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Holocene Relative Sea-Level Changes Indicated by Morphostratigraphic Sequences; Sinigfik, Disko Island, West Greenland.

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A morphostratigraphic method is introduced in a study of Holocene relative sea-level changes at Sinigfik on the south coast of Disko Island, West Greenland. The method allows detection of relative sea-level rise interrupting the general Holocene emergence. It is concluded that the Holocene relative sea-level history at Sinigfik was one of steady emergence prior to c. 3 ka B.P. A complex morphostratigraphic sequence near the present coastline might result from two emergence/submergence events within the last millenium. The geomorphology of the present coastline indicates extensive coastal recession, probably resulting from a relative sea- level rise at present.

Keywords: *Beach ridge plain, emergence curve, Holocene, morpho-stratigraphy, relative sea-level changes, Disko Island, West Greenland.*

During the last thirty years a number of emergence curves representing Holocene relative sea-level changes from local areas in Greenland have been published (North Greenland: Fredskild 1969, Weidick 1972, Bennike 1987, Funder og Abrahamsen 1988. East Greenland: Washburn & Stuvier 1962, Lasca 1969, Weidick 1972, Street 1977, Funder 1978. West Greenland: Weidick 1972, 1976 Kelly 1973, 1979, 1985, Donner & Jungner 1975, Ten Brink 1974, 1975, Funder 1979, Fredskild & Møller 1981, Frich & Ingolfsson 1990, Ingolfsson et al. 1990). Several problems are related to the construction of emergence curves (Weidick 1972, Kelly 1973, Ten Brink 1974, Donner og Jungner 1975), and as a result probably all published curves from Greenland only show a rough trend of Holocene relative sea-level changes (Funder 1989).

The goal of this paper is to describe Holocene relative sea-level changes at an arctic coast in mid West Greenland; especially focusing on the development during the last 3 ka. To avoid the uncertainties of traditional emergence curve construction, a new morphostratigraphy

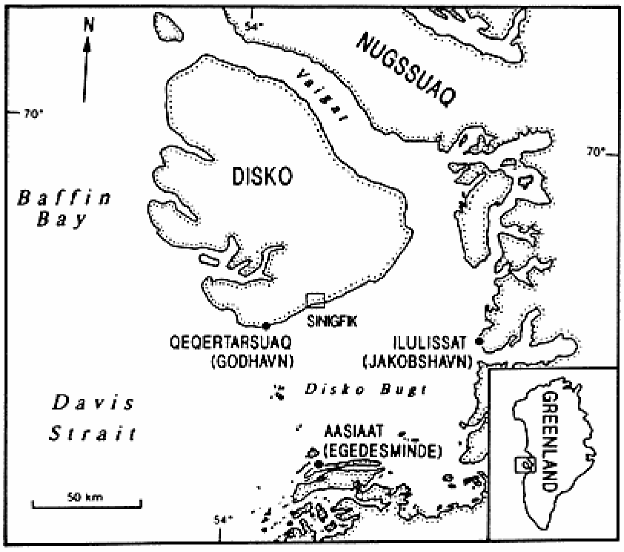

Figure 1. The study area and the nearest towns. Old Danish names in brackets.

based on high precision surveying of the coastal morphology is introduced. The word morphostratigraphy exclusively indicates that landform units are the basis of the stratigraphy.

The Study Area

The coastal landscape studied is located on the south coast of Disko Island, West Greenland, about 25 km east of the town Qeqertarsuaq, Godhavn (Fig. 1). The locality covers an area of c. 10 km^2 and consists of a terrain below an altitude of 150 m along a 7 km stretch of coast. In the eastern part of the area a large valley reaches the coast. This location is called Sinigfik (69°21'N 53°04'W).

On South Disko the climate is polar maritime with a mean annual temperature of about -4°C; the pre-Quaternary geology mainly consists of Tertiary basalts, and the landscape is one of Tertiary plateaus, heavily dissected by cirques and valleys during the Quaternary. The present glaciation of Disko covers c. 20 % of the island; mainly as icecaps on top of the plateaus.

