

The Geomorphology of Glaciomarine Sediments in a High Arctic Fiord

La géomorphologie de sédiments glacio-marins dans un fjord de l'Arctique

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Résumé de l'article

Un modèle géomorphologique général décrivant les transgressions et les régressions marines se produisant en régimes non glaciaires est appliqué à un environnement glaciaire. Ce modèle comprend deux variables : i) la vitesse du changement du niveau marin et ii) la vitesse de sédimentation en zone littorale. L'interaction de ces deux variables détermine la nature des transgressions et des régressions pour une ligne de rivage donnée. En régions à modelé glaciaire, la vitesse de sédimentation et les changements du niveau marin sont surtout commandés par les réactions de nature glacioclimatique de la glace. Ce phénomène est bien illustré le long du littoral arctique où la charge glaciostatique a provoqué d'importantes inondations, pendant et immédiatement après la dernière glaciation. L'émergence subséquente survenue au tout début de l'Holocène a entraîné l'exposition d'importants dépôts marins soulevés. À Clements Markham Inlet, sur la côte la plus septentrionale de l'île d'Ellesmere, on trouve des dépôts marins soulevés dont la distribution spatiale et séquentielle caractéristique est reliée à l'évolution glaciaire. Le modèle géomorphologique général sert à expliquer la distribution et la géomorphologie de ces sédiments. Au cours d'un cycle glaciaire, l'équilibre entre les variations de l'apport en sédiments et la vitesse de fluctuation du niveau marin aura un effet direct sur le type de séquence stratigraphique trouvé en un endroit donné.

THE GEOMORPHOLOGY OF GLACIOMARINE SEDIMENTS IN A HIGH ARCTIC FIORD

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ABSTRACT A general geomorphic model describing marine transgressions and regressions under non-glacial conditions is applied to the glacial environment. The general model recognizes two variables: i) the rate of relative sea level change, and ii) the rate of sedimentation at the coastline. The interaction of the two variables determines the nature of transgression or regression at a particular shoreline. In glaciated areas both sedimentation rates and relative sea level changes are controlled mainly by glacioclimatic responses of the ice. This is best illustrated along arctic coastlines where glacioisostatic loading caused extensive marine inundations during, and immediately after, the last glaciation. Subsequent emergence in the early Holocene has exposed extensive raised marine deposits. Clements Markham Inlet, on the northernmost coast of Ellesmere Island, Northwest Territories, contains raised marine deposits which have a definite spatial and sequential distribution related to the glacial history. The general geomorphic model is used to explain the distribution and geomorphology of this sediment. As the glacial cycle proceeds the balance between fluxes of sediment input and rate of sea level rise or fall will have a direct bearing on the type of stratigraphic sequence found in a particular area.

RÉSUMÉ *La géomorphologie de sédiments glacio-marins dans un fjord de l'Arctique.* Un modèle géomorphologique général décrivant les transgressions et les régressions marines se produisant en régimes non glaciaires est appliqué à un environnement glaciaire. Ce modèle comprend deux variables: i) la vitesse de changement du niveau marin et ii) la vitesse de sédimentation en zone littorale. L'interaction de ces deux variables détermine la nature des transgressions et des régressions pour une ligne de rivage donnée. En régions à modelé glaciaire, la vitesse de sédimentation et les changements du niveau marin sont surtout commandés par les réactions de nature glacioclimatique de la glace. Ce phénomène est bien illustré le long du littoral arctique où la charge glacioisostatique a provoqué d'importantes inondations, pendant et immédiatement après la dernière glaciation. L'émergence subséquente survenue au tout début de l'Holocène a entraîné l'exposition d'importants dépôts marins soulevés. À Clements Markham Inlet, sur la côte la plus septentrionale de l'île d'Ellesmere, on trouve des dépôts marins soulevés dont la distribution spatiale et séquentielle caractéristique est reliée à l'évolution glaciaire. Le modèle géomorphologique général sert à expliquer la distribution et la géomorphologie de ces sédiments. Au cours d'un cycle glaciaire, l'équilibre entre les variations de l'apport en sédiments et la vitesse de fluctuation du niveau marin aura un effet direct sur le type de séquence stratigraphique trouvé en un endroit donné.

РЕЗЮМЕ *Геоморфология морских ледниковых отложений в арктическом фиорде.* Общая геоморфологическая модель, которая объясняет морские трансгрессии и регрессии в нормальных условиях, применяется здесь к ледниковой среде. В модели различаются два основных явления: 1) скорость изменения уровня моря, и 2) скорость образования прибрежных отложений. Равновесие между упомянутыми факторами определяет тип трансгрессии или регрессии.

В оледененной территории, продукция рыхлого материала и изменение уровня моря контролируются глациоклиматическими изменениями ледников. Самое лучшее свидетельство этого процесса можно найти вдоль арктических побережий, где глаци-изостатическая нагрузка вызвала морскую трансгрессию в широком масштабе, которая произошла после последнего оледенения. На перешейке Клеменс Маркам (Clements Markham) на северном побережье острова Элесмер (Ellesmere) лежат морские отложения, в которых весьма специфическое пространственное распределение и стратиграфическая позиция, связанные с историей оледенения этой территории. В ходе развития глациального цикла, равновесие между постановкой материала и скоростью поднимания или опускания уровня моря имеет прямое влияние на стратиграфический тип отложений в данном месте.

