Terrace scarp deflation as a renewable source for eolian sediments in an arctic periglacial setting

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Glacial, glaciofluvial, and glaciolacustrine sediments deposited by the retreating Vibekes Glacier are being actively reworked into sand dunes and loess sheets on the tops of glaciofluvial terraces down-valley from Vibekes Glacier and Vibekes Sø. Active permafrost precludes trenching below 0.5 to 1.0 meters. However, sedimentary structures, deflationary and abrasion features in shallow and surface deposits are visible. Although an armored pavement inhibits sediment deflation on the horizontal terrace surfaces, a combination of fluvial erosion, mass-wasting, and eolian processes on terrace scarps provides a continuing source of sand- and silt-size materials for redeposition.

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Introduction

Periglacial environments have frequently been cited as contributory or pivotal to the generation of Pleistocene and older eolian deposits (Tuck 1938; Cailleux 1942; Fristrop 1952; Pewe 1955; Smalley 1966; Selby, Rains & Palmer 1974; Niessen et al. 1984). However, few studies have documented modern eolian processes and their sediments actively forming in periglacial environments. Although small in areal extent (< 10 km^2), the accumulating sand dunes and loess deposits on the terraces of Vibekes Elv (river) provide a modern example of eolian processes and their deposits. The sand and loess deposits described here are accumulating 10—20 km southeast of the present front of Vibekes Glacier in northern Hudson Land in central East Greenland at 74°5′N and 23°W (Fig. 1). Vibekes Sø (lake) is adjacent to the terminus of Vibekes Glacier. Vibekes Elv flows from the lake and courses down valley through glacial, glaciofluvial, and glaciolacustrine deposits. Numerous terraces occur at various heights on both sides of the river with the uppermost terrace being 150—200 m above the present river level. The terraces are marked by their unusually flat upper surfaces (Fig. 2). Cowie & Adams (1957) briefly described these terraces. Approximately 25 km downstream from the outlet of Vibekes Sø, Vibekes Elv converges with a valley occupied by Wordies Glacier. Northwesterly winds coming down-valley off the Greenland ice sheet predominate, although we occasionally observed up-valley southeasterly winds during our two week stay in the valley.

Description of the terraces

In this relatively short valley (25 km), Vibekes Elv has entrenched 150 to 200 m through glacial, glaciofluvial, and glaciolacustrine deposits. The glacial, glaciofluvial, and glaciolacustrine sediments that form the terraces consist of sorted and poorly sorted clay- to boulder-size materials. These sediments are mostly unconsolidated, although there is slight competency to the glaciolacustrine silt beds. The cobble- to boulder-sized material in these terraces is well to very well rounded. Approximately 35 km^2 of unconsolidated sediments at the angle of repose (=30°) are exposed along the terrace scarps. (Calculated, assuming: (1) an approximate average relief of 175 m between the valley floor and the top of the upper prominent terrace, and (2) approximately 100 km of terrace scarp surfaces along the meandering path of Vibekes Elv and its tributaries.)

