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Article

Glacial landscape evolution in the Uummannaq region, West Greenland
TIMOTHY P. LANE, DAVID H. ROBERTS, COLM Ó COFAIGH, BRICE R. REA, ANDREAS VIELI

The Uummannaq region is a mosaic of glacial landsystems, consistent with hypothesised landscape distribution resulting from variations in subglacial thermal regime. The region is dominated by selective linear erosion which has spatially and altitudinally partitioned the landscape. Low altitude areas are dominated by glacial scour, with higher elevations are dominated by plateaux or mountain valley and cirque glaciers. The appearance and nature of each landscape type varies locally with altitude and latitude, as a function of bedrock geology and average glacial conditions. Selective linear erosion has been a primary control on landscape distribution throughout Uummannaq, leading to plateau formation and the growth of a coalescent fjord system in the Uummannaq region. This has allowed the development of the Uummannaq ice stream's (UIS) onset zone during glacial periods. Fjord development has been enhanced by a down-stream change in geology to less-resistant lithologies, increasing erosional efficiency and allowing a single glacial channel to develop, encouraging glacier convergence and the initiation of ice streaming. The landscape has been affected by several periods of regional uplift from 33 Ma to present, and has been subject to subsequent fluvial and glacial erosion. Uplift has removed surfaces from the impact of widespread warm-based glaciation, leaving them as relict landsurfaces. The result of this is a regional altitude-dependant continuum of glacial modification, with extreme differences in erosion between high and low elevation surfaces. This study indicates that processes of long-term uplift, glacial erosion/protection, and spatial variability in erosion intensity have produced a highly partitioned landscape.

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Ice sheets have played a major role in mid to high-latitude landscape evolution throughout the Quaternary. The geomorphological features of these regions develop due to spatially variable ice sheet erosion and deposition over multiple glaciations. This glacial erosion creates a patchwork of different landscapes. Each landscape is defined by regional associations of erosional landforms, classified based upon morphology and inferred process of erosion (e.g. Linton 1963; Sugden 1974; Sugden & John 1976; Gordon 1981). Such landscapes record the influence of both changing glaciological conditions (e.g. subglacial thermal regime, mass flux) and external factors such as geology and topography (Benn & Evans 2010). As a result of their long-term history, landscapes of glacial erosion will broadly relate to average glacial conditions over multiple glacial cycles (Porter 1989). However, the development of subglacial thermal mosaics beneath ice sheets can lead to landscape preservation beneath cold-based ice, and widespread, intensive erosion beneath warm-based ice (see Kleman *et al.* 2008; Stroeven & Swift 2008; Swift *et al.* 2008; Di Nicola *et al.* 2009; Strasky *et al.* 2009). This process can explain the juxtaposition of over-deepened troughs and relict plateau surfaces (selective linear erosion) that are common in coastal regions bordering ice sheets, for example in Greenland, Norway, and the Canadian Arctic (Sugden 1974; Kleman & Stroeven 1997; Hall & Glasser 2003; Kleman & Glasser 2007; Swift *et al.* 2008). In recent years, the importance of ice streams in ice sheet dynamics and landscape evolution has been recognised (e.g. Angelis & Kleman 2008; Winsborrow *et al.* 2010), although the factors controlling initial ice stream inception remain poorly understood. Topography is clearly influential though we know little of the pre-glacial topography of many regions despite recent advances in imaging the bed of Greenland and Antarctica (Bamber *et al.* 2013; Fretwell *et al.* 2013). Fjords which have formed through selective linear erosion may act as conduits for ice streams by inducing outlet glacier convergence and ice flow acceleration through drawdown (Lowe & Anderson 2002; Ó Cofaigh *et al.* 2002; Ottesen *et al.* 2008; Roberts *et al.* 2013).

Although narrow, the ice-free rim of Greenland is an ideal location in which to investigate glacial landscape and ice stream evolution. Seminal work by Sugden (1974) categorised and mapped the distribution of glacial landscapes throughout Greenland, for example, identifying landscapes formed through selective linear erosion and areal scour. However, there has been relatively little research on glacial landscape evolution since that time. Swift *et al.* (2008) explored the influence of ice streaming and geology on fjord development in East Greenland and recent radar surveys and ice surface inversion techniques have imaged the ice sheet bed, but our knowledge of ice sheet influence on landscape development remains poor. The majority of palaeo-ice sheet research in Greenland has focused on ice sheet extent and behaviour at the Last Glacial Maximum (LGM) and during previous glaciations (e.g. Funder & Hansen 1996; Bennike & Bjorck 2002; Weidick *et al.* 2004; Håkansson *et al.*

2007a; Håkansson *et al.* 2007b; Roberts *et al.* 2009; Roberts *et al.* 2010; Ó Cofaigh *et al.* 2013; Roberts *et al.* 2013; Lane *et al.* 2014).

Although heavily influenced by glaciation, the presently ice-free land surfaces of Greenland have also developed as a result of uplift, through both Cenozoic tectonics, and glacio-isostatic rebound and unloading (Small & Anderson 1998; Oskin & Burbank 2005; Egholm *et al.* 2009; Nielsen *et al.* 2009). Recently, coupled models of uplift and landscape development have been developed in glaciated regions such as Scandinavia (Nielsen *et al.* 2009; Steer *et al.* 2012; Medvedev *et al.* 2013) and West Greenland (Japsen *et al.* 2006; Bonow *et al.* 2007), providing uplift scenarios for glaciated margins which can be integrated with hypotheses of landscape development. For example, high altitude surfaces throughout the Nussuaq region and further south in Disko Bugt have been identified as remnants of two uplift surfaces which are now relict (Japsen *et al.* 2005; Bonow *et al.* 2006a; Bonow *et al.* 2006b; Japsen *et al.* 2006, 2009). Those uplift surfaces were uplifted during the Neogene, and include: an Upper Planation Surface; a Lower Planation Surface; and a low elevation re-exposed early Late Cretaceous etch surface formed in the Archaen basement (Japsen *et al.* 2005; Japsen *et al.* 2006, 2009; Green *et al.* 2011); all thought to have prior to major ice sheet build up in Greenland.