INTRODUCTION

The coastlines of the high arctic were subjected to glacioisostatic loading during the last glaciation which caused widespread marine transgressions. While submerged, many coastal lowlands received large volumes of glaciomarine sediment from tidewater glaciers. Subsequent post-glacial uplift has exposed these sediments so that they can be easily studied on land. Moreover, because of the link between glaciation and sea levels, numerous studies concerning the glacial history of Arctic areas are complemented by reconstructing the glacioisostatic sea level history (e.g. Bednarski, 1984, 1986; Blake, 1970; England, 1983, 1985; Hodgson, 1985).

In addition, there have been studies concerned strictly with sedimentology of glaciomarine deposits and several process models describing glaciomarine sedimentation exist (Lavrushin, 1968; Molnia, 1983; Nelson, 1981; Powell, 1981, 1983). Most models of fiord glaciomarine sedimentation recognize three to four depositional zones beneath and in front of a glacier. The sediment characteristics in each of these zones is controlled mainly by: i) dynamics of the glacier, ii) volume and position of debris zones within the glacier, iii) the position of the grounded ice front in relation to the water line, iv) water depth, and v) the nature of circulation in fiord waters. The sediments in these zones grade from tills, coarse outwash, and colluvium in the proximal, ice-contact zone; to abundant ice-rafted debris in the intermediate zones; and in distal zones, to ever finer sediments from suspension, with an increasing relative component of ice-rafted debris.

Glaciomarine sedimentation models, such as those mentioned above, effectively describe the possible sequence of

facies found within fiords. This paper shows that the nature of the glacioisostatic response also has a direct bearing on glaciomarine facies successions and their geomorphology. A simple model is devised to demonstrate this relationship. The model is then applied to Clements Markham Inlet, a major re-entrant along the north coast of Ellesmere Island, Northwest Territories (Fig. 1). The distribution and character of surficial materials, as well as, the glacial and sea level history of this inlet is known (Bednarski, 1984, 1986), so the model can be readily assessed.

GLACIOMARINE SEDIMENTATION IN AN ARCTIC FIORD

In the broadest sense, glaciomarine sedimentation involves the interaction of glacial sediment with the sea, therefore, two factors dominate. The first factor is the character, volume and method of delivery of glacial sediment to the marine environment. This covers a very large range of sediment types derived from glacial, fluvial, or eolian environments. The second major factor relates to the dynamics of the sea which depends on the energy of waves and currents which rework the sediment, as well as, the stability of relative sea level. This paper stresses the importance of relative sea level motions in governing glaciomarine sedimentation along arctic coastlines. The rate and amplitudes of these fluctuations, coupled with their interaction with sediment input during the glacial cycle, have important effects on the stratigraphy and sedimentology. An examination of the interaction between these controls and how they result in various landform associations and stratigraphic sequences is attempted here.

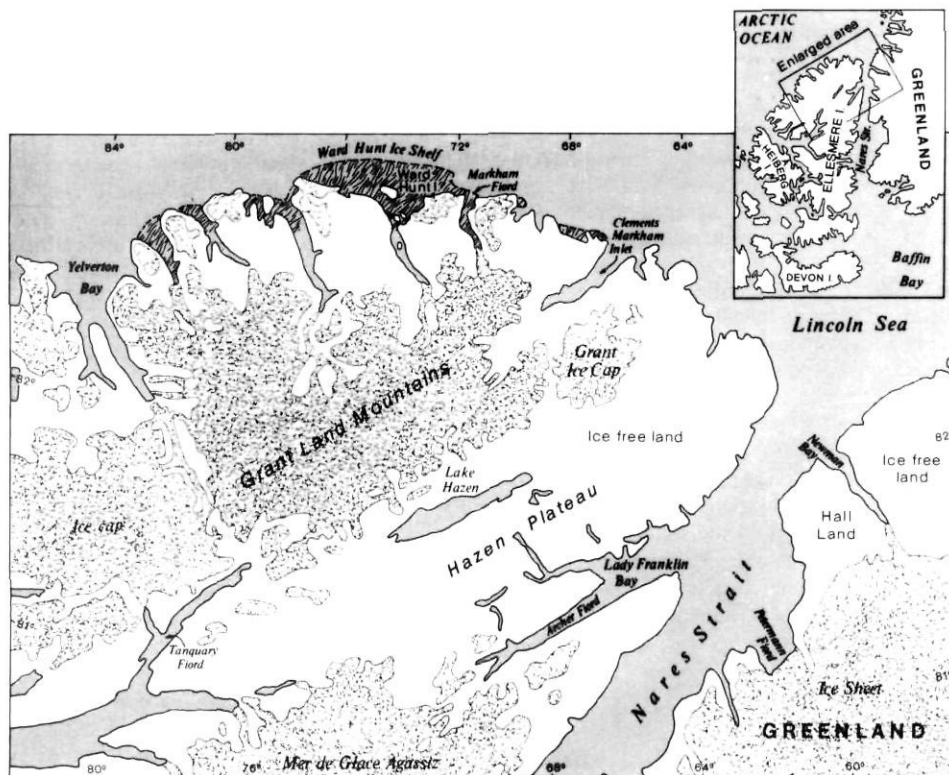


FIGURE 1. Location map of Ellesmere Island (reproduced with the permission of the NRC Research Journals).

