# Geomorphology of a Degrading Arctic Delta, Sermilik, South-East Greenland

Niels Nielsen

Niels Nielsen: Geomorphology of a Degrading Arctic Delta, Sermilik, South-East Greenland. Geografisk Tiddskrift, Danish Journal of Geography 94:xx-xx. Copenhagen, Dec. 1994.

*An arctic delta at the Sermilik Station (65°41' N., 37°49' W.), Ammassalik Island, S-E Greenland has been studied including its geomorphology, sediments, dynamics and evolution. The fluvial system is fed by a retreating glacier (30 km$^2$) and comprises an alluvial valley (1.6 km long) and a lobate delta (0.8 km$^2$). The river discharges into a polar sea, which is ice-bound for about 7-8 months a year and with abundant icebergs during the summer. Albeit exposed to the very stormy Denmark Strait, low wave energy conditions prevail, because of the presence of floating ice. Yet major wave-built coastal structures: barriers, tombolos and swash bars, strongly influenced by macro tidal conditions, are superimposed on the delta flat. Recent investigations indicate that the alluvial valley now acts as a sink for glacial discharge of coarse clastic sediments. Furthermore, sequential surveys document a rapid landward migration of the coastal forms. The delta has changed from active progradation to degradation within this century. Profile adjustments by waves and tidal currents are significant factors in the development of the delta suface.*

Keywords: *delta evolution, coastal geomorphology, delta sediments, arctic delta, impact by sea ice and icebergs.*

Niels Nielsen, Associate professor, Institute of Geography, University of Copenhagen, Østervoldgade 10, DK-1350 Copenhagen K, Denmark.

Delta geomorphology, sedimentology and dynamics have been described extensively (e.g. review by Wright, 1985). Most of this literature, however, concentrates on deltas developed in temperate and tropical climates. Except for Naidu & Mowatt's investigations of deltas in northern Alaska (Naidu & Mowatt 1975), studies of the recent dynamics of polar deltas are generally restricted to scattered observations.

Basically, arctic river systems consist of the same morphological components (drainage basin, alluvial valley, delta plain and receiving basin), and the deltas are formed by the same processes, as those found in lower latitudes (Coleman & Prior 1982, Wright et.al. 1974, Morgan 1970). However, certain elements differ; e.g. vegetation, which is essential for tropical delta evolution, may be totally absent in polar regions. In turn, the presence of ice in the arctic is fundamental for the understanding of sediment characteristics and the transport processes in both the terrestrial and the marine environment. Freezing of arctic rivers cause cessation of flow for long periods of the year and the annual discharge is often concentrated within relatively short periods (Wright 1985), resulting in violent spring floods, which may transport coarse and poorly sorted material to the coast. The ability of coastal processes to remould the river sediments into wave-built features is extensively affected by the presence of sea ice and icebergs; wave energy is reduced, sediments are redistributed by ice rafting and the delta body is scoured by grounding ice (Dionne 1988, Hume & Schalk 1976, Kovacs 1983, 1984, Nielsen 1979, 1982, 1992, Reimnitz et al. 1990, Forbes & Taylor 1994). Finally, Holocene sea level fluctuations, which implicate most coastal development in the arctic, are very important.

In 1989 and 1991 investigations of a small arctic delta were carried out at Sermilik Research Station (65°41' N., 37°49' W.), Ammassalik Island, SE-Greenland (Fig. 1). The study is part of a coordinated research programme concerning climatic control of the dynamics of an arctic landscape consisting of a retreating glacier named Mitdluagkat (30 km$^2$), an alluvial valley (1.6 km long) and a delta (0.8 km$^2$). During the last 30 years, the glacier's mass balance and the discharge within the drainage basin have been recorded. However, observations of the coastal zone, where sediments from the catchment area are deposited have not yet been reported. Today, the delta obviously has a negative sediment budget and is being degraded. Tides, waves and sea ice dynamics now dominate delta evolution. Based on a general description of the delta physiography, a baseline mapping, this study discusses when and why there has been a change in the flow of material and evaluates the reasons for the present changes of the delta form.

## Setting

The coastal section studied here is situated on the southwestern part of Ammassalik Island, which is separated from the mainland of Greenland by the Sermilik Fiord (Fig. 1). The fiord is about 80 km long and its width varies between 7 and 13 km. At the northern end the fiord branches into three, each containing major ice-calving glaciers. With 6 minor tidal glaciers along the fiord, the production of icebergs is substantial, resulting in a continuous ice drift out through the fiord (sermilik = ice-fiord in Greenlandic).

