformis								2				
Navicula contenta											1	
Navicula mutica	5		9	13	29	12				1		1
Navicula peregrina	7	9	3	5	1	1	1	1	2		9	9
Navicula pusilla		1										
Navicula radiosa												2
Navicula salinarum	20	44	30	19	63	41		75	39	109	96	18
Navicula tripunctata				1		3						
Nitzschia debilis												
Nitzschia palaea		31	2		2	3		1	1	8	3	2
Nitzschia sigma												
Opephora martyi	1	2	1	1	3	5	24	7	6	7	22	27
Paralia sulcata											2	
Pinnularia appendiculata								2				
Pinnularia borealis												
Pinnularia intermedia												
Pinnularia major							1					
Pinnularia subcapitata												
Pinnularia subcapitata									1			
Plagiogramma staurophorum		1									3	7
Plagiotropus lepidoptera												
Rhabdonema minutum		1	2		1	2		5	3	4	4	1
Rhopalodia musculus		1	1	2	1	3	1		3	2	2	2
Synedra acus												
Tabellaria flocculosa												

c) Fossil diatom counts; each section extends 1cm down from the stated depth.

Block	1					2					3			
Depth of section in block	0	1	2	4	7	0	1	2	3	5	0	1	2	6
Total diatom count	260	104	258	54	104	234	252	299	101	99	232	207	222	112
Species														
Acnanthes brevipes														
Acnanthes delicatula						1								
Amphora exigua														
Amphora graeffiana							1							
Amphora holsatica														
Amphora marina														
Amphora tenerrima														
Caloneis alpestris	7													
Caloneis bacillum		2		2	5				21	13			73	5
Cocconeis scutellum						1								1
Cymbella norvegica														
Cymbella subaequalis														
Diploneis interrupta						2	2	1		1				
Diploneis stroemii														
Eunotia arcus			1											
Eunotia glacialis					1				1					
Eunotia serra														
Eunotia praerupta		2	8	2	4			3	5	8		1	4	3
Eunotia tenella		1	16	15	5			4	5	3			4	
Fragilaria brevistriata	1													
Gomphonema angustum														
Hantzschia amphioxys	21	3			1	3		5					4	
Hyalodiscus scoticus							1							
Melosira nummaloides														
Navicula brockmanii						1					3			
Navicula cincta		75	8			4		1		2	11	7	3	13
Navicula contenta		2	109	26	44	1	6	35	36	36	26	9	75	11
Navicula mutica	4				3	2						1		
Navicula peregrina					1	1		0				1		
Navicula pusilla	10					34	114	15	1		8	5		9
Navicula radiosa														
Navicula salinarum						0		0						
Neidium calvum								7						
Nitzschia debilis						2					1	2		2
Nitzschia palea						1	2					6		12
Opephora martyi							1							
Opephora pacifica											1			
Paralia sulcata														
Pinnularia borealis	46	6	2	4	15		2	82	25	34	51	45	49	21
Pinnularia divergentissima								1						
Pinnularia intermedia	171	13	100	5	25	178	118	142	7	1	117	121	10	31
Pinnularia lata								2						
Pinnularia major							1							
Pinnularia schoederi			13								6	4		
Pinnularia subcapitata						3		1			8	4		
Plagiogramma staurophorum							1							
Plagiotropus lepidoptera														
Rhabdonema minutum							2							4
Rhopalodia musculus														
Stauroneis producta														
Synedra acus												1		
Tabellaria flocculosa										1				
Trachyneis aspera							1							

Fossil diatom counts (cont.)