Carte de localisation de la partie nord de l'île d'Ellesmere (droit de reproduction accordée par la direction du Conseil national de la recherche)

It is emphasized that sedimentary environments within a fiord can be highly variable as a fiord glacier advances or retreats, or as sea level rises and falls. Do the depositional zones merely migrate down or up the fiord as the glacier advances or retreats, or is the process more complicated? In order to understand this, the relative glacioisostatic and eustatic fluctuations affecting glaciomarine sedimentation must be considered.

EUSTATIC AND GLACIOISOSTATIC CONTROL

Clark *et al.* (1978) estimated the magnitude and character of eustatic and isostatic movements which occurred in arctic areas following deglaciation at ca. 16 ka BP. Clements Markham Inlet may fall into two possible zones proposed by Clark *et al.* (1978). The location of these zones depends on the extent of the last glaciation and hence the magnitude of the ice load which depressed this area. If the last glaciation extended well into Clements Markham Inlet, the fiord head would fall into Clark's Zone I. Zone I is characterized by continuous and ongoing postglacial emergence because glacioisostatic unloading exceeded the postglacial sea level rise. If the last glaciation did not inundate the fiord during the last glaciation, the fiord would fall into the Zone I/II transition. Transition zone I/II is characterized by the collapse of the forebulge. Although this model (Clark *et al.*, 1978) is theoretical and based on the instantaneous uniform melting of the ice sheet, it does give an approximation of the types of responses which will likely occur given different glacial histories. The results of this model are also supported by recent geophysical solutions for different glacial histories in Atlantic Canada (*i.e.*, Quinlan and Beaumont, 1981). These authors stressed the difficulty in separating out the eustatic and isostatic components from overall relative sea level movements. However, they noted the dominance of the isostatic component near former ice sheets. It is assumed here that the relative movements of land and sea will depend solely on the extent of ice during a glaciation and this, in turn, will dictate the depositional sequence.

ANALYSIS OF STRATIGRAPHIC SEQUENCES

Major facies transitions in a fiord are controlled by the relative movements of land and sea coupled with the influx of sediment. Several workers have investigated these relationships from onlap-offlap sequences found in ancient sediments, especially the Cretaceous marine transgressions in the interior of North America (e.g. Lane, 1963; Curray, 1964; Franks, 1980). Andrews (1978) suggests that, although the origin of these transgressions and regressions is different, these basic stratigraphic models can be applied to glacially-induced sea level fluctuations. Such an application will be attempted here.

Curray (1964) sought to classify ancient marine transgressions and regressions by analysing the balance between sediment input versus sea level rise or fall. His model (Fig. 2) illustrates the possible conditions leading to transgressions and regressions, and is adapted here in order to describe the different sediments that may accompany sea level changes

caused by a glacial cycle. However, a major distinction must be made between conventional transgressions and regressions, as used by Curray (1964), and marine inundations in glacierized terrain. In ice-covered areas where the glacier displaces the sea, marine incursions are directly controlled by glacial advance or retreat. In this sense deglaciation of a fiord would cause rapid marine inundation having the same effect as rapid marine transgression in Curray's model, but it is inappropriate to apply the conventional terms to this environment. Adjacent, unglacierized areas would experience transgressions and regressions in the conventional sense.

Table I indicates the possible sequence which Curray's (1964) classification may follow during a glacial cycle. In this case, the cycle begins with ice occupying the fiord. It is assumed that any preceding glaciomarine sediments are overlain by till deposited by this advance. As the ice retreats, submergence occurs within Zone I of Clark *et al.* (1978). Because the land is depressed well below sea level, a rapid marine inundation takes place simultaneously with the retreating ice margin. If the inundation rate greatly exceeds the rate of sedimentation, normal facies changes associated with marine onlap will not occur (case VII, Fig. 2). Rather, the glacial deposits (*i.e.* till) will be overlain immediately by deepwater marine deposits, and lateral facies changes will be negligible. The unconformity formed between the deeper water sediments and the underlying till is termed "overstep" (Dunbar and Rodgers, 1957).

In many fiords and valleys the above condition existed until the glaciers receded above the marine limit. However, in proglacial areas along ice free valley sides where the sea was in contact with the land, the rate of sedimentation may increase relative to the rate of transgression (case VI to V, Fig. 2) during the culmination of the glacial cycle. If both of these rates remain high, the material supplied could have been redistributed parallel to the shoreline by waves and currents. Currently, in some High Arctic areas, however, open water is limited by landfast sea ice, and thus wave action is weak and limited to the short summer season. Such conditions may have been more widespread during a glaciation. Given some littoral processes, the coarsest material would be found near shore, fining seaward. As this type of transgression

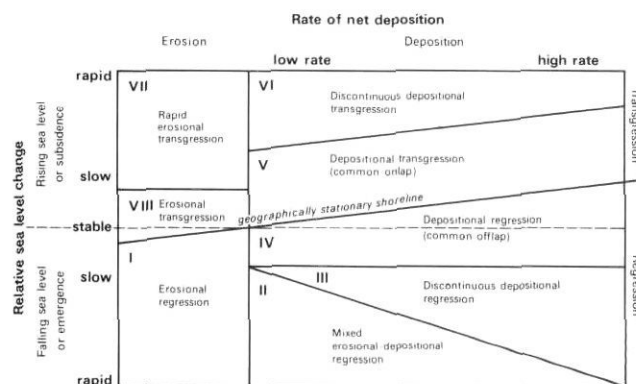


FIGURE 2. A classification of transgressions and regressions (after Curray, 1964).

Classification des transgressions et des régressions selon Curray, 1964.