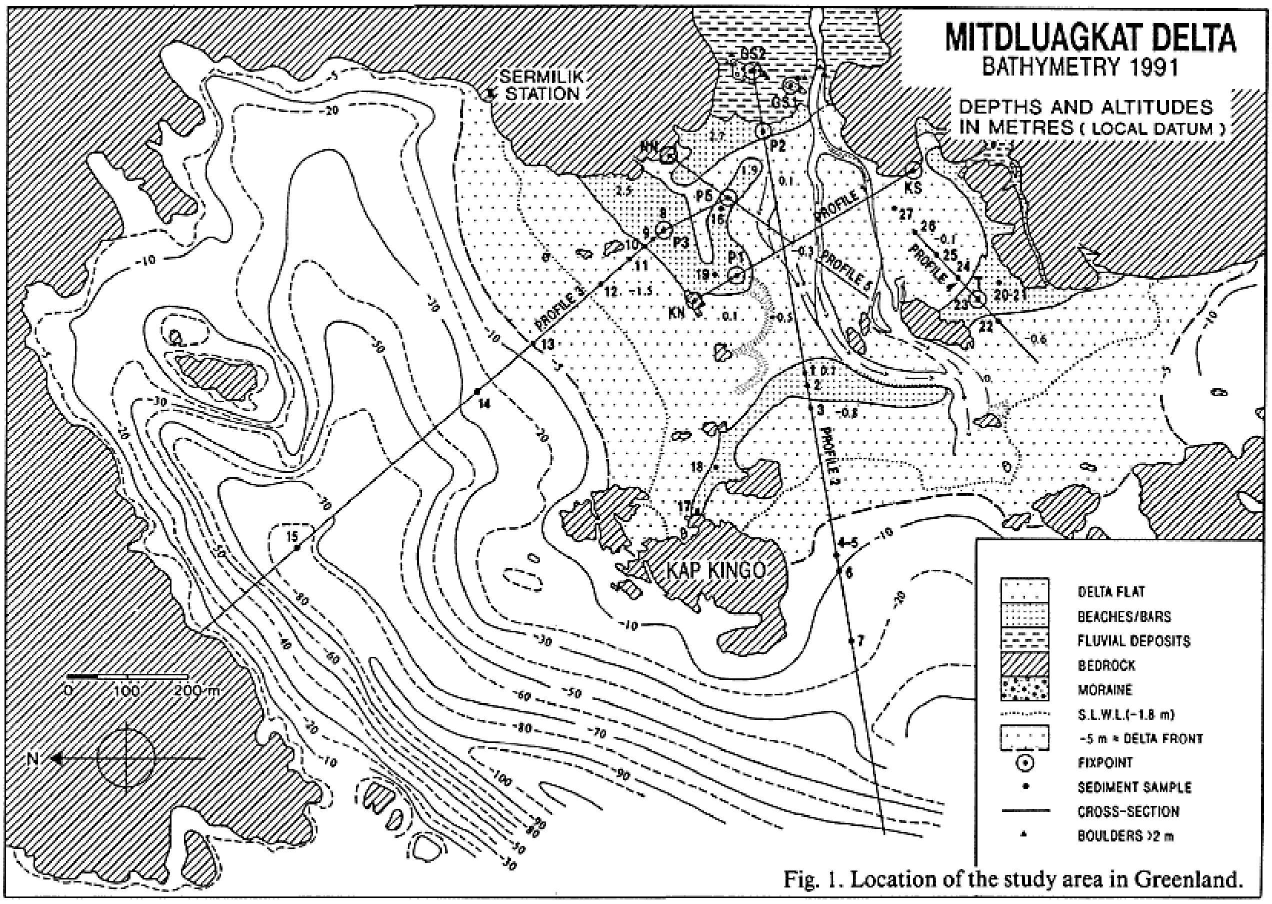


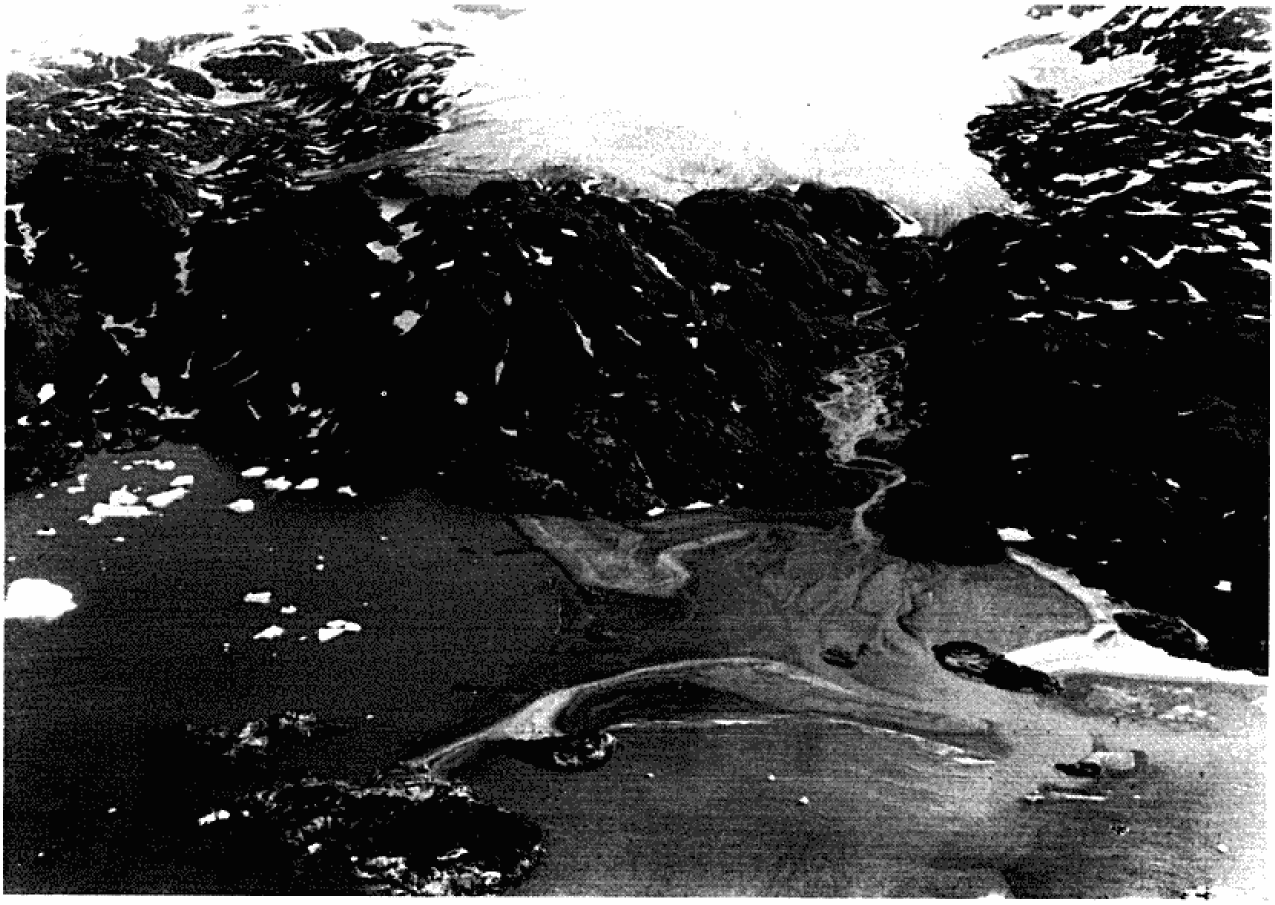
Fig. 1. Location of the study area in Greenland.

Geologically the area is a part of the Nagssugtoqides belt and the rocks are dominantly gneiss, one being a resistant type with coarse-grained feldspar and the another being rich in garnet and easily erodible. Basalt intrusions are common. The terrain is deeply dissected by glacial valleys and geologically-controlled fissure valleys in a criss-cross pattern; the landscape appears rugged and alpine. Several inland peaks above than 1000 m asl. are found, and elevations of 300-600 m are frequent close to the coastline. Coastal plains are nonexistent, except for very few and restricted areas at stream outlets.

In southeast Greenland the Holocene marine limit is c. 75 m above sea level (Bøgvad 1940, Pirazzoli 1991). At the northwestern corner of the Ammassalik Island a delta plain was observed at 60 m asl., but evidence for raised beaches and shorelines is sparse, presumably because of the steep coast and easily erodible bedrock, which dominates the area. Transgression is now recognized along most of the coastline of Greenland. At Ammassalik, tidal records from 1885 to 1950 show subsidence of 2.7 mm +/- 0.5 mm per year (Nielsen 1952).

The climate is subarctic with a mean annual temperature of - 1.2°C. The warmest and coldest months are July and February with average temperatures of 6.9°C and -14.9°C respectively (meteorological observations in Ammassalik 1895-1970). Mean annual precipitation (1921-1950) is 749 mm with a maximum in October-November. Because of the proximity of the Greenland Ice Cap, the weather conditions are generally uniform for long periods. Lows centred over Western Greenland may, however, cause gale force foehn winds (Jensen 1990). Lows tracking along the east coast can result in warm spells, with the temperatures above zero and rain even during the winter.

Low wave energy conditions characterize the environment of the study area. Gales are frequent in the Denmark Strait, but large waves seldom reach the coast, partly because of the damping effect of the polar ice stream along Greenland's east coast and partly because of the drifting icebergs in the fiord. Swell, on the other hand, may penetrate the drifting ice belts and temporarily affect the delta. A semi-diurnal and mixed tide, ranging from 1 to 4 m seems to be fundamental in understanding the coastal development.



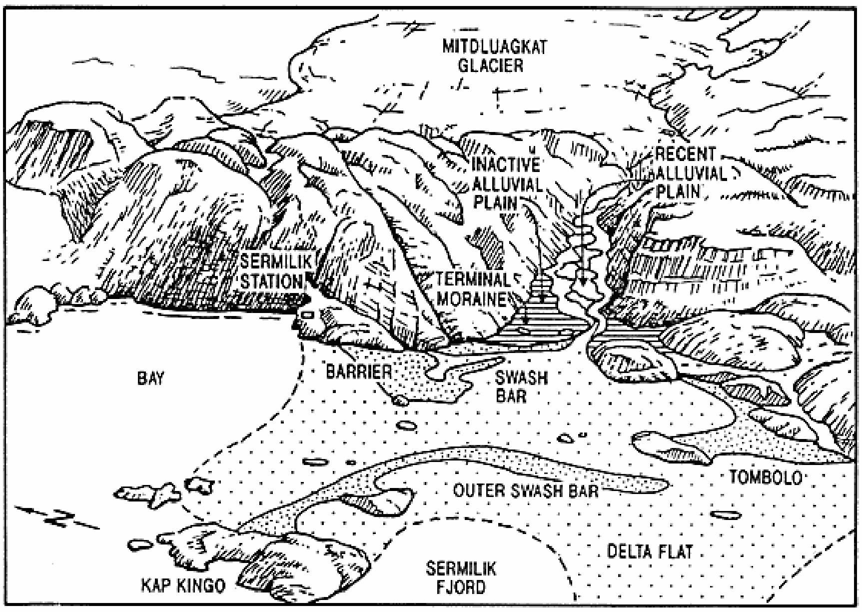


Fig. 2. Oblique aerial view towards the east showing the landscape system including the Mitdluagkat glacier, the alluvial valley and the delta. (Photo NN-910821). Terminology used in the paper and the positions of the forms are illustrated in the sketch.