Description of the eolian deposits

Two genetically distinct types of eolian deposits

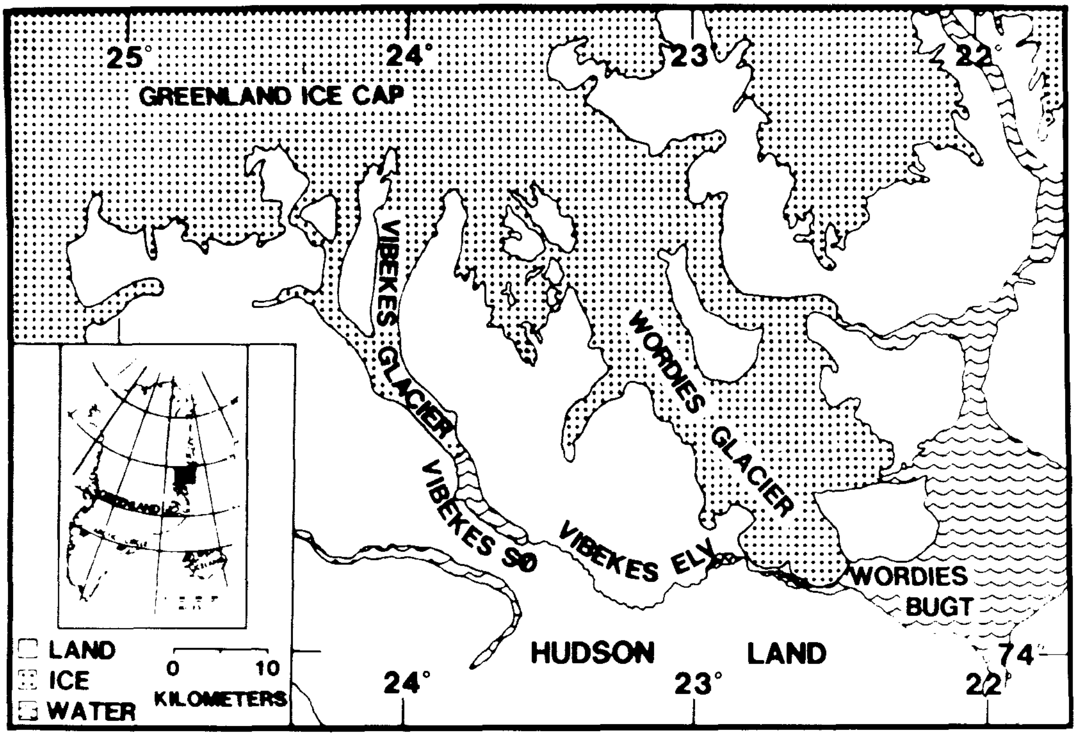

Fig. 1. Map of a portion of central East Greenland showing geographic relations of Hudson Land, the Vibekes Glacier, Vibekes So (lake), Vibekes Elv (river) and Wordies Glacier. Insert shows locality of area in East Greenland.

exist within the Vibekes Elv valley: wind-shadow, 'cliff' dunes and vegetative-baffled loess sheets. The cliff dunes are visually more prominent, but the loess sheets are probably more significant volumetrically and areally. Hobbs (1931) also observed these two types of deposits in southeast Greenland.

The cliff dunes range in size from a single large longitudinal dune nearly 0.75 km in length, 100 m wide and 20 m high (Fig. 3) to minor sand 'drifts' behind vegetated tufts (Fig. 4), or behind large boulders and cobbles. The larger dunes, restricted to terrace margins adjacent to the angle of repose scarps, appear to result from vertical eddies formed where the wind currents transport sand up the scarps shear at the horizontal terrace tops.

Sedimentary structures of the sand dunes include large-scale cross-bedding (larger than the access of our permafrost-limited excavations), ripples (Figs. 5 and 6) and surface scours (Fig. 7). Two surprises emerged from the excavations made to observe internal sedimentary structures in the dunes: (1) cross-bedding on the up-wind, erosional side of the dunes (except for a thin veneer < 1 cm) was inclined at an angle consistent with the slip face on the lee side of the dune (Fig. 8), and (2) the existence of a ~ 25 cm thick, tabular bed of snow lying 18 cm beneath the surface, but above the permafrost surface on the lee side of the largest dune (Fig. 9). The volume and distribution of snow and ice layers deeper within the dune is an interesting subject for speculation, but further investigation would require equipment more persuasive than our folding shovels to excavate through the permafrost. Slump structures on the surface of many dunes may result from melting or sublimation of such snow or ice layers within the dunes. This process should be considered as a potential cause of erratic internal structures within periglacial and perhaps northern temperate zone dune deposits. Similar snow layers and associated slumping structures have been observed elsewhere in

Fig. 2. Photo looking northwest up the Vibekes Elv valley showing the prominent and flat upper terrace level and the angle of repose scarps to present river level. Here the terrace is approximately 150 meters above river level. Some bedding within the fluvial terrace gravels can also be seen.

Fig. 3. View across the upper terrace in the Vibekes Elv valley looking to the southwest. In the distance is the largest of the observed dunes, approximately 20 m high, that sits on the edge of the erosional bank of the terrace. Closer to the photographer is a smaller longitudinal dune 2—3 m high.