TABLE I
 Classification of a transgression and regression that
 occurs during a glacial cycle

Classification (Curry, 1964)	Glacial Cycle	Conditions	Results
—	Glacial	Ice occupying fiord	Glacigenic deposition
VII	Deglaciation	Submergence >> Sedimentation	Overstep marine over glacial deposits
VI*†		Transgression > Sedimentation	Thin veneer of littoral sands overlain by discontinuous marine sediments
	Decreasing ice load		
V*†	(approaching marine limit)	Transgression ≥ Sediment supply	Marine onlap
VIII*	(of short duration)	Geographically stable coast	Marine limit reached
I	Uplift = Eustatic sea level rise	Emergence >> Sedimentation	No beaches, dissection of uplifted marine sediments.
Isostatic Zone I		Sea level rise < Uplift	
	II*	Emergence > Sedimentation	Mostly wave cut beaches, regressive strandline
	III		
	Decreasing rebound		
		Emergence ≥ Sedimentation	Marine offlap, regressive beaches, delta building
Isostatic Zone I/II	VIII	Net erosion from wave action, local subsidence from compaction	
	V	Collapse of the forebulge	Marine onlap

* shorelines may be preserved

† areas beyond the glacial limit

proceeds the littoral facies would shift landward resulting in a common marine onlap sequence recorded in the sediments. Nonetheless, the onlap sequence may be complicated if sediment is temporarily stored within sandurs and deltas during the transgression and therefore unavailable for littoral processes. In this case the water may rise over the terrestrial deposits, without the graded deposition associated with common marine onlap (Matthews, 1974).

During the establishment of the marine limit in areas beyond the glacial limit the rate of transgression decreases until it is balanced, and then overcome, by isostatic rebound due to the removal of the ice mass. During this time, there may be a brief interval when relative sea level is stable at the marine limit (case VIII, Table I, Fig. 3). Moreover, a brief transgression may follow due to net erosion by wave action or local subsidence due to compaction of sediments. However, it has been demonstrated that the rate of postglacial emergence in the Arctic, within the glacial limits, is initially very rapid and then logarithmically decreases to the present (cf. Andrews, 1968; Blake, 1975). These conditions of initial emergence would be represented by case I (Fig. 2). Here, the initial rate of emergence would be very rapid relative to the rate of sedimentation. Under these conditions the expected seaward shift of coarse terrigenous facies would be discontinuous. Following emergence, areas at the head of the fiord would

be mantled by fine marine sediments which lack a cover of the coarser offlap facies. These exposed marine sediments would be subject to gullying and deflation, moreover, no littoral facies marking past strandlines would be present.

As the rate of emergence decreases through time, the rate of sedimentation will eventually balance the rate of emergence. Initially only wave-cut strandlines would form (case II, Fig. 2); however, they would soon be succeeded by depositional beaches as a normal seaward progression of coarse terrigenous facies occurred (marine offlap, case III to IV, Fig. 2). Furthermore, if the supply of sediment remained high a depositional regression would occur because of rapid progradation by deltas. Although the most pronounced phases of delta building would be expected during times when the rate of emergence approaches zero, in Arctic areas these periods are generally coupled with greatly reduced sediment supply due to diminished glaciers.

If the zone I/II transition of Clark *et al.* (1978) is encountered within the fiord, a condition of limited submergence may occur (case VIII). Although case VIII submergence in Curry's model is due to the compaction of sediments or net wave erosion, the same sequence could result from Clark *et al.*'s (1978) forebulge collapse.

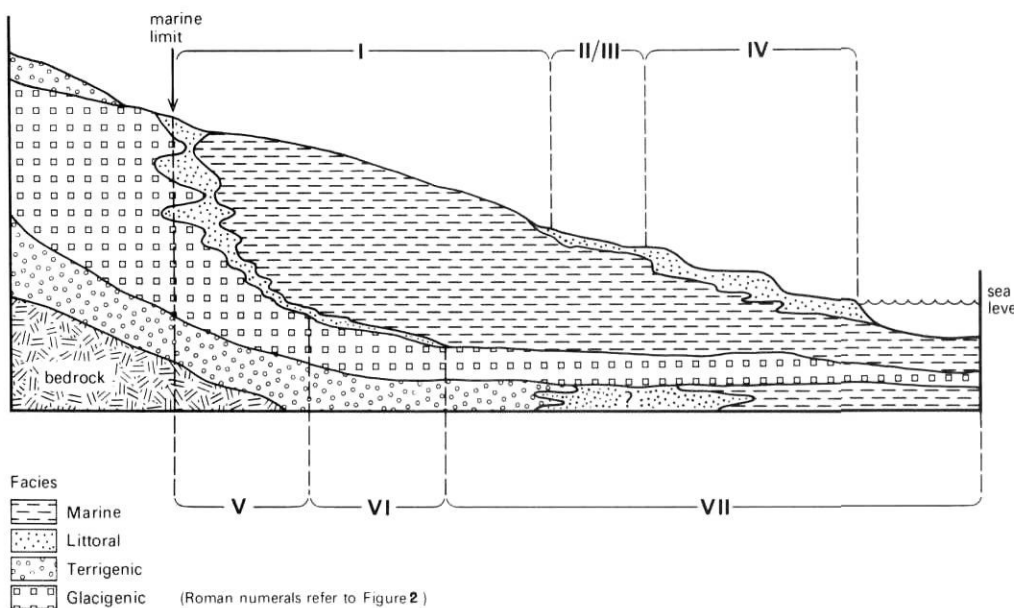


FIGURE 3. A schematic section along an Arctic fiord following a glacial cycle. Unglacierized areas experience conventional transgression/regression (e.g. case V and VI) that are absent in areas where retreating glaciers contact the sea.