Along the south coast of Disko, the land generally rises steeply from the shoreline to the Tertiary plateaus c. 800 m.a.s.l. Lowland with coastal deposition only appears at the mouth of N-S trending U-shaped valleys.

The coastal part of South Disko was deglaciated at 10 ka B.P. when the Greenland ice shield melted back to a position east of Disko (Ingòlfsson et al. 1990). During the deglaciation, the relative sea-level rose to the marine limit: c. 90 m above the present sea-level (c. 9 ka B.P.). Subsequently, isostatic rise began and the relative sea-level started to fall. According to existing emergence curves, the relative sea-level in Disko Bugt has been falling with a decreasing rate from c. 9 ka B.P. to c. 3 ka B.P (Donner & Jungner 1975, Frich & Ingòlfsson 1990, Ingòlfsson et al. 1990). At c. 3 ka B.P. the relative sea-level approached the present sea-level and from then on very little is known about the relative sea-level changes in Disko Bugt. In fact, besides early tidal observations at Qeqertarsuaq (1897 – 1946 AD), partly submerged eskimo ruins at the mainland coast of Disko Bugt are the only local evidences of relative sea-level changes from this period (Mathiassen 1934, Mathiassen in Gabel-Jørgensen & Egedal 1940, Saxov 1958). In a climatic sense, the last c. 3 ka were a period of glacial readvance; denoted the Neoglacial (Kelly 1980) or Vesterbygd glacial (Funder 1989).

The landscape at Sinigfik is composed of marine terraces, fluvial terraces and a single major landslide (Fig. 2). Marine terraces occur discontinuously in a vertical zone from the present shoreline to the Holocene marine limit. In general, the marine terraces consist of parallel coarse clastic beach ridges with typical heights above the surrounding terrain ranging from 1 to 3.5 m. Marine terraces without beach ridges occur only in a smaller area adjacent to the elongated lake in the central part of the study area. This marine terrace has been classified as a fossil lagoon bottom (Rasch 1991).

Both recent and fossil beach ridges at Sinigfik consist of a well-sorted sediment of rounded to well-rounded basaltic pebbles and cobbles. At the surface, fine-grained sediments appear only in fluvial terraces and in scattered dune fields. Underneath the surface, fine-grained sediments also appear in a Gilbert-type delta being the basement of a marine terrace in the central part of the study area (Fig. 4).

At Sinigfik, the present coast is a reflective, coarse-clastic beach with a semi-diurnal, mixed tide and a spring tidal range of 2.9 m (Farvandsvæsenet 1993 (Sea Water Authority 1993)). The wave climate is characterised by westerly and southwesterly wind waves and swell caused by cyclonic depressions in the Davis Strait and by more frequent but minor wind waves from the east, caused by catabatic winds blowing off the ice-shield of Greenland. Longest fetch is towards the SE. The sea off Sinigfik is usually frozen from the middle of December to the end of May. Except from a few short events with break-up of the ice, no wave action occurs in this period, and the shoreface is solely subjected to ice-foot processes and ice-pushes (Nielsen 1979, 1982).

The recent coastline configuration around river outlets and beach pillars indicates a net littoral drift directed towards the east. The structure of fossil marine terraces

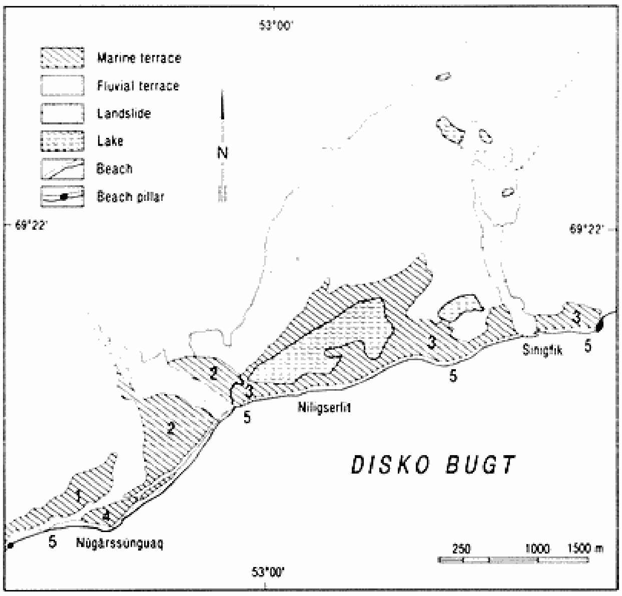

Figure 2. The study area at Sinigfik. A: Aerial photograph 268L/93 (Copyright: The National Survey and Cadastre, Denmark). The two black lines mark the position of the profiles shown in figures 6 (A – B) and 7 (C – D). B: Simplified geomorphologic map. The five regions of well-defined geomorphologic units are marked by their respective numbers.