## Main Features of the Geomorphology

### *Alluvial plain*

The terminus of the Mitdluagkat glacier is situated 1.6 km from the delta (Fig. 2). Below the glacier, the first 3-400 m of the valley bottom is covered by boulders and the profile slopes at an angle of 6-7° to the flatter, main section of the valley, which continues to the delta at a slope of 0.3-1°. Steep rocky hillsides restrict a 2-300 m wide valley floor (braided channels), which is covered by silt, sand and well-rounded pebbles and cobbles. Only a few bedrock outcrops and single large boulders disturb the impression of an even surface. Remnants of two terminal moraine systems cross the valley, one halfway down the valley and one close to the shoreline. For the last few hundred metres before the river debouches onto the delta, the stream is restricted to one single channel. According to a detailed survey (Hasholt 1986) the alluvial plain in this area is slightly higher (about 2 m) than further up-stream. Lichens on coarse clastic sediments and an old superficial channel pattern suggest that the outer part of the valley was created by former fluvial activity. Today only the middle section of the valley shows evidence of recent active braiding. It is possible that this part has been overdeepened by a glacier, and now acts as a sink for meltwater sediments and debris from hillside erosion.

### *Delta*

Basically the outline of the delta forms a semicircle with a radius of about 800 m, covering an area of 0.8 km$^2$. However, the outer limit of the delta is irregular because of 5 larger and several smaller bedrock inliers and rocky islands, which are scattered along the coast and suggest considerable relief of the basement surface. The depth of the junction between the lower delta front and the prodelta varies considerably. According to bathymetric surveys based on 13 echo sounder profiles (Fig. 3), the lower level of the delta front is estimated to be about 50 m below msl. to the north. The corresponding value in the western part is more difficult to detect, but is perhaps situated at only -13 to -18 m (Fig. 6).

Just off the outer skerry islands the depth changes abruptly (27° slope) into the Sermilik Fiord. Only 1 km off the delta front, the fiord floor drops below – 640 m (maximum range of the echo sounder). The northern delta front is built out into a bay, approximately 900 m wide. Depths of 100 m were recorded at the bay mouth and 80 m in the central part. The front of the delta slopes 11° at this location. The proximal 5-600 m of the delta (about half the delta body) are above sea level at spring low-water. At spring high-water only wave-built features attached to the mainland are exposed.

Ignoring bedrock outcrops and coastal forms, the delta flat appears almost horizontal. It slopes seaward at less than 0.1° between -0.3 and -0.5 m msl. (Fig. 3). The junction of the delta front and delta flat is situated at about -5 m msl., 2-300 m offshore from the features constructed by waves. This part of the delta is characterized by seaward slopes of 2° on average. Deltas in tidal environments normally demonstrate a rather smooth transition between the alluvial plain and the delta (Wright 1985). Often such deltas are separated into an upper inactive (abandoned) zone, a lower tidal inundated and active zone and a subaquatic deltaic plain (Coleman et al. 1974). The upper deltaic plain at the study site is reduced to a narrow zone, consisting of a beach, 10-15 m wide and more than 2 m high.

### *Coastal features*

Forms created by marine processes (wind waves and swell in combination with the tide) are conspicuous elements in this deltaic environment (Fig. 4). Because of the skerries, tombolos control the framework of the coastal structures, which now almost enclose a central basin on the delta flat. After an initial phase of evolution, where the bedrock outcrops were connected by wave transported sediment, washover dynamics took over. Cross-section geometry of the barrier and the tombolo (Fig. 7 a and b), displays asymmetrical forms, only occasionally affected by overwash and may be termed washover beach ridges or barriers, with steep beach faces and flatter reversed lee slope. These ridges are 4 and 3 m high, respectively, and sharply demarcated at the delta flat. The total widths range from 60-100 m.

An elongated outer swash bar with a gently sloping seaward and steep landward side confines the inner delta basin to the west. The bar rises about 1.5 m above the outer delta flat and is overwashed by most high tides (except a few at neap tide).

The transition between the alluvial plain and the delta flat is marked by a steep slope. On aerial photos as well as in the field, this coastal sector may look like a barrier beach welded to the alluvial plain, but it is primarily developed as an erosional beach, 20 m wide and 2.3 m high, with a thin (10-20 cm) veneer of washover deposits on top of the alluvium.

A feature shaped like a "boomerang" is attached to the distal part of the barrier (Fig. 4). It extends more than 300 m into the central part of the delta and rises about 2 m above the surrounding delta flat with a width of only 25 m. According to the cross-sectional geometry, demonstrating a steep sloping lee-face a couple of metres from