Schéma d'une coupe le long d'un fjord arctique à la suite d'un cycle glaciaire. Les zones libres de glace subissent les transgressions et les régressions courantes (les cas V et VI) que ne connaissent pas les zones où le glacier en retrait est en contact avec la mer.

MODEL OF GLACIOMARINE STRATIGRAPHY

The stratigraphic sequences expected in an Arctic fiord during a glacial cycle are shown in Figure 3. This diagram attempts to describe the succession of deposits within a fiord. However, variation in Figure 3 will occur depending on which side of the glacial limit it is applied. Behind the glacial limit, usually at the fiord head, case V and VI describing transgression to the marine limit, is not expected. Given the instantaneous nature of inundation to the marine limit case VII will dominate. Short term case V and VI may exist very near the marine limit, but at a much smaller scale shown in Figure 3. Moreover it is evident that some deposits may contain complex assemblages of grain size, sorting, and sedimentary structures that cannot be readily accommodated by such a large scale model. In general, Figure 3 disregards the variability in sediment supply from one area to the next, as well as temporal fluctuations in sediment output from the glaciers. Another limitation to the model is that it only considers a single glacial cycle. Should there be a more complex glacial history (*i.e.*, multiple glaciations), the isostatic and eustatic responses would also be more complex. Lastly, as pointed out by Andrews (1978), there is an intrinsic problem of coarsening or fining-upward sequences in glacial fiords. For example, the nature of the sediment will change not only with the depth of water, but also with its proximity to a glacier. At least three conditions can produce a coarsening-upward sequence: i) an approaching glacier, supplying increasingly coarser sediments; ii) falling sea levels; or iii) rising sea level with very high sediment input (Matthews, 1974).

By outlining the major factors controlling fiord sedimentation during a glacial cycle some insight can now be provided on the past depositional environments of Clements Markham Inlet. An important benefit of this model is that it anticipates complications which may be encountered in the field as well as providing an explanation of the spatial distribution of glaciomarine facies. For example, it was noted that glaciomarine

sediments can be carried long distances out the fiord as well as be deposited considerable distances upvalley during glacial retreat. Therefore, recognizing the correct sedimentary environment for deposits below the marine limit becomes important (*e.g.*, esker sands versus littoral sands). In addition, lateral gradation of facies and interlayering facies may be expected in specific areas of the fiord. For instance, one would not expect to find evidence of former strandlines in areas of extensively gullied marine silts. The surface silts themselves indicate an extremely rapid regression. Furthermore, if certain stratigraphic relationships can be recognized, such as an overstep sequence, the model can provide constraints on the conditions that prevailed (*e.g.*, fast or slow glacial retreat), and aid further stratigraphic interpretations of the fiord deposits.

APPLICATION OF THE MODEL TO CLEMENTS MARKHAM INLET

The last glaciation in Clements Markham Inlet culminated with the inundation of the inlet head by a major trunk glacier which terminated in the sea (Bednarski, 1984, 1986). At this time much of the outer inlet was ice free except at the mouths of tributary valleys where smaller glaciers debouched into the sea. Slow deglaciation began at ca. 11 ka BP and continued until 8 ka BP, during which time sea level dropped from 124 m to 104 m asl. After 8 ka rapid deglaciation of the fiord head occurred, which was coupled with marine transgressions up to 10 km inland from the present coast (Fig. 4). Consequently, the emergence after 8 ka BP was also rapid and of similar pattern as in other recently deglaciated areas in the Arctic (*cf.* Andrews, 1978; Blake, 1975). Most of the chronological control for the above sequence was provided by dating marine mollusks and driftwood found within the raised marine deposits.

Given the present distribution of surficial materials (Fig. 4) and logged sections, the model (Fig. 3) can be applied to Clements Markham Inlet. However, a qualification must first