This paper investigates the impact of geology, pre-Quaternary uplift, and glacial erosion on landscape evolution and explores the factors that control ice stream onset in the Uummannaq region.

Study site

The Uummannaq region in West Greenland is characterised by fjords and steep mountains, with plateaux and summits reaching 2000 m above sea level (a.s.l.) (Fig. 1). This area is ~20 000 km^2 and bordered by the Svartenhuk and Nuussuaq Peninsulas (Fig. 1). The area is underlain by three north-south trending, fault bounded geological terranes: Precambrian (~2800 Ma) basement orthogneisses in the east of the region (Area 1 in Fig. 1) (Kalsbeek *et al.* 1998; Bonow *et al.* 2007); the Nuussuaq Basin, infilled with Cretaceous-Tertiary marine mudstones and sandstones (Area 2 in Fig. 1) (Pedersen & Pulvertaft 1992; Dam *et al.* 2000; Henriksen *et al.* 2000); and Tertiary basalts, which form Ubekendt Ejland, Svartenhuk, the western half of Nuussuaq, and extend offshore (Area 3 in Fig. 1) (Henriksen *et al.* 2000). The Uummannaq region is dissected by east-west trending fjord system which routes outlet glaciers towards the sea where they converge to form the onset zone of the Uummannaq Ice Stream System (UIS) (Ó Cofaigh *et al.* 2013; Roberts *et al.* 2013; Dowdeswell *et al.* 2014; Lane *et al.* 2014). During the LGM, ice from the north coalesced with flow from the south through the UIS onset zone. The onset zone is thought to have been situated to the southeast of Ubekendt Ejland (Roberts *et al.*

2013; Lane *et al.* 2014). This form an ice stream trunk zone in the Uummannaq trough, and reached a maximum position at the continental shelf edge (Ó Cofaigh *et al.* 2013; Roberts *et al.* 2013; Dowdeswell *et al.* 2014; Lane *et al.* 2014).

Methods

Mapping was carried out using: 1:150,000 topographic maps; geological maps (Henderson & Pulvertaft 1987); aerial photographs (Kort and Matrikelstyrelsen); and digital elevation models derived from ASTER GDEM2 imagery. The geometric resolution of the aerial images (primary tool for landform identification) is ~3 m, allowing landforms larger than this to be identified. This remote mapping was accompanied by detailed field mapping in a number of areas including: from Uummannaq island toward the ice sheet margin (see Figs 1, 4A); Ubekendt Ejland; Rink-Karrat Fjord; Ingia Fjord; and western Svartenhuk. Both individual and groups of glacial and non-glacial landforms were identified, and their location and spatial extent transferred onto a topographic base map through georeferencing and manual referencing against coastlines, lake shorelines, and mountain summits. Alongside landforms, ice limits (both ice sheet and independent glaciers) were digitised using aerial photographs.

Landscape zonation

Glacial landforms were mapped on a number of scales. Initially, macro-scale erosional forms (km to 10's of km) were mapped to delineate fjords, plateaux, and ice cap/ice sheet limits. Following this, individual meso- to micro-scale glacial landforms were mapped in the field (m-2 to m2 after Sugden & John 1976). These included bedrock bedforms such as p-forms, roches moutonnées, and whalebacks (Gordon 1981; Lindstrom 1988; Glasser & Bennett 2004). These bedrock features are common beneath warm-based ice sheets and ice streams (Roberts & Long 2005). These varied in size, elongation, and smoothness, principally in response to the geology of their host rock (Lane *et al.* 2015). Moraines were mapped, recording previous ice limits either vertically or laterally. Where possible, moraines were identified as either ice sheet or independent glacier palaeo-margins. This was done using moraine position and orientation, or clast provenance (in the field). Trimlines were mapped both remotely and in the field, and were used to delimit areas of low level glacial erosion from higher altitude regions of plateaux (e.g. Kelly 1985; Roberts *et al.* 2009), and identify englacial thermal boundaries (Fabel *et al.* 2012).

Autochthonous and allochthanous blockfields were mapped across much of the region, with frost-shattered bedrock, talus slopes and glacially derived input often completely covering the underlying material (Rea *et al.* 1996; Roberts *et al.* 2013). Blockfields are known to represent periods

of either long-term exposure under periglacial conditions, or existence and preservation under cold-based ice (Rea *et al.* 1996; Fabel *et al.* 2012). Fluvial valleys, terraces, and present-day stream channels were also mapped.

Geomorphological zones were categorised and delimited based on their mode of genesis: ice sheet; independent glacier; both; or non-glacial. Based upon this zonation and morphological setting, areas were classified into the following landscapes of glacial erosion, as defined by Sudgen (1974): glacial scour; dissected plateau; non-dissected plateau; mountain valley and cirque; selective linear erosion; and little or no evidence of glacial erosion. In addition, several areas were classified as depositional, subglacial ice marginal landform assemblages.