and the morphology of fossil beach ridges suggest that this drift direction has occurred throughout the Holocene (Fig. 5).

Morphostratigraphic Nomenclature

A morphostratigraphic unit is defined as a stratigraphic unit identified primarily from the surface form it displays. Five different morphostratigraphic unit types have been identified at Sinigfik. The characteristics of each of these are summarised in Table 1.

The relative time sequence of beach ridge plains is very simple. The beach ridge farthest from the sea will always be the oldest, and the age of beach ridges will always decrease towards the recent shoreline. Most often succeeding beach ridges are parallel with almost identical morphology and sedimentology giving an impression of cyclicity (Fig. 2). Such a morphostratigraphic unit is herein called a regressive beach ridge plain.

The beach ridges within regressive beach ridge plains are normally narrow and sharp-crested with internal beds dipping towards the sea (Carter & Orford 1984, Tanner 1988). This kind of beach ridges originates from the swash, and they have been termed simple beach ridges (Tanner 1988).

Sometimes the impression of cyclicity is disturbed by: 1. Younger beach ridges truncating older ridges. 2. Younger beach ridges rolling over older ones, keeping parallelism, but disturbing the similarity of sedimentology and morphology. 3.

Coastal cliffs cutting off the regressive beach ridge plains. In all of these cases erosion has removed part of the morphological sequence and in accordance with common stratigraphic terminology, the line of erosion is denoted a morphologic unconformity. Morphologic unconformities will normally appear very distinctively in coastal landscapes. Even the smallest coastal cliff is easy to pinpoint in the field. It might seem more difficult to distinguish morphologic unconformities resulting from one beach ridge rolling over another. However, landward moving beach ridges will differ from simple beach ridges by being higher and wider and by having a rounded crest and gently sloping internal beds following the over-all curvature of the beach ridge surface (Carter & Orford 1984, Tanner 1988). Following the terminology of Tanner (1988), landward moving beach ridges are termed washover ridges.

In coastal landscapes morphologic unconformities will arise when coastal progradation is followed by coastal recession as a consequence of either a water-level rise or a change in littoral sediment transport. A morphologic unconformity arising from a water-level rise will be expected to have a large geographical distribution and to be found in areas with different exposure and sediment sources. On the other hand, a morphologic unconformity arising from changes in littoral sediment transport will be expected to

Morphostratigraphic unit type	Characteristics	Indication of	Code
Simple beach ridges	Narrow sharp-crested beach ridges with internal beds generally dipping 5° - 10° towards the sea. The simple beach ridge is the basic unit of regressive beach ridge plains (RBRP).		SBR
Washover ridges	Beach ridges with rounded crests and with internal beds following the surface of the ridge. Washover ridges are normally higher and wider than simple beach ridges. Typical internal bed slopes are less than 5°.	Coastal recession	WR
Regressive beach ridge plains	Gently sloping marine terraces with several more or less parallel simple beach ridges on the top.	Coastal progradation	RBRP
Coastal cliffs	Coastal cliffs are normally more or less straight, coast parallel cliffs. Coastal deposits will always occur at the foot of a coastal cliff.	Coastal recession	CC
Morphologic unconformity	Limit between morphostratigraphic units of very different age.	Coastal recession	MU

Table 1. Characteristics of the five morphostratigraphic unit types identified in the coastal landscape at Sinigfik.

have either a local distribution or to occur only on beaches with specific exposure. As a consequence, if synchronous morphologic unconformities are observed on localities with different exposure and sediment sources, it is likely that the unconformities result from a relative sea-level rise.