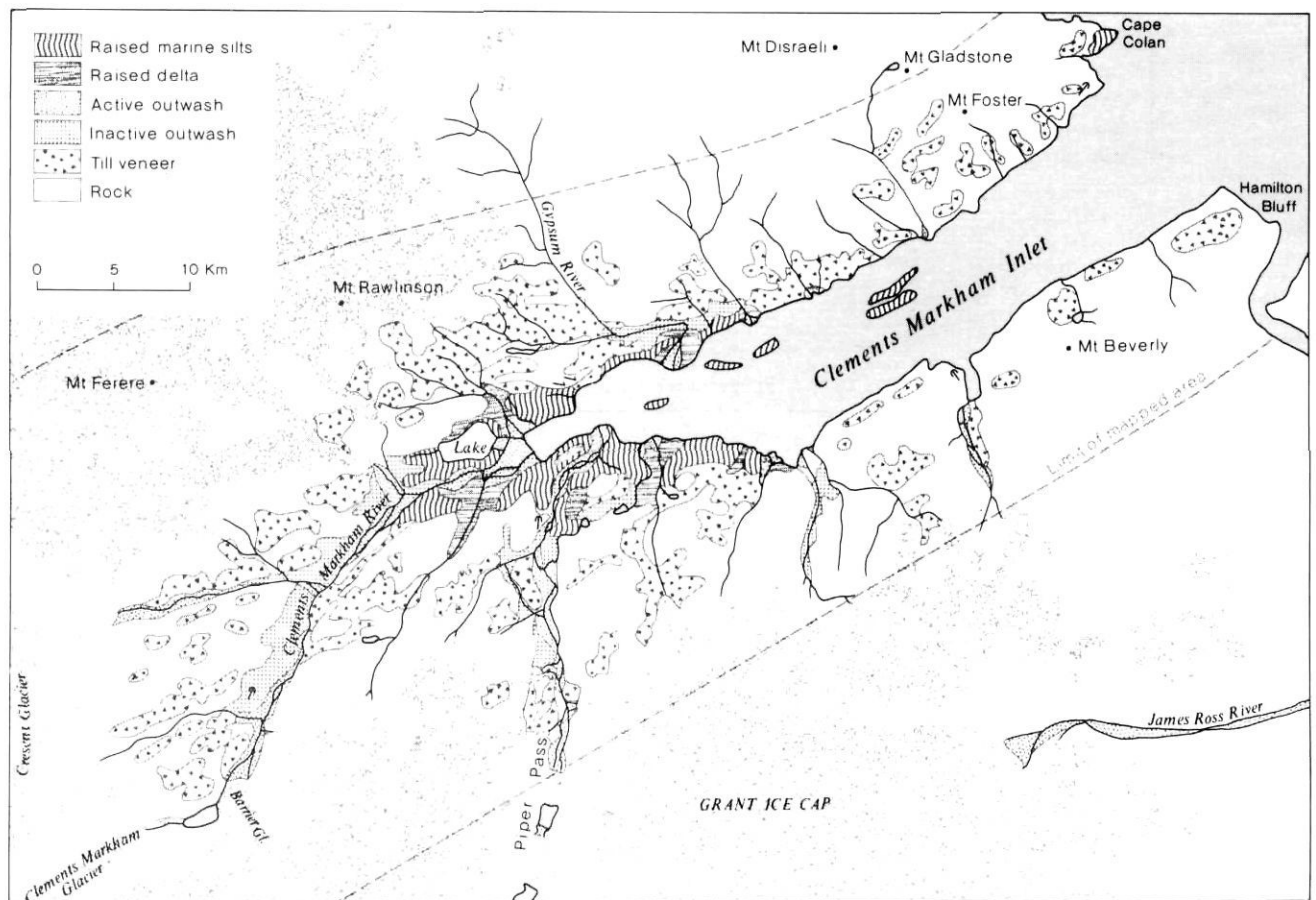


FIGURE 4. Generalized map of surficial materials in Clements Markham Inlet (reproduced with the permission of the NRC Research Journals).

Carte générale des matériaux de surface, Clements Markham Inlet (droit de reproduction accordée par la direction du Conseil national de la recherche)

be made to the model because Clements Markham Inlet was not totally inundated by ice along its entire length and many areas remained ice-free throughout the last glaciation. In areas where raised glaciomarine sediments were deposited beyond the ice limit case VII, shown in Figure 3, may not occur. In fact, one would expect these unglaciated areas to have experienced a slow transgression to the marine limit as the nearby ice load accumulated. Based on the model, this slow rate of transgression should enhance the preservation of shorelines beyond the ice limit. However, this may be offset by a lack of sediment input because of the minor amounts of meltwater produced by a restricted ice cover in the outer part of the inlet. This direct relationship between sediment production, fluvial transport, and upvalley glaciers is readily apparent in the present landscape, as well as during the last glaciation (Fig. 4). Evidence for the initial marine transgression into these outer areas comes from units of fine-grained marine sediment which overlie either bedrock or locally derived colluvium. These sediments settled out of suspension probably as the sea approached the marine limit during the glacial maximum. The glacial maximum in the outer inlet was marked by a high relative sea occupying the proglacial isostatic depression (full glacial sea of England, 1983). This condition may have been stable for several thousand years as the last glaciation cul-

minated. This lengthy interval with a stable sea level would have allowed for considerable sedimentation to occur near the marine limit and maximum progradation of outwash would have been concentrated at the mouths of glaciated tributary valleys. This is particularly evident along the northwest shore of Clements Markham Inlet where shorelines from the full glacial sea can be traced continuously from 124 m asl, near the ice limit, to 92 m asl at the mouth of the inlet (Fig. 5).

The model (Fig. 3) becomes more applicable landward of the ice limit where the marine transgression was coupled with ice retreat. The main areas discussed are the lowlands at the head of the inlet and the mouths of the larger tributary valleys (Figs. 4, 6). Large contemporary sandurs incise plains of fine-grained marine deposits which are, in turn, bordered by large raised delta complexes centered on the mouths of valleys. Glaciofluvial deposits and moraines are common farther up the valleys (Fig. 4); however, the most impressive deposits in the area are the fine-grained marine sediments which lie along the perimeter of deltas and in the central lowlands (Fig. 6). These delta sediments are composed of horizontally stratified silts and fine sands, individual units are 5 to 20 m thick and have been extensively gullied in post-glacial time forming spectacular badland topography (Fig. 6).