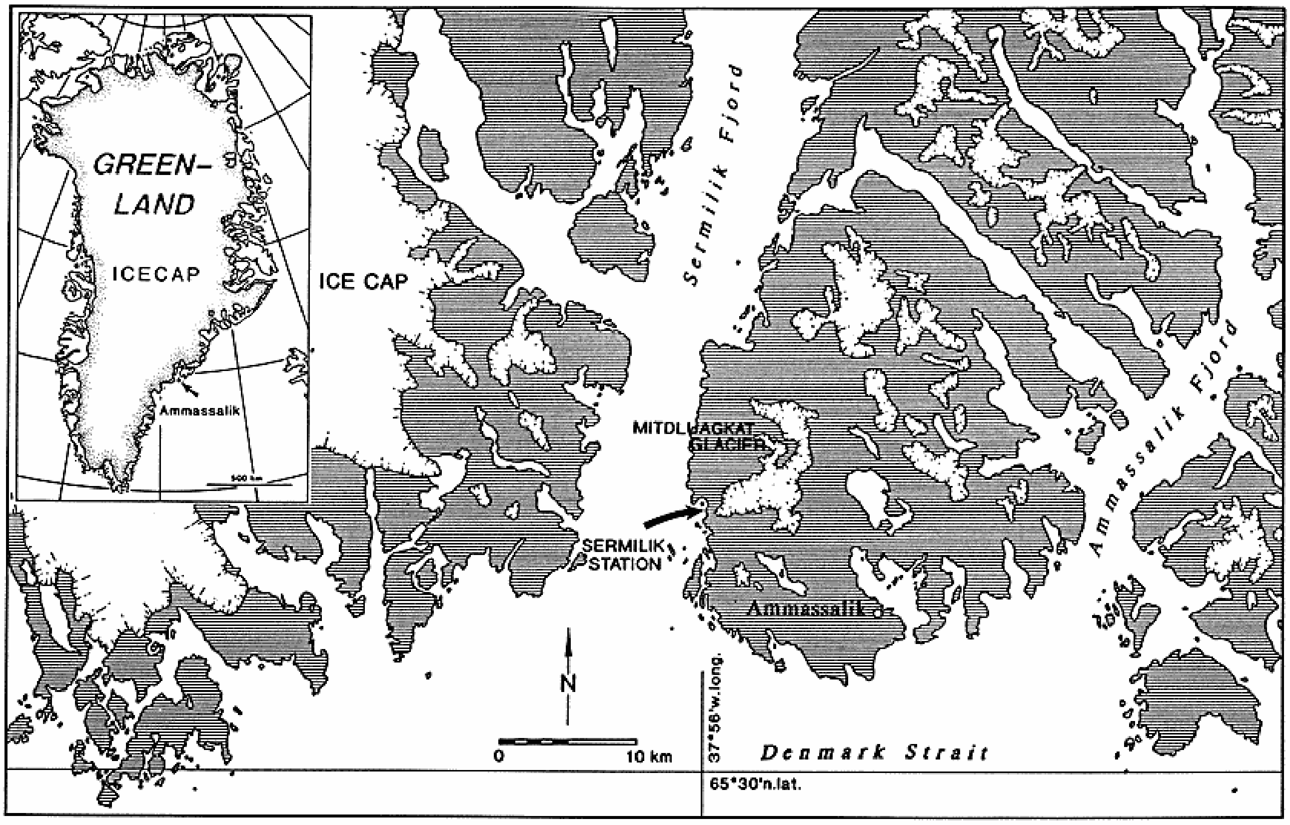


Fig. 3. Typical elevations of the delta flat and coastal forms, and the seaward bathymetry. S.L.W.L.: spring tide low water level. Locations of sediment samples, surveyed profiles and fixed coordinated reference points are indicated.

the crest, and internal sedimentary structures showing cross beddings dipping landward throughout the profile, it must be termed a swash bar (Fig. 7c).

## Delta Sediments

In contrast to many descriptions of deltaic sedimentary environments (Coleman & Prior 1982, Wright 1977, 1984) the delta is very difficult to categorize according to sediment sizes and sequential textural distributions. Sample sites and results from textural analyses are shown in Fig. 3 and Table 1. The samples represent surfaces of fairly homogeneous character in selected morpho-units. The ever shifting pebble bands, typical on the exposed barrier swash zone, are therefore excluded.

The delta flat sediments are almost identical inshore and offshore of the superimposed coastal formations. Most of the area is covered by sand and gravel with a thin marginal of fines (fine sand and silt), especially after periods of calm weather. But scattered all over, with intervals of a few to several metres, small piles of coarse clastics (shingles to pebbles) were found. Several sections cut into the flat demonstrated that the sandy top bedding rested on a massive concentration of pebbles about 25-30 cm below the surface. This depth equals the lowest level of the active channels braiding on the delta flat. The bottom of the channels were paved by coarse clastic, shingle to cobble sizes. Observations from different years indicate shifting courses on the inner delta flat, and this might explain the pebble lag deposits, 25-30 cm below the surface.

During open-water periods, high tides enable small icebergs, ice blocks and growlers to ground seaward of the coastal ridges. This induces complex sediment deposits in the area. If grounded during spring tide, icebergs (5-8 m high) may stay in the same position for several days, perhaps until the next spring tide. The weight and the wave-induced rocking of the ice results in almost circular

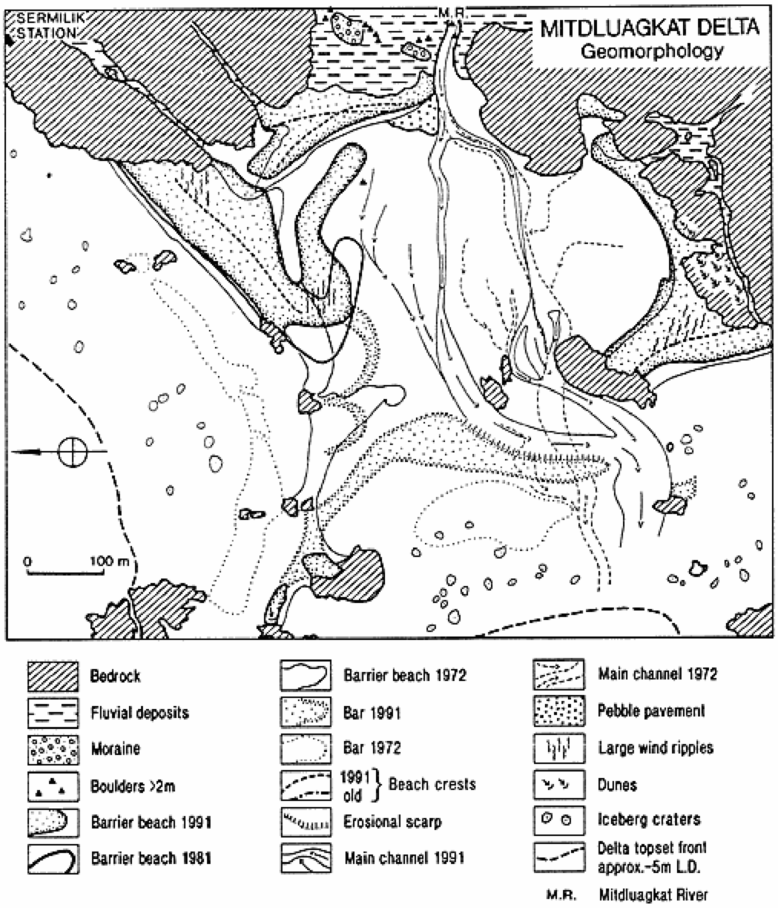


Fig. 4. Characteristic elements of the delta and valley mouth geomorphology compiled from field observations in 1989 and 1991 together with information from aerial photos from 1972 and 1981.

craters often surrounded by low ramparts (Fig. 5). This phenomenon plus trenches ploughed by drifting icebergs cause a highly diversified pattern of sediment texture. Topset sediments are constantly reactivated by waves and tidal currents. Fines, transported in suspension, may be totally removed from the delta, or may settle in ice excavated pools. Even silt and clay fractions are found here (Table 1, no 5). The ramparts, mentioned above, are especially exposed and therefore display concentrations of coarse lag material. Temporarily, homogeneous sand deposits may dominate in between the pits, and bubble sand structures (Reineck and Singh 1975) are typical.

The sediments on the delta front and prodelta display increasing concentrations of fines with depth. Only three grab-samples represent this area (Table 1, no 13-15). Homogeneous silt deposits, usually found in deep basins receiving glacial meltwater (Elverhøi et al. 1983), were not recorded here. Even in the bay at -84 m, the silt and clay fraction accounts for less than 50% of the sample.

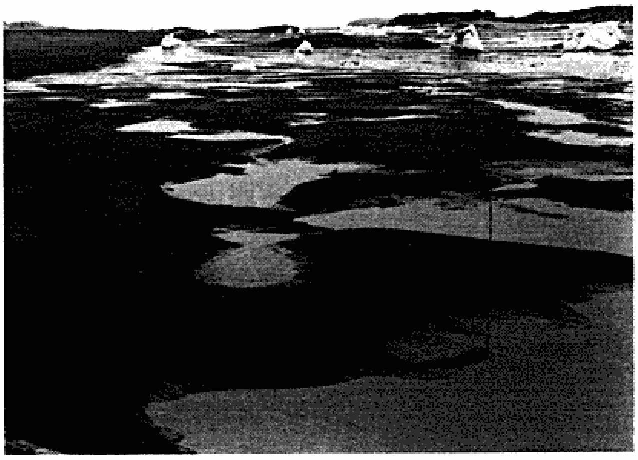


Fig. 5. Beach and nearshore at the northern barrier. The view is towards the southwest. The nearshore sediment surface is strongly disturbed by stranded growlers and ice blocks. (Photo: NN-890717).