Fig. 4. View of small sand 'drifts' to the lee of vegetated tufts. Entrenching tool handle is 50 cm long. Arrow indicates principal wind direction.

modern sand dunes (Selby, Rains & Palmer 1974; Ahlbrandt & Andrews 1978; Ahlbrandt & Fryberger 1982), but perhaps have been overlooked as the cause of contorted or slumped bedding structures in ancient eolian deposits.

Size-frequency distributions over the surface of the sand dunes are so variable that their analyses are judged to be non-significant. Of significance, however, are observations of the grain shapes on the dune surface. The sands were separated into 1/2 Phi class intervals, and the only grains on the stoss or lee sides of the dunes to show any degree of rounding were those larger than 0.125 mm; these were subangular. All of the grains smaller than 0.125 mm were angular to very angular. This may reflect the relatively short distance of fluvial and eolian transport and hence opportunity for abrasion, or may merely reflect the lesser susceptibility of smaller grains to abrasion (Kuenen 1960). The loess sheets, comprised principally of silt-size detritus, are mainly deposits trapped by tufted vegetation (species of *Dryas* and *Silene* constitute the major vegetative tuft builders or 'bunch plants'). Tufted vegetative surfaces (Fig. 10) occupy a considerable portion of the upper terraces and thus must trap volumes of loess far exceeding the sediment volume of the cliff dunes, albeit in a less conspicuous fashion. At one locality where a tributary stream dissected a loess deposit we observed 1 to 1.5 m of structureless loess, although some mottling and irregular ferruginous or organic staining boundaries were apparent within the loess (Fig. 11). We also observed lemming burrows on the surface, but did not see evidence of burrowing exposed in the cuts. Surficial tracks of musk oxen, fox, and birds abound, but preservation of these structures would be an unlikely event. Wind blown sand often fills the polygonal desiccation cracks that commonly exist between vegetative tufts. Surficial mud cracks are also present in several non-vegetated areas on the terrace surface, particularly adjacent to the small ponds.

Figs. 5 and 6. Views of dune surface showing ripple marks of two different sizes. Entrenching tool handle is 50 cm in each photo.

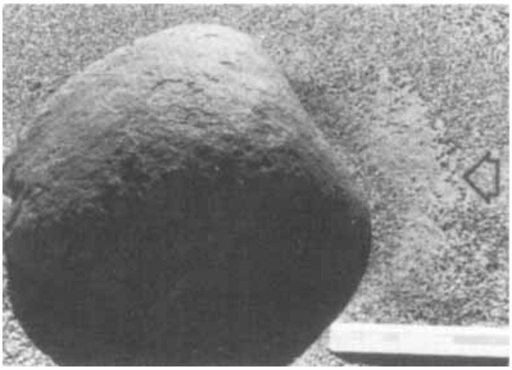

Fig. 7. A granitic cobble on the edge of the dune with a wind scoured excavation on the stoss (right) side. Scale beneath the scour structure in the photo is 3.5 cm wide. The granitic cobble is polished and incipiently fluted by sand abrasion. It also exhibits minor exfoliation on its upper surface, perhaps due to feldspar expansion during weathering. Arrow indicates principal wind direction.

Less significant are deposits of silt-sized materials trapped in the small ponds that have formed either as kettle lakes or as abandoned channels on the terrace surfaces. That this sediment is actively accumulating was confirmed by the ease with which the fine sediment was stirred into suspension during a brief excursion into one of the ponds to bathe.