Methods

The coastal landscape at Sinigfik has been divided into five regions (Fig. 2). The division is based on a detailed geomorphologic mapping of the research area (Rasch 1991). In each region terrain profiles with demarcation of morphostratigraphic units have been drawn. Examples are given in Figure 6 and Figure 7. Finally, the morphostratigraphic units of each region have been projected into a vertical log (Fig. 8).

To ensure high precision of measured altitudes and to allow exact comparison of altitudes between different subregions, profiles and point altitudes have been surveyed with theodolite, and with local datum based on tidal observations from a period of 14 days. The absolute error on altitude measurements is considered to be approximately ± 0.5 m, while the relative error is considered to be less than ± 0.2 m.

Unfortunately, no marine fossils have been found at Sinigfik. As a result, no absolute datings of relative sea-levels exist. In Figure 8, the inverse function for a local emergence curve made by Frich & Ingòlfsson (1990) has been used for the construction of an approximate time-axis.

Morphostratigraphy

Region 1

In the western part of the study area, a marine terrace appears between 37.2 and 89.7 m.a.s.l. (Fig. 2). The top of the terrace is the Holocene marine limit of the study area (Fig. 3). From the marine limit, the terrace slopes gently (< 5°) towards SSW. To the north, the terrace is bordered by a fossil coastal cliff with several fossil beach pillars at the foot. To the south and to the west, the terrace is truncated seaward by a coastal cliff. On the upper part of the terrace, three beach ridges appear. In general, these beach ridges are the highest and most coarse-grained simple beach ridges within the study area. On the lower part of the terrace, beach ridges are absent. In a morphostratigraphical sense the terrace has been classified as a regressive beach ridge plain bordered by coastal cliffs.

Region 2

Region 2 consists of two gently sloping (< 5°) marine terraces separated by an incised river plain (Fig. 2). The terraces were probably coherent at the time of origin. Several parallel and almost identical simple beach ridges

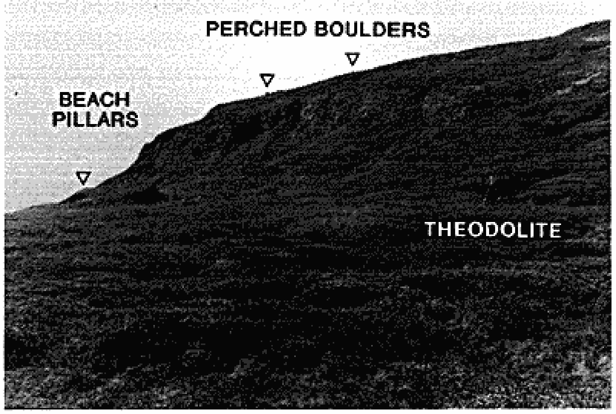

Figure 3. The marine limit of the study area c. 90 m.a.s.l. The two knolls at the foot of the cliff are solid rock and has been interpreted as fossil beach pillars (Rasch 1990). Above the cliff, perched boulders are seen on the bare rock.

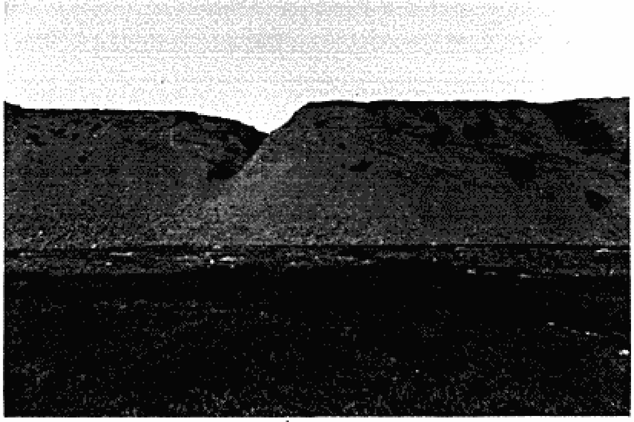

Figure 4. Foreset beds exposed in a fluvial cliff in Region 2. The grain sizes of the foreset sediments vary from a few millimetres to c. 30 cm. The cliff is c. 15 metres high.

occur on top of the terraces. On the upper part of the terraces, the transition towards the landscape behind is marked by a small change of the terrain slope 46.4 m.a.s.l. There are no signs of erosion at this transition. Towards the sea, the terraces terminate at the top of a coastal cliff 7.7 m.a.s.l.