Results

Regional scale landscape-types

Selective Linear Erosion - The entire Uummannaq area has become a region of selective linear erosion characterised by low altitude linear bands of scoured troughs separated by high altitude plateaux harbouring cold-based ice caps or blockfield terrain (Sugden & John 1976). Throughout the Uummannaq area fjords are regularly spaced (15-20 km) and deeply incised into the Precambrian basement, and juxtaposed by intervening high level (>1000 m a.s.l.) plateau surfaces which are particularly pronounced in the north part of the study area. The inner fjords are 4.2- 6.9 km wide (at sea level) (Table 1), and 34.5 - 75.4 km in length (from current ice snout to fjord mouth). There are eleven large, marine terminating outlet glaciers that feed into these fjords (Box & Decker 2011) (Fig. 1, Table 1). The neighbouring plateau surfaces would have formed peripherally through repeated selective erosion, producing near vertical fjord walls with a maximum relief of ~3300 m (2000 m a.s.l. mountains and 1300 m below sea level fjords). Such deeply incised fjords are common in parts of Greenland and the Canadian Arctic (Briner *et al.* 2005; Swift *et al.* 2008).

Local scale landscape-types

Glacial scour - Superimposed over the regional landscape are several smaller scale glacial landscapes. Glacial scour is ubiquitous at low elevations and along fjord walls, up to at least 300 m a.s.l. South of Kangerdluarssuk Fjord it dominates the landscape up to 1000 m a.s.l. (Roberts *et al.* 2013); including high elevation, intra-fjord interfluves (Fig. 4A, C). Its distribution is more restricted in the northern Uummannaq region, limited to the base of steep fjord walls (below 300 m a.s.l.) in areas otherwise dominated by selective linear erosion (Fig. 4B, D). There is also a marked difference in the type and morphology of glacially scoured terrain between the north and south. In the south, glacially scoured

terrain is devoid of regolith and displays clearly rounded, ice-smoothed bedforms, with classic "knoc and lochan" features (Sugden 1974) such as roches moutonnées and whalebacks, interspersed with small lakes (Fig. 4C). Conversely, terrain in the north is characterised by more angular bedforms with high elongation ratios (Fig. 4D) (Lane *et al.* 2015). Bedforms are composed of angular roche moutonnées and do not resemble the smoothed "knoc and lochan" landscape seen in the south. Alongside this, glacially scoured terrain in the south shows variation with altitude; lower altitude areas (<500 m a.s.l.) display elongate (elongation ratios >2:1), streamlined bedforms whereas at higher altitudes (>500 m a.s.l.) the terrain is characterised by less elongate "knoc and lochan" topography (Fig. 4A, C).

The preferential occurrence of glacial scour in the south and dissected plateaux in the north was also identified by Sugden (1974). However, based upon the new mapping the boundary between these two landscapes is placed further north. In contrast to Sugden (1974), this study also records clear evidence for glacial scour in the north, though restricted to regions below 300 m a.s.l., at the base of steep fjord walls.

Dissected and non-dissected plateau - Dissected plateaux dominate high elevation surfaces (>1500 m a.s.l.) throughout the northern Uummannaq system (North of Qioqe; Fig. 1, 3B) and some surfaces in the south. Plateaux surfaces are part of the regional landscape and are juxtaposed next to fjords. In the Uummannaq region they are represented by both high elevation ice-free landsurfaces, and high elevation surfaces fostering cold-based icefields. They are low gradient surfaces, often covered by cold-based icefields perched on the interior remnants of plateau surfaces, feeding small valley glaciers (Fig. 3D). The amount of dissection varies throughout the entire region (Fig. 3B-D). In areas where a great amount of dissection has occurred, deep glacially eroded valleys close to sea level separate the plateaux, with valley floors typically containing extensive glaciogenic and fluvial sediments. Close to the ice sheet margin, small outlet glaciers emanate from the ice fields into small valleys. In the south of the region, plateaux are far less frequent, with only four isolated instances mapped. Where present in the south, plateaux are non-dissected and foster large ice caps, with no evidence of fluvial dissection.

Mountain valley and cirque glaciers - The majority of mountain valley and cirque landscapes are found on the Svartenhuk and Nuussuaq peninsulas (Fig. 1). Some intermittent patches of mountain valley landscapes exist on heavily dissected plateaux surfaces between fjords, but these are very restricted in distribution (Fig. 2B). Mountain valley landscapes vary in their appearance, generally characterised by small feeder valleys either containing small glaciers or ice-free. Current glaciers in the interior of

Svartenhuk and Nuussuaq are predominantly north facing and confined to the smaller upland valleys with clear depo-centres downstream. The largest glacier on Svartenhuk is 12.6 km^2, and the largest on Nuussuaq is 7.5 km^2, however the vast majority are much smaller (<4 km^2). Cirque development is prevalent on both the Svartenhuk and Nuussuaq Peninsulas, with a series of cirque basins incised into upland areas, predominantly north facing. These basins are 0.5 - 1.0 km wide, and up to 400 m in depth (from headwall summit to cirque floor). Some contain contemporary glaciers whilst others are presently ice free. Small moraines likely to represent Little Ice Age or earlier historical advances (Laursen 1944) are present on several of the cirque floors (Fig. 5A).