| No | Sample | $M_z$ mm | Sort. $\delta_1$ | >200 μ % | <60 μ % |
|---|---|---|---|---|---|
|  | **PROFILE P2.** |  |  |  |  |
| 1 | Outer swash bar, crest | 0.41 | 1.00 | 12.0 | 0.0 |
| 2 | - - foreshore | 0.31 | 0.97 | 2.1 | 0.0 |
| 3 | Second bar, top | 0.22 | 0.91 | 1.0 | 0.5 |
| 4 | -8 m (surface) | 0.05 | ? | 0.0 | 65.0 |
| 5 | -8.05 m | 0.09 | 0.81 | 0.0 | 0.6 |
| 6 | Delta front, -10 m | 0.14 | 1.09 | 2.3 | 5.0 |
| 7 | Delta front, -17 m | 0.05 | ? | 0.3 | 83.0 |
|  | **PROFILE P3.** |  |  |  |  |
| 8 | Barrier crest | 0.45 | 0.91 | 1.2 | 0.0 |
| 9 | Foreshore m.w.l. | 0.38 | 0.77 | 0.3 | 0.0 |
| 10 | Foreshore/nearshore | 0.67 | 0.46 | 22.8 | 0.0 |
| 11 | Shoreface, -1 m | 0.10 | 0.50 | 0.5 | 0.0 |
| 12 | Shoreface, -2 m | 0.10 | 0.81 | 0.2 | 12.0 |
| 13 | Delta front, -5m | 0.25 | 1.41 | 6.0 | 3.1 |
| 14 | Delta front, -25 m | 0.11 | ? | 0.0 | 26.0 |
| 15 | Prodelta -84 m | 0.07 | ? | 0.0 | 45.0 |
|  | **SWASH BAR, NW-TOMBOLO, WIND RIPPLE.** |  |  |  |  |
| 16 | Inner swash bar, crest | 0.41 | 0.64 | 0.0 | 0.0 |
| 17 | Tombolo, crest | 0.20 | 0.53 | 0.0 | 0.0 |
| 18 | Tombolo, foreshore | 0.16 | 0.41 | 0.0 | 0.0 |
| 19 | Aeolian ripple crest | 1.08 | 0.59 | 1.8 | 0.0 |
|  | **TOMBOLO** |  |  |  |  |
| 20 | Aeolian ripple crest | 1.85 | 0.45 | 1.6 | 0.0 |
| 21 | Aeolian ripple trough | 0.36 | 0.74 | 0.0 | 0.0 |
| 22 | T - 50 m S | 0.25 | 0.86 | 2.0 | 0.0 |
| 23 | T - 0 m | 0.54 | 0.83 | 0.2 | 0.0 |
| 24 | T - 50 m N | 0.19 | 1.19 | 6.5 | 1.2 |
| 25 | T - 100 m N | 0.38 | 1.75 | 12.0 | 3.2 |
| 26 | T - 150 m N | 0.12 | 0.97 | 0.8 | 12.0 |
| 27 | T - 200 m N | 0.35 | 2.46 | 18.0 | 8.0 |

Table 1. Selected sediment parameters. Mean size ($M_z$), sorting $\delta_{1)}$ (Folk and Ward 1957), gravel and coarser, silt and clay in weight percent. Depths are below mean water level (Local Datum).

The coastal forms may be separated into three sedimentary units:

*(i)* The barrier and inner swash bar exhibit a large variation in sediment texture, both vertically and horizontally, even though the surface is dominated by a matrix of sand. Trenches more than 1 m deep across the ridges revealed alternating beds of sand, gravel, shingle and pebbles.

*(ii)* The beach face sediments, both at the river outlet and along the alluvial plain, consist entirely of rounded to subangular clasts with diameters of 5-15 cm. The same kind of pebbles are found on a fan-shaped pavement radiating about 100 m onto the delta flat (Fig. 4).

*(iii)* The beach, bar and tombolo systems to the south, west and northwest, are composed of far more uniform sediments dominated by sand and gravel. Pebbles are also found here, but only sporadically and as individuals.

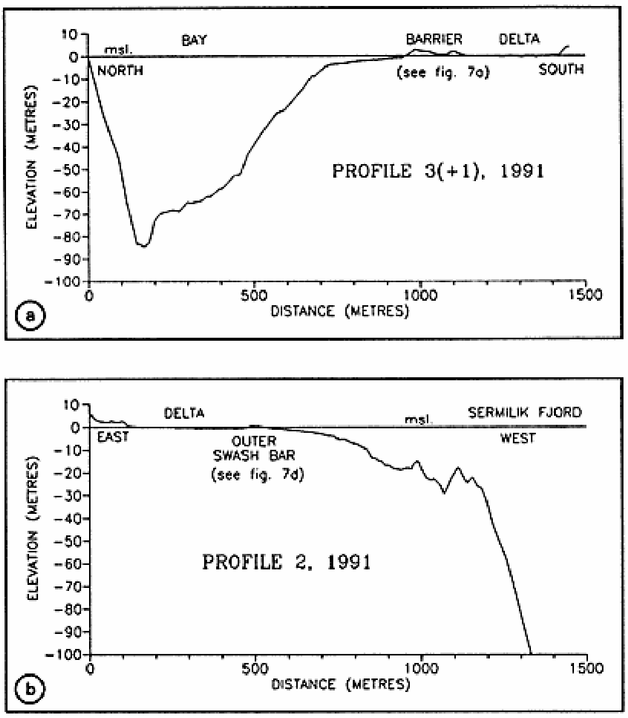


Fig. 6. Cross-sections of the delta. Profile P3(+1) is broken at the barrier crest.

## Modern Coastal Impact in the Delta Area

The delta development is linked exclusively to a sediment supply from the Mitdluagkat valley. On both sides of the delta, steep rock walls drop into the sea. The western part of the delta front almost reaches the junction between the north-south aligned edge of the several hundred metres deep Sermilik Fiord and a deep channel that enters the bay. This setting impedes any kind of sediment supply to the delta by littoral drift. Consequently, the sediment balance of the delta depends exclusively on materials supplied from the river outlet, minus losses to the deep submarine surroundings.

Towards the west, all grain sizes transported in suspension are released into the deep fiord and dispersed by tidal currents. The northern delta front rests on the side of a NE-SW aligned submarine valley, which may explain the asymmetrical cross-section of the bay (Fig. 6 a). This is the only possible receiving basin for accumulation of prodel-

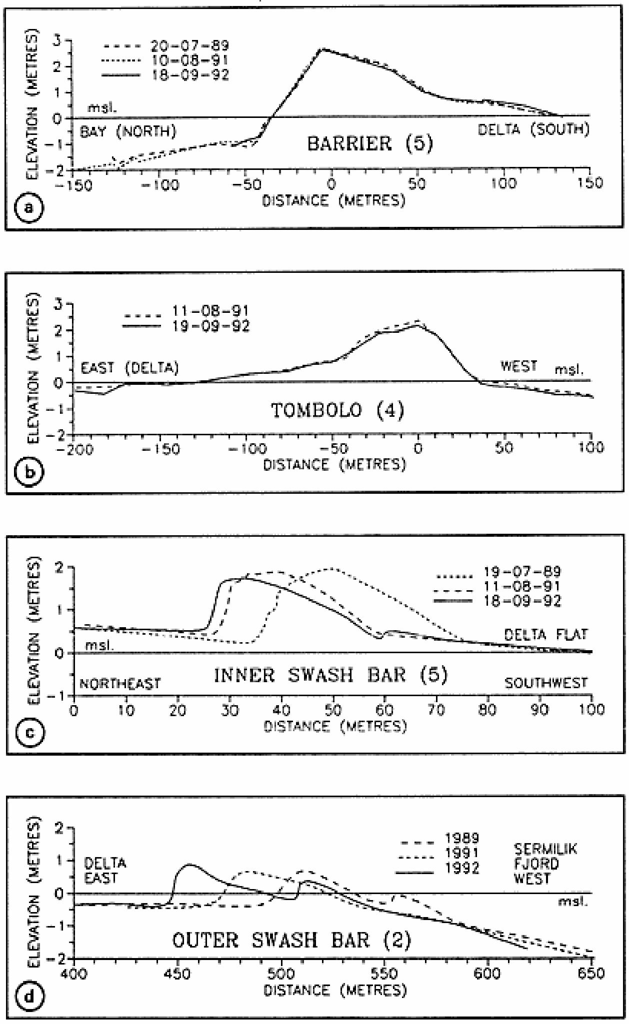


Fig. 7. Cross-sections of the dominant coastal forms: a) barrier, b) tombolo, c) inner swash bar and d) outer swash bar.