Deflation and abrasion features

A deflated and abraided armored pavement (Fig. 12) veneers virtually all of the terrace surfaces that are not covered by low vegetation (commonly clumped as 'bunch plants') or covered by water (the small ponds in abandoned channels or kettles). In a similar environment in southeast Greenland, Hobbs (1942) reported the deflation of dust, sand and smaller pebbles from outwash plains to form an armor of pebble pavement that protected the materials below from further deflation. In areas of active eolian sand transport, the pebbles, cobbles, and boulders exhibit highly polished surfaces and often show preferential removal of weathered rinds on the windward (generally up-valley) side (Fig. 7). Many of the rounded cobbles and boulders on the terrace surface show in situ frost shattering (Fig. 13) that produces modifications of clast shapes on the surface. Examination of cobbles and boulders buried within the terraces indicates that the frost shattering occurs only on the upper surface of the terraces and not within the buried gravels. Faceting, fluting, and polishing of the pebbles, cobbles, and boulders on the armored pavement are common and well developed. Limestone clasts exhibit the highest degree of faceting and fluting, but even granite (Fig. 14) and quartzitic cobbles show discernible fluting. We observed multi-faceted wind-polished and fluted cobbles. It is unclear whether eolian abrasion generated the facets, or if merely eolian abrasion of fracture-formed facets produced them.

An interesting type of eolian faceting, though of dubious geological significance, occurs where clumped vegetation (bunch plants) has trapped eolian sediments. Erosion of these clumps has produced 'facets' on their stoss sides much like the cobbles and boulders elsewhere (Fig. 15).

Geomorphic processes and hypotheses of dune formation in the Vibekes Elv valley

Although Vibekes Elv presently flows along the southwest flank of Wordies Glacier to the fjord

Fig. 8. Cross-bedding in the slip-face of a dune that is parallel or sub-parallel to the surface of the dune. Painted dark and white intervals on the monopod are 10 cm each.

Fig. 10. View of irregular tufted vegetation on the upper terrace. The 'bunch plants' serve as an effective baffle to trap silt-sized sediment over large areas of the terrace. Individual tufts are approximately 10 cm high.

Fig. 9. Excavation into the slip face of the largest dune that exposes a tabular snow layer 25 cm thick beneath 18 cm of sand. Bedding structures within the snow as well as the sand indicate that both the snow and the sand were prograded by eolian deposition on the lee side of the dune. Thin sand laminae within the snow further suggest that at the time the snow was being added to the dune, the snow cover was probably relatively thin so that both snow and sand surfaces were being deflated.

Fig. 11. Scraping of an erosional bank in the loess reveals faint irregular and cross-cutting ?Liesegang color mottling. Some of the organic or ferruginous stains cross-cut faint bedding planes.

at Wordies Bugt, the terraces and lacustrine sediments observed in the lower Vibekes Elv valley offer convincing evidence that Vibekes Elv was, at one time, dammed by the Wordies Glacier to form a lake. This lake not only caused deposition of the glaciolacustrine sediments seen in the lower portions of the valley, but persistent lake levels, determined by the Wordies glacial dam, were also apparently the base level control for the prominent glaciofluvial terraces throughout the valley. Ephemeral standstills and periodic lowering of the Wordies glacial dam appear to have produced the prominent upper terrace and several minor terrace levels (Fig. 16).

Thick glacial, glaciofluvial, glaciolacustrine and tributary fan deposits composing the broad terraces in Vibekes Elv constitute the immediate provenance for the modern eolian deposits. The ultimate bedrock source of the sediments is glacial and fluvial erosion of a diverse suite of igneous, metamorphic and sedimentary rocks of Archean, Proterozoic, and Phanerozoic age. Schists, slates, phyllites, granites, gabbros, dolerites, sandstones, conglomerates, cherts, limestones, and dolostones are all prominent lithoclast types in the cobble- to boulder-sized detritus of the terraces.

Katabatic winds that cascade southeastward down from the Greenland ice sheet (Fig. 17) are reworking the finer-grained terrace sediments into cliff dunes and loess sheets. The cliff dunes appear to result from both vertical and horizontal wind eddies with steady progradation and progressive thickening of the eolian sand deposits through time.

The derivation of eolian sediments from poorly sorted glacial and periglacial precursor sediments poses an enigma. The eolian deposits or a densely packed lag deposit of pebbles, cobbles and boulders (i.e. an armored surface) veneer the upper terrace surfaces. Therefore, except for reworking, the upper surfaces of the terraces cannot now be providing a sediment source for the eolian sand and loess. In this setting, modern deflation processes acting on the terrace gravels would seem to be self-inhibiting because of the armored pavement.