The internal structure of the marine terraces is exposed in a fluvial cliff bordering the incised river plain in the central part of the region (Fig. 4). The exposure uncovers delta-like foresets being overlain by beach ridge sediments (reorganized topsets). The sequence probably represents a wave-dominated Gilbert-type delta (Colella 1987, Massari & Parea 1990).

Region 2 has been logged as a regressive beach ridge plain extending from 46.4 to 7.7 m.a.s.l., terminating at a coastal cliff.

Region 3

Region 3 includes the coastal landscape surrounding an elongated lake in the central part of the study area (Fig. 2). Towards the north and the east, the region is bordered by an extensive landslide. The Holocene marine limit of the region is marked by coastal cliffs in the landslide 40.8 m.a.s.l.

The elongated lake is interpreted as a lagoon. The patterns of beach ridges on top of the isthmus south of the lake and the presence of a fossil tidal inlet at the southern coast of the lake indicate that the lake once was open to the sea (Fig. 5). The lowest level of Region 3 appears at 7.8 m.a.s.l. corresponding to the bottom-level of the fossil tidal inlet.

Several marine terraces occur within Region 3. However, in a morphostratigraphical sense, the marine terrace constituting the isthmus is representative of the region. Region 3 has been logged as a regressive beach ridge plain surrounded by coastal cliffs at 7.8 and 40.8 m.a.s.l.

Region 4

In the south-western part of the research area, a cuspate foreland occurs (Fig. 2). The foreland is built up by two marine terraces separated by a washover ridge (Fig. 6). The lower terrace contains 11 simple beach ridges and slopes gently ((5°) towards the SSW from 12.4 m.a.s.l. to the present shoreline. The upper terrace contains 3 simple beach ridges and slopes gently towards the SSE from 19.5 to 16.0 m.a.s.l. Behind the upper terrace a fossil coastal cliff occurs. Both marine terraces have been logged as regressive beach ridge plains.

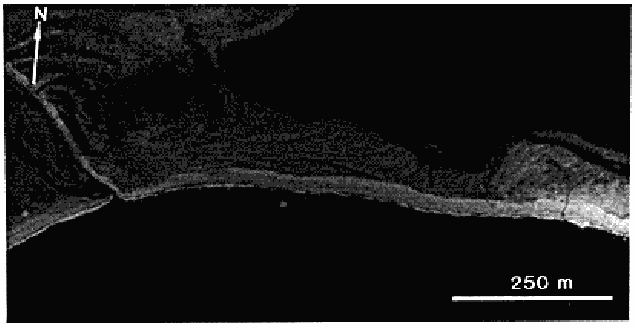

Figure 5. Aerial photograph of the fossil tidal inlet on the isthmus in the southern part of region 3. The bottom of the inlet is c. 8 m.a.s.l. Notice the fossil flood tidal delta north of the tidal inlet. The patterns of beach ridges on the fossil spit west of the tidal inlet indicate littoral drift towards the east at the time of origin (Aerial photograph: 268L/93, Copyright: The National Survey and Cadastre, Denmark).

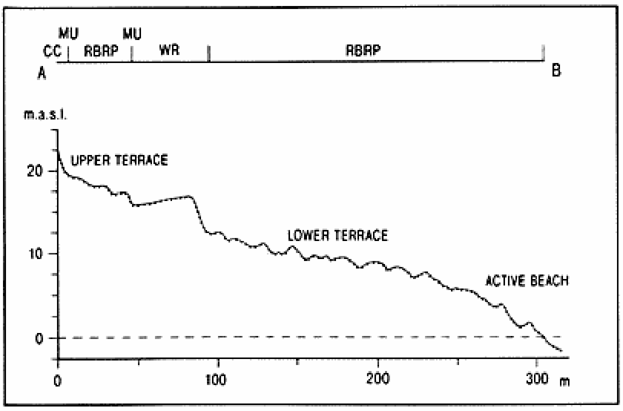

Figure 6. Topographic profile and morphostratigrapic log from the cuspate foreland in Region 4. The position of the profile is shown in figure 2.B and the abbreviations used in the morphostatigraphic log above the profile have been defined in Table 1.