All of these mountain valley and cirque systems feed into larger valleys which drain to the coastline, and are currently inhabited by contemporary fluvial systems. Four such valleys dissect the southern Svartenhuk coast (Fig. 5B). They are ~3 km wide at their mouth, and 10-20 km in length, emanating from the interior of the peninsula, demonstrate a glacial morphology, and are a clear mismatch for the contemporary fluvial systems they host. For example, Tasiussaq (Fig. 5B) has a flat valley floor containing a braided stream system, with valley walls rising steeply to higher elevations on either side. There are a large number of small circular lakes up to ~500 m wide on the valley floor, connected to a well-developed salt-marsh system. The southern corner of the valley contains an extensive flat topped delta at 14 m a.s.l., overlain by a series of eskers. A series of inset lateral moraines, oriented sub-parallel to the valley's long axis, sit on higher ground (>200 m a.s.l.), providing clear evidence of ice marginal deposition from an outlet glacier sourced from the interior of the Svartenhuk Peninsula.

Landscapes of mountain valley erosion include the west of the Svartenhuk peninsula, a region previously mapped as an area of "no or little evidence of glaciation". This region is considerably lower in relief than the rest of the Uummannaq region, with altitudes reaching a maximum of ~900 m a.s.l. The topography is characterised by a series of NNW – SSE trending bedrock ridges, elevated up to 100 m above the surrounding terrain, reflecting local bedrock structure (Henderson & Pulvertaft 1987). Some previous investigation had been carried out into the glaciation of the Svartenhuk Peninsula, with Laursen (1944) observing moraines related to a restricted advance of local valley glaciers and ice caps in the peninsula's interior. This is supported by recent field observations which recorded subtle evidence of mountain valley and cirque glaciation expansion in the past, with local glaciers reaching the present coastline.

Ice marginal and subglacial depositional terrain - Two areas exhibiting ice-marginal deposition were mapped. The largest of these is found on Ubekendt Ejland (Fig. 2, 6A). The low lying saddle across the centre of the island (200-350 m a.s.l.) displays a distinct suite of depositional glacial landforms recording ice margin recession and readvance/stillstand. The landform assemblage includes three components: (1) low amplitude, fragmentary, lobate moraines deposited in crude arcuate patterns, composed of gravelly diamict, with a 'smudged' geomorphology, suggesting they have been overridden (Roberts *et al.* 2013); (2) a suite of eskers, including a large single east-west trending ridge, and a series of smaller discontinuous eskers between the subdued moraines. These are superimposed on the smudged moraines and have not been overun; (3) a series of ice-margin deltas north of the moraine system, formed during ice downwasting and retreat. A second, smaller area of ice marginal terrain is located on the southern side of the Nuussuaq Peninsula (Fig. 6B). The valley is a north-easterly extension of the large Kugssuaq valley, which bisects the Nuussuaq Peninsula. The valley floor is mantled in sediment, and dissected by a mountain fed fluvial system. At the northern end of the valley are a series of subdued, hummocky moraines which cluster to form a dissected arcuate latero-frontal moraine ridge (Benn & Evans 2010). This is likely to record an ice marginal position of a glacier from either Vaigat Fjord or the Kugssuaq valley, advancing inland.

Areas with no or little evidence of glaciation - Areas displaying little or no evidence of glaciation were mapped on the western sides of Nuussuaq, broadly concordant with an area mapped by Sugden (1974). Features of glacial erosion or deposition were not observed at the western end of the Nuussuaq Peninsula, which is characterised by a fluvial landscape. It is a relatively low elevation area (<1000 m a.s.l.), fluvial valleys incising a deep mantling of regolith. This was the only region in Uummannaq classified as showing no or little evidence of glaciation, though was not ground-truthed in the field. It sits between the reconstructed flow pathways for the Uummannaq Ice Stream and the hypothesised Vaigat Ice Stream (Ó Cofaigh *et al.* 2013; Roberts *et al.* 2013; Lane *et al.* 2014).

Discussion

Initiator conditions of fjord formation and ice stream onset

The location of the UIS and its onset zone is controlled by the position of the convergent fjord system, which is primarily a product of selective linear erosion. However non-glacial factors have also led to the development of the regional topography. These include the geological composition of the region, the initial topographic surface upon which glacial erosion is imprinted, and the region's uplift history.

Several geological factors have also been important in influencing trough evolution. The first is the shallow submarine sill, located at the boundary between the Cretaceous and Tertiary bedrock at Qeqertat Imat (Fig. 1). This shallow sill is thought to have forced active ice from the northern Uummannaq fjords south into Igdlorssuit Sund (Roberts *et al.* 2013; Lane *et al.* 2014). Secondly, Igdlorssuit Sund is a wide (13km) north-south trending trough that marks a transition from multiple small fjords into a single trough and is coincident with a Cretaceous basin filled with marine mudstones and sandstones (Fig. 1) (Pedersen & Pulvertaft 1992; Dam *et al.* 2000; Henriksen *et al.* 2000). These softer lithologies are more susceptible to both basal and lateral erosion than Archean basement rocks and Tertiary basalt and we propose that the decrease in the number of fjords into a single broad trough is geologically controlled. The development of a single channel consequently allows the establishment of a fast flowing, efficient glacial system (Augustinus 1992; Brook *et al.* 2004; Swift *et al.* 2008). This is as focusing of ice into a single channel results in glacial valley widening, and increases driving stresses and the areal extent of basal melting (Paterson 1994; Kleman *et al.* 1997). This in turn increases basal meltwater flux and hence facilitates basal lubrication and fast ice flow (Swift *et al.* 2008). Furthermore, the subsequent decrease in lateral confinement and increase in ice flow efficiency within Igdlorssuit Sund would have encouraged the drawn-down of ice from the inner fjord system, and promoted the establishment of the UIS trunk zone. This situation is not unique to the Uummannaq region. Scoresby Sund in East Greenland is also hypothesised to have evolved as result of feedback mechanisms operating between fjord morphometry, basement geology, and ice flow behaviour (Swift *et al.* 2008).