Periodic advance and retreat of the glaciers might expose fresh surfaces of unwinnowed materials, but would readily erode the unconsolidated materials in the valley and, almost certainly, would rework and modify the eolian deposits beyond recognition. The outlet of Vibekes Sø appears to be morainally dammed with no discernible outwash that might serve as a source of sand and/or loess. Direct observations of the processes currently operating in the valley of Vibekes Elv, however, offer fresh insight into a renewable source of deflatable sand- and silt-sized sediments. During our stay in the valley, the suspended air-borne sediment was often so thick as to obscure visibility, and near the terrace scarps the saltating sand was intolerable. Of tangential interest during these dust storms was that, if the day was sunny, one could observe the reflections of light from the cleavage planes of fine micas (mainly muscovite) that were suspended in the air.

Fluvial erosion of the thick gravel deposits by the present course of the Vibekes Elv has produced vast exposures of angle of repose gravel slopes adjacent to the river. As wind deflates the finer particles (sand, silt, and clay) from these angle of repose surfaces, the pebbles, cobbles, and boulders roll downslope and accumulate at the base of the slope rather than remaining as a lag on the steeply inclined surfaces. Cowie & Adams (1957), referring to material cascading down these slopes, stated that it includes 'large boulders which, in the spring, can bowl at speed across the frozen river to the diversion of those who use it for sledging'. To an observer standing on the terrace cliff edge during the strong katabatic wind storms there is little doubt that sand-, granule-, and pebble-sized materials are being transported up the scarp faces and onto the upper terrace. Meandering and lateral cutting by the river at its erosional level remove the coarse clasts from the bases of the slopes, and the process continues to slowly broaden the valley floor. Thus, the combined processes of lateral cutting by the river and mass wasting of the coarse detritus down the angle of repose slopes generate renewable and abundant sources of deflatable detritus to form the eolian deposits of Vibekes Elv.

Summary and conclusions

In the periglacial valley of Vibekes Elv in northern Hudson Land, central East Greenland, retreat of the Vibekes Glacier, probably during the last 6000 years, coupled with damming of the valley by a convergent glacier has left thick deposits of glaciofluvial and glaciolacustrine sediments as prominent terraces on either side of the valley. Deposition and subsequent incision of these terraces by the river have produced vast areas of angle of repose slopes that are subject to deflation by present day katabatic winds. The deflated material derived from these scarps is being redeposited both as sand dunes and as vegetative-bound loess deposits on the tops of the terraces. The observed complimentary mechanisms of fluvial erosion, mass wasting, and deflationary processes acting on these scarps provide a constantly renewable source of fine sediment. The horizontal surfaces of the terraces are inhibited from deflation by the armored pavements.

Fig. 12. Surface of the terrace in a deflated area showing the coarse desert pavement of mixed lithologies. Fluting and polishing of the pebbles and cobbles are apparent. Scale at lower right is 3.5 cm wide.

Fig. 15. Eolian faceting of a vegetative tuft. The consistent orientation of these 'facets' indicates that they are the product of eolian abrasion. Height of tuft is approximately 15 cm. Arrow indicates principal wind direction.

Fig. 13. Photo of a partly buried dolomitic siltstone on the upper terrace surface showing in situ frost shattering of the cobble into flakes parallel to the bedding. Scale at upper left is divided into cm.

Fig. 16. View across Vibekes Elv showing the multiple erosional terrace levels formed during ephemeral 'stand-stills' in the lowering of the glacial dam at the confluence of the Vibekes Elv and the Wordies Glacier.

Fig. 14. A partly buried granitic cobble on the deflation surface of the upper terrace showing fluting of the stoss side by eolian abrasion. Scale is 17 cm long. Arrow indicates principal wind direction.

Fig. 17. Photo across the Vibekes Elv valley on a mildly windy day showing the wind-born sand and silt moving from right to left down-valley (southeastward). At times the sediment cloud reached heights of several hundred meters. Arrow indicates principal wind direction.

The integration of complementary erosional and mass-wasting processes to provide a mechanism for generating continually deflatable sediments merits consideration as an explanation for other modern, Pleistocene, or older periglacial eolian deposits.

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