Region 5

Region 5 includes the present coast and a small strip of marine foreland situated between Region 2 and the present coast (Fig. 2). The marine foreland consists of only one beach ridge having approximately the same altitude as the present beach ridge. It has probably been formed at a relative sea-level close to the present.

In the eastern part of the study area, the present beach is generally bordered by active coastal cliffs, and the morphostratigraphy simply consists of a simple beach ridge terminating at a coastal cliff. In front of the cuspate foreland in the western part of the study area, the morphostratigraphy of the present beach is represented by simple beach ridges simply continuing the regressive beach ridge plain of Region 4. However, in the central part of the region, the morphostratigraphy is more complex. At the wedge-shaped marine foreland, a profile perpendicular to the shore line consists of the active beach ridge, the wedge-shaped marine foreland, and a fossil coastal cliff leading to the marine terrace of Region 2 (Fig. 7). The wedge-shaped marine foreland has been logged as a simple beach ridge and the present beach has been logged as a washover ridge. The recent beach ridge cuts off the beach ridge of the wedge-shaped marine foreland at an angle of c. 5°, and a distinctive change of vegetation coverage occurs at the border between the two units. While no lichen appears on the recent beach sediments, the sediments on the marine foreland are completely covered by lichen, *Rhizocarpon jemtlandicum*.

The border between the present beach and the wedge-shaped marine foreland is situated at 2.9 m.a.s.l., and the foot of the fossil coastal cliff is situated at 3.6 m.a.s.l.

Discussion and Conclusion

Morphostratigraphic logs of the 5 regions are shown in figure 8. Region 5 is represented by 3 logs showing the morphostratigraphy of respectively the eastern, the central and the western part of the region.

At Sinigfik, no synchronous morphologic unconformities appear in more than one region above 5 m.a.s.l. It is therefore supposed that all morphologic unconformities above 5 m.a.s.l. result from local changes of the littoral drift. The lack of morphologic evidences of transgressive events above 5 m.a.s.l. suggests that the early Holocene sea-level history at Sinigfik was one of steady emergence. If the relative sea-level fall had been interrupted by shorter periods of rising relative sea-level, morphologic unconformities would be expected at specific levels throughout the study area.

Transgressive interruptions of the postglacial relative sea-level fall are reported from the northern part of East Greenland and from the east coast of Baffin Island. In the northern part of East Greenland, it has been suggested that a transgression took place c. 6 ka B.P. (Hjort 1973, 1981). On the east coast of Baffin Island, at least one transgression occurred between 10 and 8 ka B.P. (Nelson 1981, Andrews & Miller 1985, Andrews 1989). It might seem surprising that no similar transgressions have been reported from West Greenland. One possible explanation is that the transgressions in East Greenland and on Baffin Island resulted from local isostatic events. In fact, Andrews and Miller (1985) have suggested neo-tectonics or

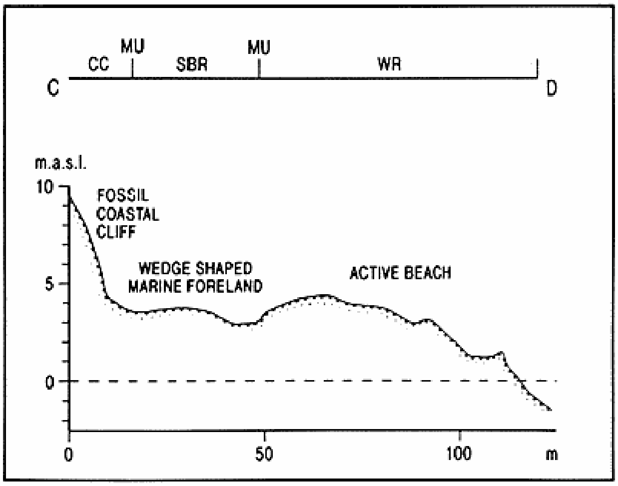

Figure 7. Topographic profile and morphostratigrapic log from the present coast and the wedge-shaped marine foreland in the central part of Region 5. The position of the profile is shown in figure 2.B and the abbreviations used in the morphostatigraphic log above the profile have been defined in Table 1.