The pre-existing topography has played a critical role by determining trough morphometry and trough location. In places the inner Uummannaq fjords appear relatively sinuous and to deviate from straight paths. This has been used in previous work to suggest that the fjords represent a modification of a preglacial valley network (cf. Swift *et al.* 2008). Trough formation by outlet glacier erosion, the process on which selective linear erosion relies, is highly efficient at basal erosion and valley over-deepening, but inefficient at widening through lateral erosion (Harbor 1992). As a result, the location and sinuous nature of fjords remains close to that of the original preglacial fluvial systems. Initial fjord position is likely to have been dictated by the location of these fluvial valleys, or guided by inherent structural weaknesses within the bedrock (Bonow *et al.* 2007).

Landsurface elevation and uplift rates at the onset of, and during, glacial cycles have also been critical in influencing glacial landscape evolution in this region. The earliest evidence of glaciation from Greenland is found in ice rafted detritus (IRD) dated to 47-48 Ma (St John 2008), 38-30 Ma, (Eldrett *et*

al. 2007) and 18 Ma (Wolf & Thiede 1991; Thiede *et al.* 2011). However, the onset of extensive glaciation and permanent ice sheets is thought to have not occurred until c.3.3 Ma, indicated by an increase in North Atlantic IRD flux (Maslin *et al.* 1998; Kleiven *et al.* 2002; Bartoli *et al.* 2005; De Schepper *et al.* 2013). Based upon Japsen *et al.*'s (2009) Neogene uplift model several periods of uplift have affected the Uummannaq region during the last 3 Ma. These uplift periods have influenced the altitudinal distribution and development of glacial landscapes through the Pleistocene. Prior to glaciation, Jaspen *et al.* (2009) suggest the Upper Planation Surface (~2000 m a.s.l.) formed during two uplift events at 10.5±0.5 Ma and 4.5±2.5 Ma (Fig. 9). Following initial uplift to 1000 m a.s.l., the Upper Planation Surface was incised to base level and formed the surface which subsequently became the Lower Planation Surface. Subsequent uplifting of the Upper Planation Surface and Lower Planation Surface at 4.5±2.5 Ma raised them to 2000 and 1000 m a.s.l. respectively (Fig. 9) (Japsen *et al.* 2009).

Fluvial incision of the Upper Planation Surface and Lower Planation Surface would therefore have been spatially widespread prior to 3 Ma, preconditioning the landscape for selective linear erosion by developing preferential flow pathways for ice to follow (Bonow *et al.* 2006a; Japsen *et al.* 2006). At 3 Ma the Upper Planation Surface would have been at a height of >1000 m a.s.l. and the Lower Planation Surface somewhere close to sea-level. During initial ice sheet build-up, ice at high elevation (i.e. over 1000 m a.s.l.) would have been relatively thin, cold-based and unerosive. Only low elevation terrain (below 1000 m a.s.l.) would have been selectively eroded, with maximum erosion occurring along pre-existing topographic lows such as fluvial channels. Thus, much of the higher elevation Upper Planation Surface would have been precluded from the full effects of lowland warm-based glaciation at the opening of the Pleistocene, while the Lower Planation Surface was subjected to more intense, warm-based ice sheet erosion due to its lower elevation in the landscape and later uplift history. Throughout the Pleistocene, as uplift continued and preferential ice sheet flow and erosional feedbacks developed, the Upper Planation Surface would therefore have become rapidly relict and subject to the development of cold-based ice caps over plateaux areas. In contrast, land below 1000 m a.s.l. at the onset of glaciation would have initially been subject to intense warm-based lowland glacial activity. Gradually, post 3 Ma the intensity of erosion acting upon the Lower Planation Surface would have also decreased as it was uplifted to ~1000 m a.s.l., removing the surface from the main zones of selective glacial erosion as the ice cut downwards through successive cycles (Fig. 8, 10). In opposition to the Neogene uplift model (Japsen *et al.* 2009) an alternate theory has been proposed, which does not require two exclusively Neogene periods of uplift (Redfield 2010; McGregor *et al.* 2012). Instead a single rift event, likely to have occurred in the late Cretaceous to Palaeocene, is sufficient to explain the topographic hypsometry of the Uummannaq region.

It is also highly likely that the isostatic impact of glacial erosion has influenced the uplift of this region of West Greenland. Although this would have an impact upon the level of landsurface modification through glacial activity, such alternative uplift interpretations do not alter the model of altitudinally dependent variation in Quaternary glacial erosion (Fig. 10). Such erosion can account for up to 50% of uplift in some polar settings where protective cold-based ice at high elevations and warm-based erosive ice at lower altitudes results in enhanced erosion (Stern *et al.* 2005; Medvedev *et al.* 2008; Medvedev *et al.* 2013). Studies of this nature are complicated by the absence of knowledge of preglacial surfaces. Though the current fjord systems are thought to have exploited preglacial fluvial systems, the relief and altitude of any pre-existing surfaces are unknown. Work from relict high plateau environments in western Scandinavia demonstrate that high elevation plateaux have experienced 100 – 400 m of erosion (Steer *et al.* 2012). This is in stark contrast to previous work (e.g. Lidmar-Bergström *et al.* 2000; Bonow *et al.* 2007) which suggests selective linear erosion has been the overwhelming landscape modifier in western Scandinavia, leading to little erosion from plateau surfaces. If plateaux such as those in the Uummannaq region have experienced extensive glacial erosion and surface lowering, calculating original surface altitude and relief becomes far more difficult if total eroded sediment volumes are unknown. However, results from Roberts *et al*. (2013) suggest that high-elevation surfaces experienced minimal modification by glacial activity, at least over the last glacial cycle, and possibly over multiple glacial cycles, with dual isotope (^{10}Be/^{26}Al) results from the Nuussuaq Peninsula implying that plateau surfaces above 1200 m a.s.l. experienced minimal erosion over at least the past 120 ka (reflecting of the protection of these high level surfaces).