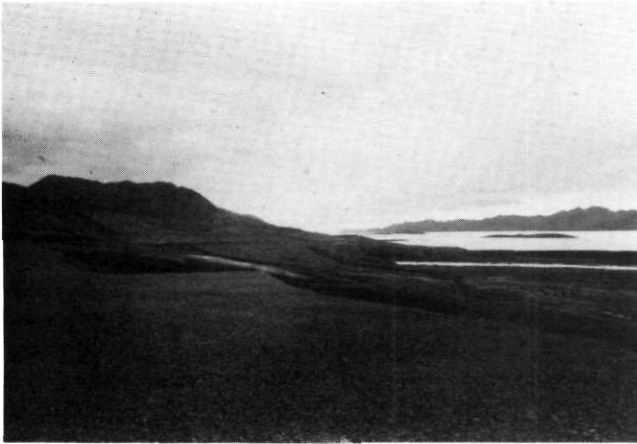


FIGURE 5. The uppermost strandline marking the full glacial sea along the northwest shore of Clements Markham Inlet. The view is to the northeast toward the Arctic Ocean. Relatively small glaciers flowed out of the valleys from the left and debouched into the sea.

La ligne de rivage supérieure montre le niveau de pleine mer glaciaire le long de la côte nord-ouest de Clements Markham Inlet. La vue donne au nord-est, vers l'océan Arctique. Quelques glaciers relativement petits se sont écoulés des vallées pour se jeter dans la mer.



FIGURE 6. The lowlands of the head of Clements Markham Inlet. Note the extensively gullied marine silts and fine sands (5 to 20 m thick) which were truncated by the contemporary Clements Markham River sandur. An ice-contact terrace which prograded into a 100 m relative sea is in the right centre of the photograph.

Les basses terres à l'embouchure de Clements Markham Inlet. À noter les silts marins et les sables fins très ravinés (5 à 20 m d'épaisseur) tronqués par un dépôt de sable d'épandage contemporain de la rivière Clements Markham. Une terrasse de contact glaciaire a progressé jusqu'à la mer dont le niveau était alors de 100 m au dessus du niveau actuel (centre droit de la photo).

The areas landward of the ice limit were rapidly deglaciated after 8 ka BP (at least $7 \text{ km } 100^{-1} \text{ yr}$; Bednarski, 1984). The initial marine transgression which occurred during deglaciation is recorded in numerous sections. These sections are compared with Figure 3 to give an indication of the conditions that prevailed.

One of the most illustrative sections in the central lowlands is shown in Figure 7. This particular section is exposed along the north side of the Clements Markham River where it is about 4 m high and extends for about 4 km. The section consists of orange-weathering, limestone breccia and gypsum overlain by a till which is, in turn, overlain by horizontally bedded silts. The contact between the bedrock and till is abrupt and the bedrock has a smooth, undulating surface. Some of the bedrock was sheared and partially incorporated into the base of the till. The contact between the till and overlying silts is sharp and conformable (Fig. 8). Occasional thin bands of gravel, silt, or fine sand form discontinuous beds within the upper parts of the till and may suggest minor interaction between the two units, perhaps when the till was in a highly saturated state during the initial transgression or as the thinning glacier began to lift from its bed during retreat. For the most part, the uppermost marine sediments are undisturbed and lie in horizontal beds. The sediments contain few dropstones; nonetheless, erosion has concentrated the dropstones to form a lag of angular rock debris.

When comparing this section to the model (Fig. 3) we see that an overstep condition occurs between the till and the

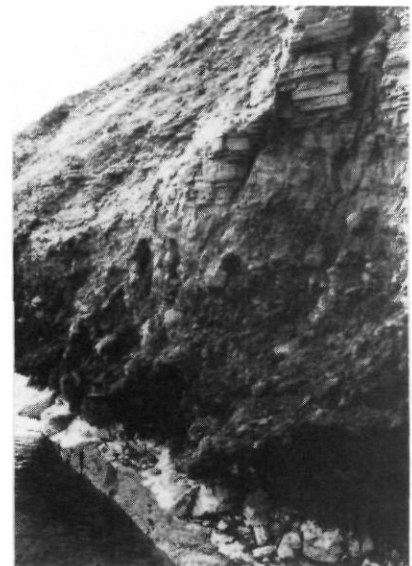


FIGURE 7. An illustrative section in the central lowlands of Clements Markham Inlet. Light toned gypsum bedrock at the base of the section is overlain by 3 m of till, which in turn is overlain by horizontally laminated silt and fine sand.

Coupe dans les basses terres centrales de Clements Markham Inlet. À la base, la roche en place composée de gypse pâle est recouverte de 3 m de till, lui-même recouvert de silt et de sable fin laminés à l'horizontale.



FIGURE 8. Detail of the overstep conditions between the till and the overlying marine sediments shown in Figure 7. The till has a dominant fabric in the down-fjord direction to the right.

Détail du contact, illustré à la figure 7, entre le till et les sédiments marins les recouvrant. Le till montre une nette orientation vers l'aval du fjord, à droite.

overlying silt (case VII). In this case, the Curray model indicates that the rate of transgression greatly exceeded the rate of sedimentation, however, in the glacial situation inundation to depth was instantaneous making the rate of sedimentation insignificant. Given the location of this section this is not too surprising. The central lowlands at the head of Clements Markham Inlet were subject to rapid deglaciation as the main glaciers calved back in over 100 m of water.

The overstep sequence was also found on the floor of some of the tributary valleys where a similar style of deglaciation occurred. However, in some sections, till underlying the marine sediments was not found. The overstep is characterized by glacially polished and striated bedrock being directly overlain by the marine silts and fine sands. The absence of the till may be due to a combination of factors which include: relatively clean basal ice; erosive bottom currents; and/or calving icebergs which transported the englacial debris away from the immediate area.