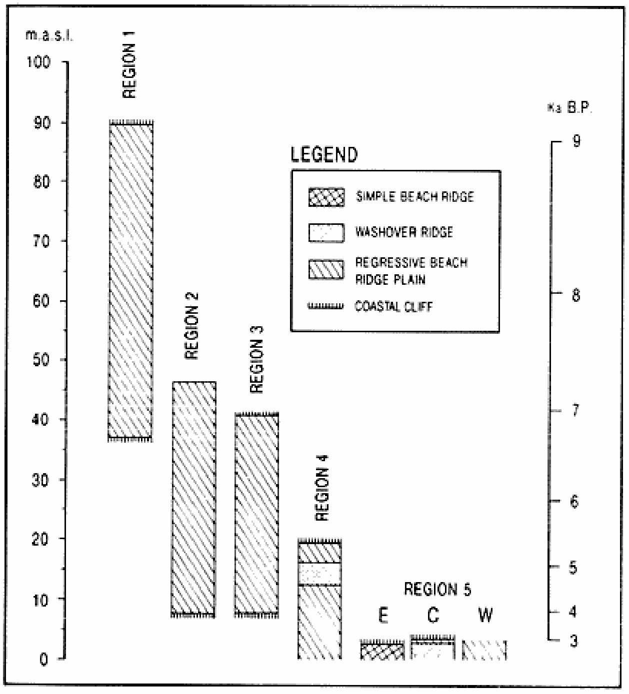

Figure 8. Morphostratigrafic logs of the five regions at Sinigfik. Region 5 (the present coast) is represented by three logs showing the morphostratigraphy of the western (W), the central (C) and the eastern (E) part of the region.

forebulging as possible triggers of the transgression at the east coast of Baffin Island. Alternatively, the differences in relative sea-level history might result from differences in the rate of glacio-isostatic uplift. In West Greenland, the Holocene marine limit is generally situated well above the Holocene marine limit in East Greenland and along the east coast of Baffin Island. Therefore, relatively high glacio-isostatic uplift rates would be expected in West Greenland. Any mechanism engendering a relative sea-level rise should first overcome the glacio-isostatic uplift to actually cause a rise of the relative sea-level. This means that transgressions are less probable in areas with relatively high glacio-isostatic uplift rates, as for example in West Greenland.

At Sinigfik, the most prominent morphologic unconformities appear along the present coastline in Region 5. In fact, coastal recession has been observed on 6 out of 7 kilometers of coastline. Only at the western side of the cuspate foreland, the coast is bordered by a regressive beach ridge plain and shows no signs of coastal retreat.

The present coast at Sinigfik constitutes only a small part of a littoral cell, and the coast is exposed to the south throughout the study area. This means that the coasts might be expected to respond similarly to either a relative sea-level rise, an increasing severity of the wave climate or a depletion of sediment sources. However, active coastal cliffs, active washover ridges and other signs of transgression have been reported from other localities in Disko Bugt as well as throughout the Arctic (Disko Bugt: Mathiassen 1934, Larsen & Meldgaard 1958, Saxov 1958, Bojsen & Frederiksen 1980, Binderup 1985. West Greenland: Mathiassen in Gabel-Jørgensen & Egedal 1940, Kelly 1980, Funder 1989. East Greenland: Hjort 1973, 1981. Canada: Dyke 1979, Blake 1975, Andrews & Miller 1985. Spitsbergen: Feyling-Hansen 1955, Boulton & Rhodes 1974, Forman 1990, Salvigsen & Mangerud 1991), and this apparently general pattern of coastal recession suggests a recent relative sea-level rise.