TABLE 2. Migration rates of the swash bars.

| Year | outer swash bar | inner swash bar |
|---|---|---|
| 1972-89 | ca. 110 m | - |
| 1989-91 | 26 m | 8 m |
| 1991-92 | 24 m | 3 m |

Table 2. Lee-side migration rates of the outer and inner swash bars.

taic fine sediments, see Table 1, sample no 15. However, two facts indicate that deposition of clay and silt is probably restricted in the bay:

*(i)* The sea bottom in front of the delta still maintains its V-shaped form; and

*(ii)* tidal currents in combination with seiches are common in the bay, and will prevent settling of fine sediments. The strengh of such currents is substantiated by observations of floating ice on time-lapsed video records during a tidal period. The flood current runs clock-wise and turns to an anticlock-wise circulation during ebb tide. No velocity mesurements were made, but current speeds of 20-30 cm $s^{-1}$ were estimated from ice drifting at mid-tide; the current was unsteady, pulsating on a time scale of several minutes. Suspended sediment are thereby washed out into the Sermilik Fiord.

Comparisons of airphotos from 1972 and 1981 and a bathymetric survey in 1991 demonstrate a generally stationary delta front. On the other hand, the coastal landforms superimposed on the delta flat changed rapidly during the same period (Fig. 4). All the forms can be recognized through the two decades, but there is a common tendency for them to migrate away from the fringe of the delta.

In 1972, the mainland was connected to the westernmost skerry, Kap Kingo, by an almost unbroken barrier but a breaching occurred in 1977/1978 (B. Hasholt, pers. comm.). At the breach, the ridge sediments were reorganized into a recurved spit, in continuation of the northeasternmost part of the barrier. The recurve has since been substantially elongated and has migrated/prograted towards the east. Recently, small crescentic bars (concave

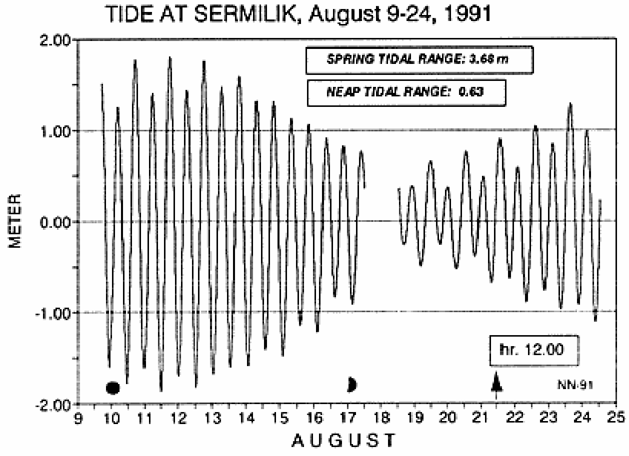


Fig. 8. Tidal curve recorded in the bay, close to the Sermilik research station, during the field campaign 1991. Full and first quarter moon is indicated.

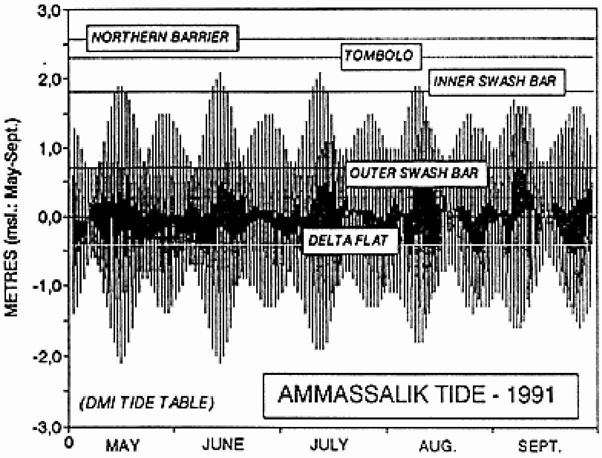


Fig. 9. Ammassalik tidal curve, 1991. Elevation of the coastal forms and the average delta flat level at Sermilik are indicated.

seaward) have developed in the breach and are now migrating onto the central delta flat.

The outer swash bar has changed considerably both in position, shape and size (Fig. 4 and Table 2). From an isolated form in 1972 it has now developed into a coherent ridge, narrowing the tidal channel through which the majority of the water and sediment discharged by the river is channelized at low tide. Three surveys (1989, 1991 and 1992) clearly demonstrate that landward migration of the forms mentioned above is still going on; figure 7 c and d, document migration rates of 6 m/y and more than 25 m/y for the inner and outer swash bars respectively. These observations contrast with the state of the barrier and the large eastern tombolo (Fig. 7 a and b), which have been almost stationary during the same period.

The stability of the high ridges and the rapid migration of the low ones may be due to the height of the ridges in relation to the character of the tide (mixed tide with large variation of the tidal range between neap and spring) (Fig. 8). The outer swash bar is subjected to at least one transgression/regression per day. Because of the shallow water on the outer tidal flat, almost all waves will break through spilling, and the net sediment transport is directed towards and across the bar.

To evaluate the effect of the tide during a longer period, tidal measurements from Ammassalik have been used (Fig. 9). Albeit situated about 30 km from the Sermilik station, the tidal character and fluctuations at Ammassalik are comparable to that of the delta area except for a phase difference of + 1 h. and 6 min. As shown in Fig. 9, only the highest tides are able to inundate the inner swash bar and this only occurs during the three summer months of May, June and July. Furthermore, incident wave energy reaching this bar is reduced on passing the outer swash bar, although the waves are transformed to distinct solitary waves across the inner delta flat and are, therefore, extremely constructive. During a period from neap to spring tide, sediment accumulates on the lower part of the bar and is constantly transported up the seaward slope, to be finally washed across the crest at maximum spring tides. The net result is a lower rate of migration of the inner bar.

The crests of the barrier and the tombolo are not inundated by the tides (Fig. 9). Profile sequences demonstrate a very slow northeastward migration of the tombolo, indicating occasional and visible overwash by waves. In contrast, the northern barrier displays no recent evidence of washover activity.

A vertical section of the northern barrier sediments showed parallel laminated sand and intercalated layers of coarser material. This indicates that wave action, and not tidal overwash, is the primary dynamic factor (Reineck and Singh 1975). When looking at the orientation of the ridge in relation to the small fetches within the bay, ordinary wind waves must be excluded from having a major effect. Extraordinary storm waves or swells are necessary; when approaching from the southwest, these may still contain enough energy after passing the 100 m deep bay entrance to have the potential to diffract and refract across the tidal flat. Then the waves may approach the barrier in alignment with its orientation. During the field work in 1991 low energy swell ($H = 0.2$ m, $T = 11$ s) were observed to follow this pattern of propagation. However, the necessity for high energy waves raises problems. If storm waves or swell were to approach from the west to southwest, the concentration of icebergs in the Sermilik Fjord plus the massive polar ice stream in the Denmark Strait would lower wave impact considerably. Observations by different visitors to the area indicate that calm weather prevails during the summer. The author has only experienced a couple of gales, both blowing from the northeast – which is offshore. Unfortunately, neither wave records nor wind records exist from the study area (or elsewhere in this part of Greenland). Automatic wind recording at the delta are commenced in 1994.