Glacial conditions and resulting landscape distribution

In addition to the controls exerted by geological and topographic factors in this region the development of glacial landscapes has been primarily a product of variations in glacial conditions, namely sub-glacial thermal regime. Studies of other currently and formerly glaciated areas report similar assemblages of glacial landscapes (e.g. Stroeven *et al.* 2002; Kleman *et al.* 2008; Stroeven & Swift 2008; Swift *et al.* 2008). Such studies propose that ice sheets are composed of a mosaic of warm and cold based ice including: ice streams; ice-stream tributaries; slower moving ice sheet areas; and frozen-bed patches (Kleman & Glasser 2007). Via selective linear erosional feedbacks, deep incision has generated the above mentioned trough and plateau landscape, and governs locations in which other glacial landscapes can develop by producing steep fjords and flat high altitude plateaux.

Based on present knowledge of selective linear erosion and fjord formation, we hypothesise that fjord formation in the Uummannaq region has occurred over million year timescales. Initial glacial erosion of the valley sides leads to valley over-deepening and further focusing of erosion, leading to the onset of selective linear erosion. Based upon modelled estimates, trough development is thought to occur over multiple glacial cycles at timescales of 100 ka to 1 Ma (Harbor 1992; Jamieson *et al.* 2008; Kessler *et al.* 2008) and fluvial landscapes were found to become recognisably glacial during a single 100 ka glacial cycle, with valleys becoming over-deepened and increasing trough width towards the valley terminus (Harbor 1992; Jamieson *et al.* 2008). Harbor *et al*. (1992) suggest this occurs as a result of focused erosion (up to 3mm a^{-1}), coupled with isostatic uplift resulting from crustal unloading. Other models estimated that the development of kilometre-deep fjords could be achieved over a ~1 Ma period of glacial erosion (Kessler *et al.* 2008).

Though the exact formation mechanisms of the troughs within the Uummannaq system are not known, we suggest a mechanism over the above timescales, and in line with Bonow *et al*.'s (2006a) model for the Disko Bugt region of West Greenland. Therefore, based on the period since the development of a persistent, extensive GrIS in central and northern Greenland (~3 Ma), timescales for fjord incision in the Uummannaq region to a maximum of c. 3000 m relate to an average incision rate of 1.3 mm a^{-1}. This value is an absolute minimum, calculated based on an average of the Uummannaq region's fjord properties. It is highly likely that erosion would have occurred in short bursts during glacial periods, and have been much reduced during interglacials. Furthermore, through time the areal extent of intense erosion would have reduced as it became focused into the developing fjords, and areas of neighbouring ice became cold-based. Actual erosion rates during glacial periods would have therefore been >1.3 mm a^{-1}, in broad agreement with modelled erosion rates, ranging from 3 to 10 mm a^{-1} (Jamieson *et al.* 2008).

As shown in Fig. 8, elevation and local topography is proposed to be linked to the basal thermal regime of the ice sheet, and corridors of ice streaming. A far more complex pattern of glacial landscapes has been recognised in the Uummannaq region (Fig. 2). However this figure

The focussing of glacial erosion on low altitude areas has left higher altitude regions (>1400 m a.s.l.) stranded from the majority of glacial erosion. This is most evident in the north of the region, where high altitude land comprises dissected plateau, covered by small presumably poly-thermal plateau ice fields with localised plateau erosion. In contrast, in the south of the study area, high elevation land is covered by extensive zones of glacial scour. During glacial periods the ice sheet overwhelmed the topography to sufficient ice thickness that the ice was at the pressure melting point

(Roberts *et al.* 2013), leading to widespread glacial erosion. It is possible that this discrepancy between the north and south is due to the combined outlet glacier ice flux in southern Uummannaq, which is considerably higher than the north (Table 1). Alternatively, initial preglacial landscape elevation could have been significantly lower in southern Uummannaq.

Areas of lowland terrestrial deposition have been identified and mapped in detail on central Ubekendt and southern Nuussuaq (Fig. 2). These areas were previously identified as "widespread occurrence of ground moraine on pre-Quaternary formations" on Quaternary maps by the Geological Survey of Greenland (Weidick 1971, 1974). These represent preserved records of ice sheet margin retreat and exist only in very restricted areas, associated with the most recent deglaciation of the region (Roberts *et al.* 2013). The restricted occurrence of these landsystems is to some extent a function of selective linear erosion, which has left few low-altitude areas in which these depositional landsystems can be preserved. The landsystem mapped across Ubekendt Ejland presents evidence for ice retreat, after the LGM, producing a suite of dissected terminal moraines to the west of the island, followed by a re-advance over the Ubekendt Ejland saddle, depositing a suite of eskers and a delta (Fig. 6A). The area of terrestrial deposition on the Nuussuaq Peninsula records a simple valley advance of an ice lobe, depositing a moraine.