In the central part of Region 5, the morphostratigraphic sequence consists of a washover ridge (the active beach), a simple beach ridge (the wedge shaped marine foreland) and a fossil coastal cliff leading to the marine terrace of Region 2 (Fig. 7). Two morphologic unconformities are represented within the sequence, and concerning coastal stability the sequence indicates a progradation (marine terrace of Region 2) followed by recession (fossil coastal cliff), and thereafter a new progradation (the wedge-formed marine foreland) again followed by recession (The active beach). As mentioned above, it is most probable that the recession of the present beach results from a relative sea-level rise. It is more uncertain whether the wedge-shaped marine foreland and the fossil coastal cliff behind result from relative sea-level changes or from local changes of the littoral drift. However, the sequence may represent a residual of a complex relative sea-level history of two emergence/submergence events now being lost by erosion in the remaining part of the region.

It is conspicious that the top of the recent beach ridge is higher than the top of the beach ridge on the wedge-shaped marine foreland (Fig. 7). There is, however, no reason to believe that this difference of height is the result of a relative sea-level rise. The recent beach ridge is a washover ridge, and the beach ridge on the wedge-shaped foreland is a simple beach ridge. Their process of origin differs and as a result their heights ought not be compared. If instead the heights a.s.l. of the simple beach ridge at the wedge shaped foreland (3.8 m) and the simple beach ridge at the present coast of the cuspate foreland (3.9 m) are compared, only a slight difference is observed. This might suggest that the beach ridge on the wedge-shaped marine foreland has been formed at a relative sea-level very close to the present one.

The border between the fossil cliff and the wedge shaped foreland is situated 3.6 m.a.s.l., and the coastal cliff seems to continue below the surface of the marine deposits. Therefore, also the cliff has apparently been formed at a

relative sea-level very close to or below the present one.

It has not been possible to obtain any absolute dates of the geomorphologic history in the central part of Region 5. However, the beach ridge of the wedge-shaped foreland is completely covered by lichen, *Rhizocarpon jemtlandicum*, with typical maximum diameters of 4 cm, and the coastal cliff behind has been extensively adjusted by gravitational processes. In the town of Godhavn, 20 km west of Sinigfik, the oldest buildings date back to the first half of the 19th century. On the base of these buildings some *Rhizocarpon jemtlandica* are found, but the coverage is relatively sparse, and the diameters of these do not exceed 1.5 centimeters. If the growth rate of lichen, diameters are presumed constant in space and time, these observations suggest that the wedge-shaped marine foreland and the fossil coastal cliff have not been formed later than the middle of the 15th century.

Based on observations by Mathiassen (in Gabel-Jørgensen & Egedal 1940) and Saxov (1958, 1961), Weidick (1993) has constructed a curve outlining the possible trend of relative sea-level changes at the outer coasts of West Greenland during the last millenium. The curve only represents low- and highstands of waterlevels; i.e. no exact altitudes of relative sea-levels are stated. On the curve, high-stands of the relative sea-levels appear in the 14th-15th centuries and in the middle of the present century. Tentatively, it is suggested that the fossil coastal cliff in the central part of Region 5 has been formed by transgression culminating in the 14-15th centuries. The simple beach ridge of the wedge-shaped marine foreland has been formed by the following regression, and that the washover ridge at the present coast has been formed by the transgression culminating in this century.

The present study documents the need for further investigations of Holocene relative sea-level changes in West Greenland. Especially, our knowledge about the relative sea-level history of the last c. 3 ka (Neoglacial time) is very vague. The morphostratigraphy at Sinigfik suggests that a complex, relative sea-level history might have occurred in this period. However, the suggestions only concern the last c. 500 years, and they need to be verified on localities with different exposure and sediment sources. Besides, absolute datings of the submergence/emergence events are needed; for example for the correlation with changes of past glacier positions and with paleoclimatic information.

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The present study documents the need for further investigations of Holocene relative sea-level changes in West Greenland. Especially, our knowledge about the relative sea-level history of the last c. 3 ka (Neoglacial time) is very vague. The morphostratigraphy at Sinigfik suggests that a complex, relative sea-level history might have occurred in this period. However, the suggestions only concern the last c. 500 years, and they need to be verified on localities with different exposure and sediment sources. Besides, absolute datings of the submergence/emergence events are needed; for example for the correlation with changes of past glacier positions and with paleoclimatic information.

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