As the land became ice free, the sea reached the marine limit; however, accelerating postglacial uplift caused the sea to regress soon after deglaciation. Although the section should contain regressive sediments overlying the fine-grained marine sediments, only relatively deep water marine sediments form the uppermost unit of it (Fig. 7). In fact, the fine-grained marine deposits are the dominant surficial deposit of this area. These sediments are found up to 90 m above present sea level, yet no regressive deposits overlie them. Figure 3 suggests that surfaces which display fine marine sediments were subject to rapid regression during a time of little sediment input (case I; Fig. 3; Table I). Indeed, these areas, being distant to the sediment sources, received mainly fine-grained sediment, probably from suspension. Moreover, a rapid regression is suggested by the postglacial emergence measured at the head of the inlet just after 8 ka BP. In fact, given the gentle slope of the inner lowlands, initial seaward migration of the shoreline could have been at a rate of 3-7 km/yr⁻¹. Clearly, there was insufficient time for coarser littoral facies to be



FIGURE 9. An ice-contact delta located behind the ice limit at the head of Clements Markham Inlet. The terminus of the glacier occupied the mouth of the valley (just off the right centre of the photograph) as coarse sediment prograded into a relative sea level at 104 m. Simultaneously, fine sediment accumulated in the more distal areas of deeper water. Subsequent emergence resulted in successively lower delta terraces to be built over the fine sediments as the mouth of the river migrated seaward (from the centre, to the left).

Delta de contact glaciaire localisé derrière la limite glaciaire à la tête de Clements Markham Inlet. Le front glaciaire a occupé l'embouchure de la vallée (centre droit de la photo), pendant que les sédiments grossiers progressaient vers la mer dont le niveau relatif était de 104 m. Pendant ce temps les sédiments fins s'accumulaient dans les parties plus éloignées en eau profonde. L'émersion subséquente a donné une succession de terrasses deltaïques peu élevées mises en place au dessus des sédiments fins, pendant que l'embouchure de la rivière se déplaçait vers la mer (du centre vers la gauche).

deposited over marine silts and sands, especially in the central areas which were several kilometers from the major sediment influxes at the glacier termini (Figs. 4, 6).

Proximal to the ice limit, prominent shorelines have developed in only two general areas: 1) at the mouths of valleys; and 2) near the present coastline at low elevations. Clearly, in the former case the sediment was being produced by upvalley glaciers and concentrated in the valley bottoms by meltwater. Here the rate of sediment influx overcame the initially rapid fall in sea level. This commonly resulted in raised deltas whose uppermost terraces mark the marine limit and that contain numerous ice-contact features immediately upvalley. As noted previously relative sea level may remain stationary for a brief interval of time right at the marine limit. During subsequent emergence, numerous lower delta terraces prograded out into the falling sea. Discrete pulses of progradation were probably controlled by minor changes in the glacioclimate (Fig. 9).

In areas removed from any immediate sediment source, shorelines are found only at lower elevations near the present coastline. These shorelines formed in the later part of the Holocene when the rate of sea level fall greatly diminished and littoral processes had time to act. This is demonstrated in Clements Markham Inlet on many slopes below the marine limit where the geomorphic expression of the surface changes with elevation. The upper slopes are usually mantled by a uniform blanket of fine-grained marine sediments lacking any



FIGURE 10. Although well exposed at higher elevations, at lower elevations the raised marines fines become increasingly covered by beach material. This is because decelerating emergence has allowed littoral processes to act. This photograph shows an increasing amount of littoral modification as the sea regressed to the present shoreline near the bottom right of the photograph.

Bien exposés en altitude, les sédiments fins sont de plus en plus recouverts de matériaux de plage avec la baisse d'altitude. Ce phénomène est la conséquence du ralentissement de l'émergence, permettant ainsi l'action des processus littoraux. La photographie montre une augmentation des entailles de sapement sur le littoral au fur et à mesure de son recul jusqu'à sa position actuelle près du bas droit de la photo.

strandlines. However, with decreasing elevation, distinct wave-cut notches have formed on the sediments which, at lower elevations, grade to depositional beaches (Fig. 10).

CONCLUSION

A comparison of the proposed model of glaciomarine stratigraphy to the known glacial and sea level history of Clements Markham Inlet indicates a broad agreement. The model explains the existence and location of some dominant surficial deposits in the study area, as well as the stratigraphic sections. However, because the model only considers a simple glacial cycle it must be applied with caution. For example, because the ice limit occurs near the head of Clements Markham Inlet, the conditions for a rapid transgression to the marine limit in the outer inlet are not met. Moreover, the sea level change between 11 and 8 ka BP does not follow the 'normal' postglacial curve, as is assumed in the model, which could result in misinterpretation of the implied sea level fluctuations. Another consideration is the high variability of conditions affecting sedimentation in Arctic fiords. For example the glacioclimatic regime of the glaciers will determine their erosive capability as well as the amount of meltwater available for sediment transport. In addition, the erodability of the bedrock can change considerably from one area of the fiord to another. Lastly, sea ice conditions in the summer will determine the effectiveness of wave action, as well as actual abrasion of the shore by the sea ice.

Finally, this model provides a possible explanation of the organization of facies in an Arctic fiord and their geomorphic expression, but it does not provide the sea level or glacial history of an area. This must be determined independently.

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