As outlined above, the landscapes of glacial erosion and deposition discussed thus far fit with models of ice thermal partitioning (Hughes 1995; Kleman & Glasser 2007), and as with glaciated landscapes, are linked to elevation and topography (Fig. 8). However, the area identified as displaying 'little/no glacial erosion' by Sugden (1974) does not directly fit with this model of thermal partitioning. This area on the Nuussuaq Peninsula characterised by landscapes showing negligible imprint of ice sheet activity despite its low elevation and proximity to the ice sheet. Similar regions of pervasive ice-free conditions in such close proximity to large ice sheets have been reported in areas close to the Fennoscandian palaeo-ice sheet (Kleman & Stroeven 1997; Hattestrand & Stroeven 2002) and East Greenland (Swift *et al.* 2008), suggesting that although unusual, this is not a unique situation. Furthermore, the Svartenhuk Peninsula to the north of the region, a region previously classified as little or no erosion, displays some similar properties which warrant discussion. The large peninsula is unique in its size within the region, and shows some evidence of previous overrunning by the GrIS (Laursen 1944). Despite this the area is covered by landscapes of mountain valley and cirque glaciation, with little impact from the GrIS. We hypothesise that these regions develop as a result of the distribution of selective linear erosion. Location and distribution of erosion in the centre of the Uummannaq region has prevented these areas from being impacted by ice sheet erosion. As well as

segregating high altitude areas, selective linear erosion has caused the large-scale abandonment of peripheral areas due ice stream onset and trunk zone development (Roberts *et al.* 2013; Lane *et al.* 2014). Once the Uummannaq Trough had developed as a significant topographic feature it would have been able to control regional ice flux during full glacial conditions, causing draw-down of ice from individual outlet glaciers and a switch to a single, large trunk zone. As a result, Svartenhuk and Nuussuaq became starved of regional ice flux and only developed local ice caps. The western end of the Nuussuaq peninsula in particular would have been bounded by the UIS to the north and the Vaigat ice stream to the south; leaving it effectively bypassed by GrIS ice moving offshore.

Conclusion

o The Uummannaq region is characterised by a patchwork of glacial landscapes, formed over several million years through glacial erosion of variable intensity. The pattern of landscape distribution fits with models of ice sheet sub-glacial thermal organisation, dominated by corridors of intense selective linear erosion.

o Positive feedbacks between topography and ice dynamics have developed a coalescent fjord system. High elevation areas are protected under cold-based ice fields or minor weathering and periglacial activity during interglacial periods.

o Regional lithological differences have led to an increase in fjord width in the outer fjords, which is indicative of efficient glacial erosion there, likely related to outlet glacier convergence. Such geological control on ice stream geometry has been reported from other areas of Greenland, suggesting that it is a key factor in producing large areas of ice streaming.

o The Upper Planation Surface has sustained minimal glacial modification since the onset of glaciation. The impact of glacial erosion upon the Lower Planation Surface has decreased through time, as further uplift events increased its altitude. Areas lower than 1000 m a.s.l. have remained within the limit of warm-based glacial activity, and display evidence of extensive glacial modification.

o Glacial erosion and its spatial variability in intensity have produced a highly partitioned landscape, with a modification continuum between highly modified trough floors and preserved plateaux on the Upper Planation Surface.