Impact by sea ice is not restricted to ploughing and pitting of the tidal flat, sediment rafting and ice-foot dynamics on the foreshore (McCann et al. 1981, Nielsen 1979, 1982, 1988, Reimnitz et al. 1990). The highest crest of the coastal ridges also displayed evidence of sea ice activity. Several piles of mixed gravels and pebbles (wind winnowd) and small craters appear all over the crests and the washover side of the barrier. A heavy pole, used as a fixpoint, P1, Fig. 3, was emplaced on top of the barrier in 1989. In 1991 it sloped about 45° towards the delta center, displaced by over-riding sea ice. Although ice-push occurs frequently during freeze-up and thaw, net sediment transport through this mechanism is of minor importance.

In contrast eolian processes play an important role in remoulding the delta surface. The orientations of large, coarse-grained wind ripples and dunes indicate temporary violent storm-events with winds directed from N-NE, corresponding to the direction of foehns in this area (Table 1 no. 17, 19, 20, 21). Eolian deposits predominate the surfaces of the proximal part of the ridge attached to Kap Kingo (dunes) and on the tombolo (dunes and ripples) (Fig. 4). On the inner swash bar, three sources of sediment could be recognized:

*(i)* Wave sorted sediments from the delta flat itself,

*(ii)* sediments from the crescentic nearshore bars migrating south and

*(iii)* eolian sand transported westward along the crest of the barrier. Considerable quantities of the latter accumulate on the delta flat at the distal part of the barrier, and are then brought to the swash bar by waves.

## Delta Evolution – a Preliminary Discussion

By and large, the delta geometry comprises all the morphological elements of a Gilbert-type delta (Gilbert 1884). The sediment balance of the modern delta is, however, negative and the delta form reflects previous environmental conditions, when colder climates prevailed.

Two different scenarios for the initial delta development may be envisaged:

1) Photography from 1930, obtained by K. Milthers in 1933, documents a conspicuous glacier advance during the Little Ice-Age (Fristrup 1970). Around the turn of the century, the terminus of the Mitdluagkat glacier reached its maximum position and a ridge of terminal moraines was built across the mouth of the valley. Today remnants of these moraines are situated only 80 m upstream from the present delta flat. The position of the relative sea-level was about 25 cm lower at that time (Nielsen 1952). During the glacier's advance to its maximum position and even more so during the first decades of the melting phase, considerably larger amounts of meltwater and sediment discharge may have occurred compared to recent conditions. This large sediment discharge led to the building of the delta.

2) The sculpturing of the main form of the Mitdluagkat valley was not made by the Little Ice-Age glacier, but by a larger one, perhaps in the late Weichelian (Humlum, O., pers. com.). This glacier may have passed the narrow entrance of the valley and then spread out into a piedmont-form, with a terminus approximately following the outer limit of the present delta. The position of the glacier front was presumably stable during this period of time, as a consequence of the deep water fronting it. It was a calving, tidal glacier and most sediments discharged disappeared into the Sermilik Fiord. When this older glacier melted away, a level ground moraine was exposed, the surface of which was further smoothed by marine forces.

An deficiency of the latter scenario is the absence of large morainic deposits. Although marine processes have had a long time to smooth out the "delta" surface, at least local concentrations of residual boulders should be expected. But as mentioned above, such particles are not found. In contrast, moraines and perched boulders are frequent on the present alluvial plain.

The "Little Ice-Age scenario" also contains problems, especially concerning the amount of sediment discharge necessary to create the delta body. With a delta flat area of about 0.5 km$^2$ and a supposed minimum thickness of 15 m on average, estimated from profiles, the delta comprises more than 7.500.000 m$^3$ of sediment. If the duration of the Little Ice-Age is set to around 500 years, an annual discharge of 15.000 m$^3$ is required. However, this figure would be an underestimate, as this cold era-glacier presumably was able to yield substantial sediment to the coast only during the last 200 years. If that is correct, the delta would have received 35- 40.000 m$^3$/y, a figure which should be increased considerably (20-50%) (Hasholt 1992), since fines disappear into the fiord. A gross amount of 50- 60.000 m$^3$/y is hard to imagine from a valley glacier with a frontal length of about 250 m. Mean daily sediment discharge varies a lot, but it is unlikely that more than 2-3000 m$^3$/y (bedload) are added to the delta body (Hasholt 1992). An investigation of the transport competance of the river (Busskamp & Hasholt 1993) indicates that only sand and finer sediments pass through the alluvial valley.

The present delta sediments can not be dated back to early/mid Holocene because of the very different (higher) relative sea level stand at that time. Therefore, if other Neoglacial glacier advances are excluded, a preliminary proposal for delta evolution might be a combination of a glacially derived basement, superimposed by delta (glacio-fluvial) sediments deposited during the glacier advance 100 to 300 years ago. This scenario is outlined in Fig. 10.

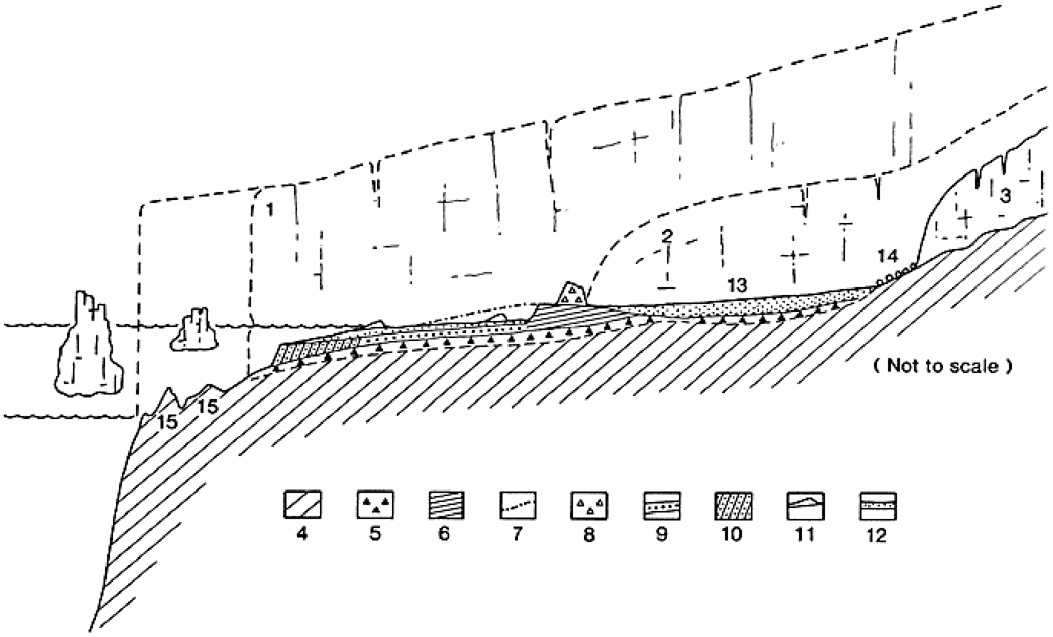


Fig.10. Simplified scenario of delta evolution and associated superficial sedimentary sequence: 1) late Weichelian tidal glacier. 2) Neoglacial, "1900"-stage; 3) present glacier terminus; 4) bedrock; 5) ground moraine from a late Weichelian glacier; 6) "1900"-alluvial deposits; 7) "1900"-alluvial and delta plain; 8) "1900"-terminal moraine; 9) delta flat with lag deposits; 10) delta foreset; 11) wave/tide-built swash bar; 12) recent ice-disturbed surface layer; 13) recent and subrecent alluvial deposits; 14) boulders; 15) bedrock or moraine.