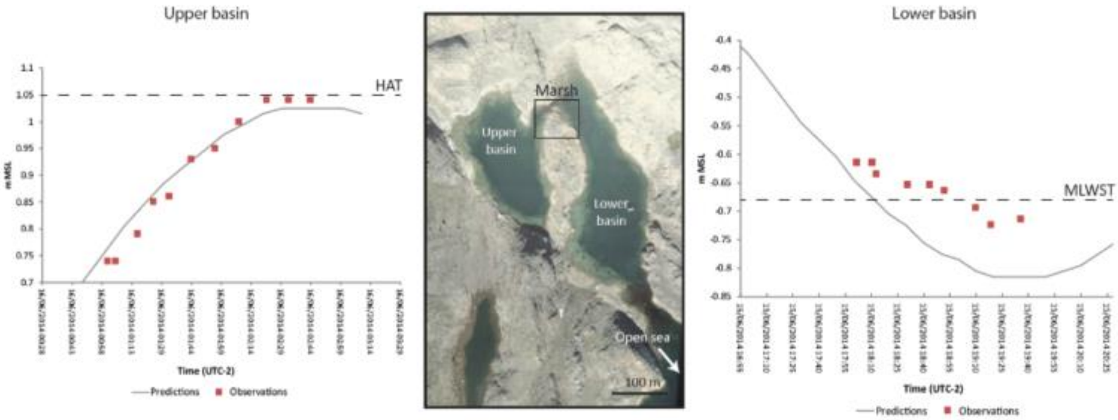
Block	4						5				
Depth of slide in block	**0**	**1**	**2**	**3**	**6**	**8**	**0**	**1**	**2**	**4**	**6**
Total diatom count	**260**	**259**	**212**	**274**	**139**	**88**	**232**	**220**	**231**	**237**	**226**
Species											
Acnanthes brevipes								2		1	
Acnanthes delicatula							2	5	3	1	
Amphora exigua	**1**										25
Amphora graeffiana											
Amphora holsatica											
Amphora marina							1				
Amphora tenerrima											
Caloneis alpestris	**4**										
Caloneis bacillum				**80**	**7**	**7**			1	87	13
Cocconeis scutellum	**1**	**6**							1		
Cymbella norvegica							1				
Cymbella subaequalis											2
Diploneis interrupta	**27**	**40**	**13**		**1**	**1**	1	12	3	1	
Diploneis stroemii											
Eunotia arcus				**1**			1			6	68
Eunotia glacialis						**1**					
Eunotia serra											
Eunotia praerupta										2	
Eunotia tenella				**6**	**9**	**22**				4	
Fragilaria brevistriata											
Gomphonema angustum											
Hantzschia amphioxys		**1**	**1**						2		
Hyalodiscus scoticus		**13**						2			
Melosira nummaloides											
Navicula brockmanii							1				
Navicula cincta	**181**	**132**	**52**	**1**	**4**	**1**	87	109	39	8	2
Navicula contenta	**14**	**1**	**2**	**117**	**48**	**40**		1	9	59	106
Navicula mutica				**1**							
Navicula peregrina	**21**	**14**	**17**		**4**		7	42	62	7	
Navicula pusilla	**7**	**29**	**21**	**2**	**1**			2	13	5	
Navicula radiosa	**1**		**4**				10				
Navicula salinarum			**10**				53	16	27	6	
Neidium calvum											7
Nitzschia debilis											
Nitzschia palea			**6**	**1**			61	4	15		
Opephora martyi	**1**						2	8			
Opephora pacifica											
Paralia sulcata	**1**	**6**	**7**								
Pinnularia borealis			**26**	**46**	**61**	**14**			8	26	3
Pinnularia divergentissima										18	
Pinnularia intermedia		**8**	**47**	**18**	**3**	**1**		4	47	6	
Pinnularia lata											
Pinnularia major						**1**					
Pinnularia schoederi											
Pinnularia subcapitata			**3**	**1**	**1**						
Plagiogramma staurophorum		**3**									
Plagiotropus lepidoptera											
Rhabdonema minutum	**1**	**5**	**3**					13			
Rhopalodia musculus							5		1		
Stauroneis producta											
Synedra acus		**1**									
Tabellaria flocculosa											
Trachyneis aspera											

Fossil diatom counts (cont.)

Block	6					7 (8)								
Depth of slide in block	0	1	2	3	4	0	1	2	3	4	5	6	7	9
Total diatom count	272	227	259	286	210	314	232	276	236	260	286	243	213	251
Species														
Acnanthes brevipes							1	1						
Acnanthes delicatula	24	16	2	1		13	12	13	2		1	3	3	12
Amphora exigua	9	23	4		1	12	4	1	4	1	1			
Amphora graeffiana		3												
Amphora holsatica									2					
Amphora marina								1						
Amphora tenerrima	2	7				4		1						
Caloneis alpestris							2			4	1			
Caloneis bacillum					30									
Cocconeis scutellum						4	6	11	4	2				
Cymbella norvegica														
Cymbella subaequalis			1	1										
Diploneis interrupta	2	2	4	1	1	1	1	2	6	8	10	6	3	7
Diploneis stroemii		1												
Eunotia arcus				12						2			1	5
Eunotia glacialis					10									
Eunotia serra					8									
Eunotia praerupta		3	1	29	4					1		1		3
Eunotia tenella					36						1			4
Fragilaria brevistriata														
Gomphonema angustum														
Hantzschia amphioxys								1					1	
Hyalodiscus scoticus										1	2			1
Melosira nummaloides														
Navicula brockmanii												3		
Navicula cincta	105	48	24	27	5	103	79	143	141	110	76	65	64	71
Navicula contenta	1		2	22	95				1	12	1	2	7	54
Navicula mutica						3						1		1
Navicula peregrina	2	13	16	7		6	15	24	34	102	144	43	27	45
Navicula pusilla										1				
Navicula radiosa		11	33	7	2	1		1	10	13	30	9	1	3
Navicula salinarum	98	68	46	21	3	123	98	54	9		14	22	6	11
Neidium calvum				8										
Nitzschia debilis														
Nitzschia palea	4	2	2	1		7	4	3	1					
Opephora martyi	11	17				25	4	18	16		1	4		4
Opephora pacifica														1
Paralia sulcata			1			4	1		3					
Pinnularia borealis		1	3	72	1							3		2
Pinnularia divergentissima			1	4	1							1	1	
Pinnularia intermedia		3	46	43	7					2	3	69	47	7
Pinnularia lata				3			2					2		
Pinnularia major		2	42	27	5						1	6	51	20
Pinnularia schoederi														
Pinnularia subcapitata					1									
Plagiogramma staurophorum														
Plagiotropus lepidoptera	2													
Rhabdonema minutum							1		1			1		
Rhopalodia musculus	9	4	1			4	2	2		1		1		
Stauroneis producta		1	28						1					
Synedra acus	2	2				2			1			1	1	
Tabellaria flocculosa	1					1								
Trachyneis aspera			2			1								

`Appendix 2

Levelling data of tidal positions



Observation of high and low tide in the upper and lower basins at Upernavik on 16/06/2014, compared to tidal predictions for the open coast. The observations of high tide closely match the predictions, those of low tide less so. The only accessible area of the low basin was very close to the outflow from the upper basin so it may have been vulnerable to the effects of ongoing sea water discharge from above over the upper sill, also influenced by ice floes obstructing drainage on both sides, but also by delayed drainage because of the lower sill.

Appendix 3

Climatic and marsh range data on saltmarshes in West Greenland.

Arranged by latitude (data from S. Woodroffe and T. Dowson)

Site Key: 1 – Nanortalik; 2 – Paamiut ; 3 – Nuuk; 4 – Sisimiut; 5- Aasiaat; 6 – Fortune Bay; 7 – Pakitsoq; 8 – Upernavik marsh one; 9 – Upernavik marsh two (for specific marsh dimension data differences)

Tidal and climate data	1	2	3	4	5	6	7	8/9
Latitude (^{O} N)	60.1	62	64.2	66.5	68.7	69.3	69.5	72.8
Tidal range m	3.02	3.56	5.04	4.66	2.86	2.6	3.1	2.1
HAT (m MTL)	1.51	1.78	2.52	2.33	1.43	1.3	1.55	1.05
Top edge of marsh (m MTL)	1.8	2.12	2.52	2.5	1.92	1.69	1.86	1.54/1.45
Height of marsh above HAT (m)	0.29	0.34	0	0.13	0.49	0.39	0.31	0.49/0.4
Marsh above HAT -%	29.6	30.4	0.0	5.8	42.6	45.9	29.8	55.7/78.4
Annual mean temp. ^{O}C	0.6	-0.9	-1.4	-3.9	-4.9	-4.9	-4.4	-6.2
Mean summer temp. ^{O}C	6.5	4.2	4.1	5.3	4.6	4.5	4.5	3.2
Rainfall (mm a^{-1} year)	810	878	752	383	302	277	257	265
monthly rain in months over 0^{O}C	72	23	64	44	29	28	26	27
months above 0^{O}C	7	6	5	4	4	4	5	4
Degree days ie months above 0^{O}C x average temperature in those months	42.5	25.2	20.5	21.2	18.4	18	18	12.8

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