## Conclusion

The shape of the delta is believed to be the result of the advance of the Mitdluagkat glacier during The Little Ice-Age. Today the sediment balance is negative, witnessed by coastline recession and landward migrating coastal forms. Large reaches of the northern and southeastern part of the delta must now be considered as relict delta sections, as barrier and tombolo formations prevent river sediment from supplying the outer delta flat along these stretches. To a certain extent the western delta front is also cut off from sediment supply, because of a threshold in the form of a landward migrating and continuously growing outer swash bar.

Two different factors acting separately or in combination might be responsible for the actual delta evolution:

1) Reduced sediment supply from the river, and 2) sea level rise.

The retreat of the glacier through this century, leaving a proglacial valley now functioning as a sink. The transport competancy of the river allows only sand and fines to be transported to the delta. The inner part of the delta has developed into a basin restricted by wave-built structures. Some sediments are deposited within this basin and some are transferred via braiding streams, which merge to a single channel before entering the outer delta flat. If the rate of subsidence at Ammassalik is correct and comparable to that of the delta area, a relative sea level rise of about 25 cm has occurred since the glacier began to retreat. This contribution reinforces the coastal recession considerably.

The overall modern geomorphology of the delta exhibits evidence of degradation. Tides with superimposed waves and ice processes dominate the controls upon macro structure of the delta; net sediment transport of sand and coarser material is almost exclusively directed landwards. The evolution of the northern barrier and the tombolo is suggested to be a result of an adjustment of the inactive, outer delta flat profile to the local wave and tidal forces. Although river sediments are still supplied to the delta, it must be concluded that the lack of supply is a critical factor and closely related to delta behavior.

## Acknowledgements

The author is indebted to K. Nielsen, D. Anthony and B. H. Jakobsen for assistance in the field and to my colleagues T. Aagaard and B. Hasholt for helpful advice and discussions. Thanks to K. M. Petersen for textural analyses and to J. Jønsson for the final drawings. Financial support was provided by the Danish Natural Science Research Council.

## References

*Busskamp, R. & Hasholt, B.* (1994): Coarse bed load in a proglacial valley, Sermilik, East Greenland. In prep.

*Bøgvad, R.* (1940): Quaternary geological observations in Southeast and South Greenland. Meddelelser om Grønland, vol. 107, no. 3, 42 p.

*Coleman, J.M & Prior, D.B.* (1982): Deltaic environments of deposition. In: Scholle, P.A. and Spearing, D. (eds.), Sandstone Depositional Environment. Amer. Assoc. Petrol. Geol., p. 139-178.

*Dionne, J.C.* (1988a): Tide-influenced sedimentary environment and facies. ed. P.L. de Boer et al., Reidel Publishing Company. p.301-332.

*Dionne, J.-C.* (1988b): Ploughing boulders along shorelines with particular reference to St. Lawrence Estuary. Geomorphology 1 (4), p. 297-308.

*Elverhøi, A. et al.* (1983): Glaciomarine Sedimentation in a modern fjord environment, Spitsbergen. Polar Research 1 n.s., p 127-149.

*Forbes, D.L. & Taylor, R.B.* (1994): Ice in the shore zone and the geomorphology of cold coasts. Progress in Physical Geography, 18,1, p. 50-89.

*Fristrup, B.* (1970): New Geographical Station in Greenland. Geografisk Tidsskrift, 69, p. 192-203.

*Hasholt, B.* (1976): Hydrology and transport of material in the Sermilik area 1972. Geografisk Tidsskrift, 75, p.30-39.

*Hasholt, B.* (1986): Mapping of the Midtluagkat Glacier and some Hydro-glaciological observations. Geografisk Tidsskrift, 86, p. 8.

*Hasholt, B.* (1988): Sermilik – a field station in Eastern Greenland. The seventh northern research basin symposium. Danish Society for Arctic Technology, Denmark, p. 87-93.

*Hasholt, B.* (1992): Sediment transport in a proglacial valley, Sermilik, East Greenland. Geografisk Tidsskrift, 92, p. 105-110.

*Hasholt, B. & Walling, D.* (1992): Use of caesium-137 to investigate sediment sources and sediment delivery in a small glacierized mountain drainage basin in eastern Greenland. IAHS Publication no 209, p. 87-100.

*Hayes, M.O.* (1975): Morphology and sand accumulations in estuaries. Estuarine Research, vol. 2, p.3-22.

*Hume, J.D. & Schalk, M.* (1976): The effect of ice on beach and nearshore, Point Barrow, Alaska. Review Geography Montreal, 30, p. 105-114.

*Jensen, P. H.* (1990): Piteraq. Atuakkiorfik, 127 p.

*Kovacs, A.* (1983): Shore ice ride-up and pile-up features, Part I: Alaska's Beaufort Sea Coast. US Army Corps of Engineers, Cold Region Research and Engineering Laboratory Report, 83-9. Hanover, NH, 59 p.

*Kovacs, A.* (1984): Shore ice ride-up and pile-up features, Part II: Alaska's Beaufort Sea Coast. US Army Corps of Engineers, Cold Region Research and Engineering Laboratory Report, 84-26. Hanover, NH, 29 p.

*McCann, S.B, Dale, J.E. & Hale, P.B.* (1981): Ice conditions and effects in a macrotidal subarctic environment, southeast Baffin Island. In Dionne, J.-C. (ed.): Workshop on Ice action on shores. Proceedings, National Research Council, Canada, ACROSES, 3, p.105-115.

*Morgan, J. P.* (1970): Depositional processes and product in the deltaic environment. In J.P. Morgan (ed), Deltaic Sedimentation, Modern and ancient. Society of Economic Paleontologists and Mineralogists. Special Publication no 15, Tulsa, Oklahoma, U.S.A., p. 31-47.

*Naidu, A.S. & Mowatt, T.C.* (1975): Depositional Environments and sediment characteristics of the Colville and adjacent deltas, northern arctic Alaska. In Broussard M.L. (ed): Deltamodels for exploration, Houston Geological Society, p. 283-309.

*Nielsen, N.* (1979): Ice-foot processes. Observations of erosion on a rocky coast, Disko, West Greenland. Zeitschrift f. Geomorphologie, N.F., 23(3), p. 321-331.

*Nielsen, N.* (1982): Periglaciale former på kyster opbygget af løse sedimenter – nogle iagttagelser fra Disko, Vestgrønland. Geogr. Tidsskrift 82, p. 67-73.

*Nielsen, N.* (1992): A boulder beach formed by waves from a calving glacier; Eqip Sermia, West Greenland. Boreas, 21, p. 159-168.

*Nielsen, E. W.* (1952): A determination of subsidence of the land of Angmagssalik. Meddelelser om Grønland, vol 136, no. 2, p. 3-11.

*Pirazzoli, P.A.* (1991): World atlas of Holocene Sea level changes. Elsevier Oceanography, Series 58. p. 300.

*Reimnitz, E. et al.* (1990): A review of beach nourishment from ice transport of surface materials, Beaufort Sea, Alaska. Jour. of Coastal Research 6(2), p. 439-471.

*Reineck, H.-E. & Singh, I.B.* (1975): Depositional Sedimentary Environments. Springer Verlag, Berlin. 439 p.

*Wright, L. D.* (1977): Sediment transport and deposition at river mouths: A synthesis. Geol. Soc. Am. Bull., 88, p. 857-868.

*Wright, L. D.* (1985): River Deltas. In Coastal Sedimentary Environments. Second revised and expanded ed., R.A.Davis (ed), Springer Verlag, New York, p. 1-76.

*Wright, L.D., Coleman, J.M. and Erickson, M.W.* (a 1774): Analysis of major river systems and their deltas: morphologic and processes comparisons. Louisiana State Univ., Coastal Studies Inst. Tech. Rept. 156, 114 p.