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Fig. 1. Topographic overview map of Uummannaq region. Altitudes are taken from ASTER imagery, and bathymetry from GEBCO. Location and fjord names discussed in the text are identified. Regional-scale geological boundaries are marked by the dashed white line. Area 1 is Precambrian basement (gneiss and metagreywacke); 2 is Cretaceous sandstone and mudstone; and 3 is Tertiary basalts.
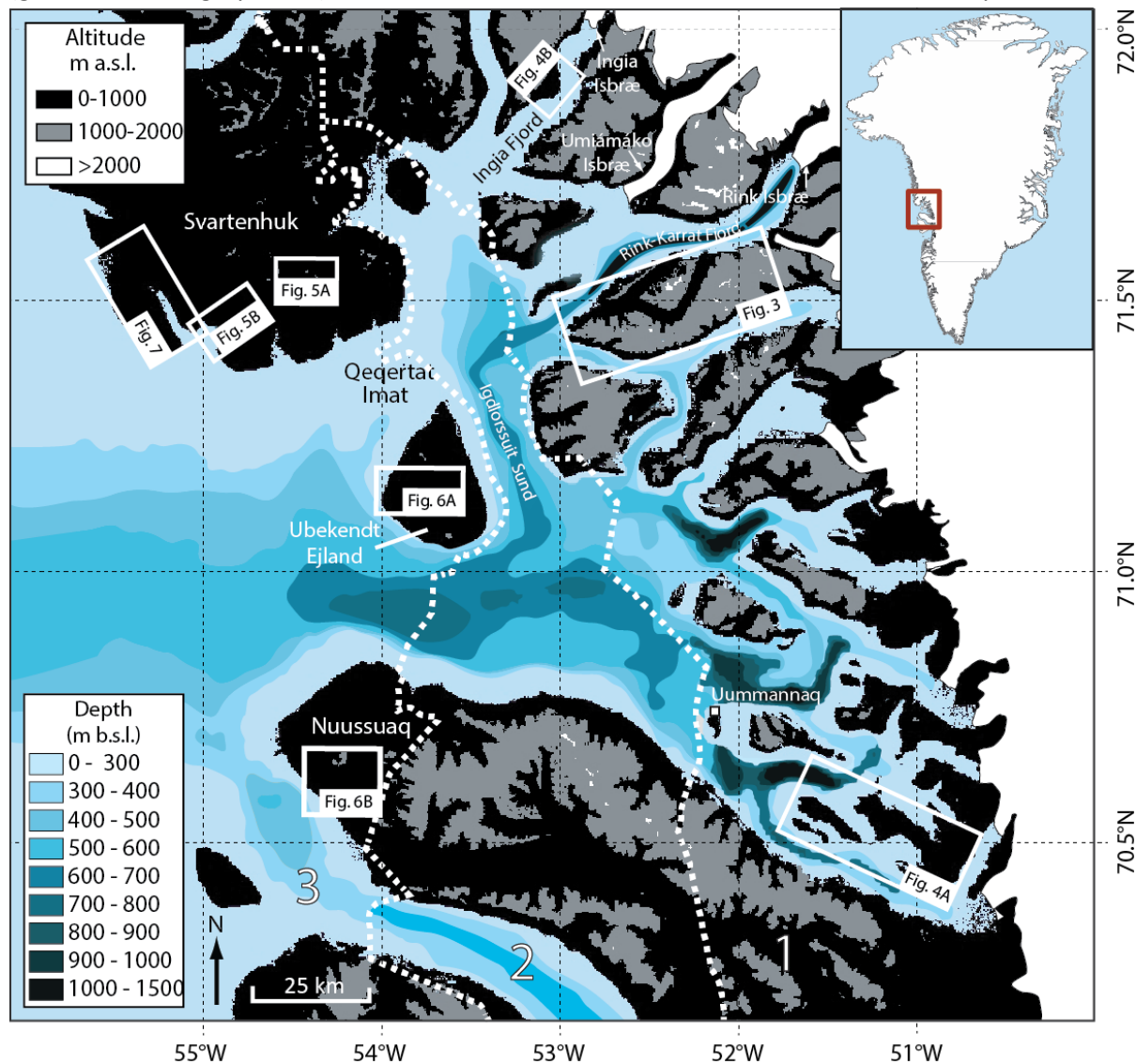
Fig. 2. A. Map of the landscapes of glacial erosion on the ice-free rim of Greenland, as mapped by Sugden (1974). B. New map of glacial and non-glacial landscapes throughout the Uummannaq region. Selective linear erosion has not been presented in in this figure as it would have hindered the presentation of other landsystems.
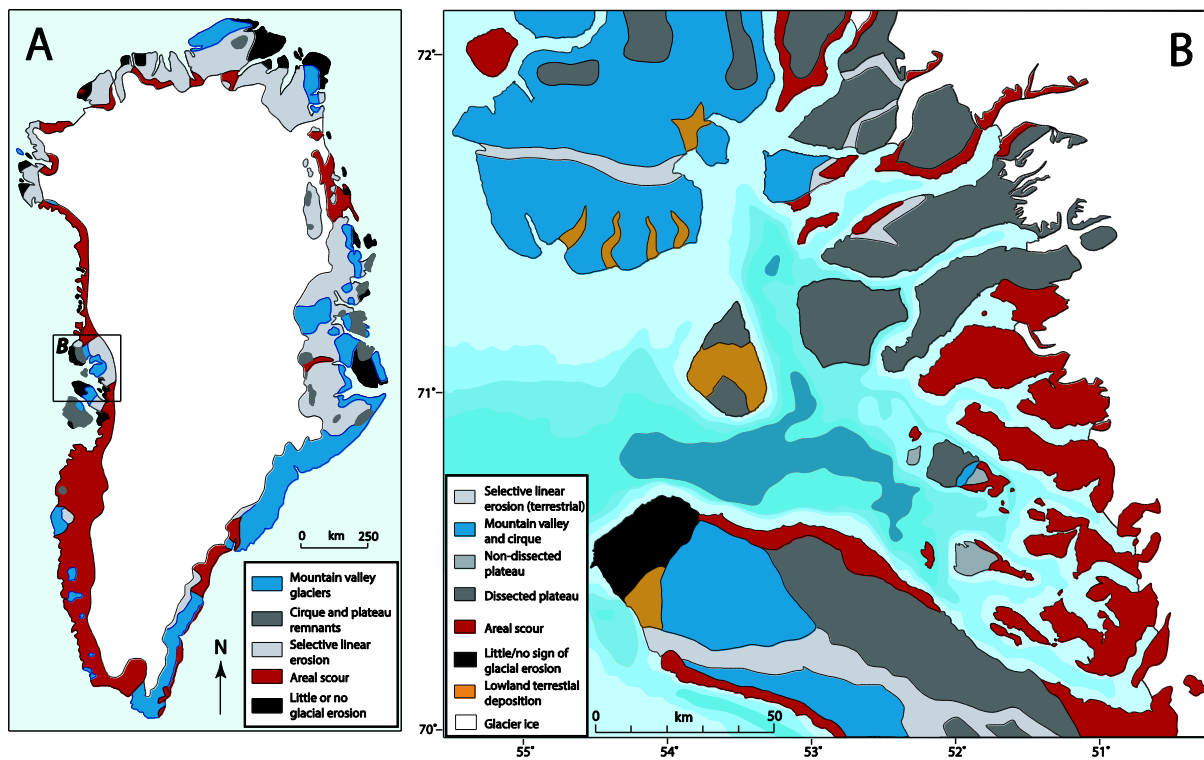
Fig. 3. A. Geomorphological map overlain on an aerial photograph, showing an example of a dissected plateau; (B - D) aerial photographs of locations within the Uummannaq region, showing the continuum of types of dissected plateau present. B. The landsystem is still in the form of a relatively coherent plateau, with some dissection. C. More dissection has taken place, but the majority of the icefields remain connected. D. Intense dissection has taken place, the icefields now appear far more fragmentary, with large inter-plateau valleys present.
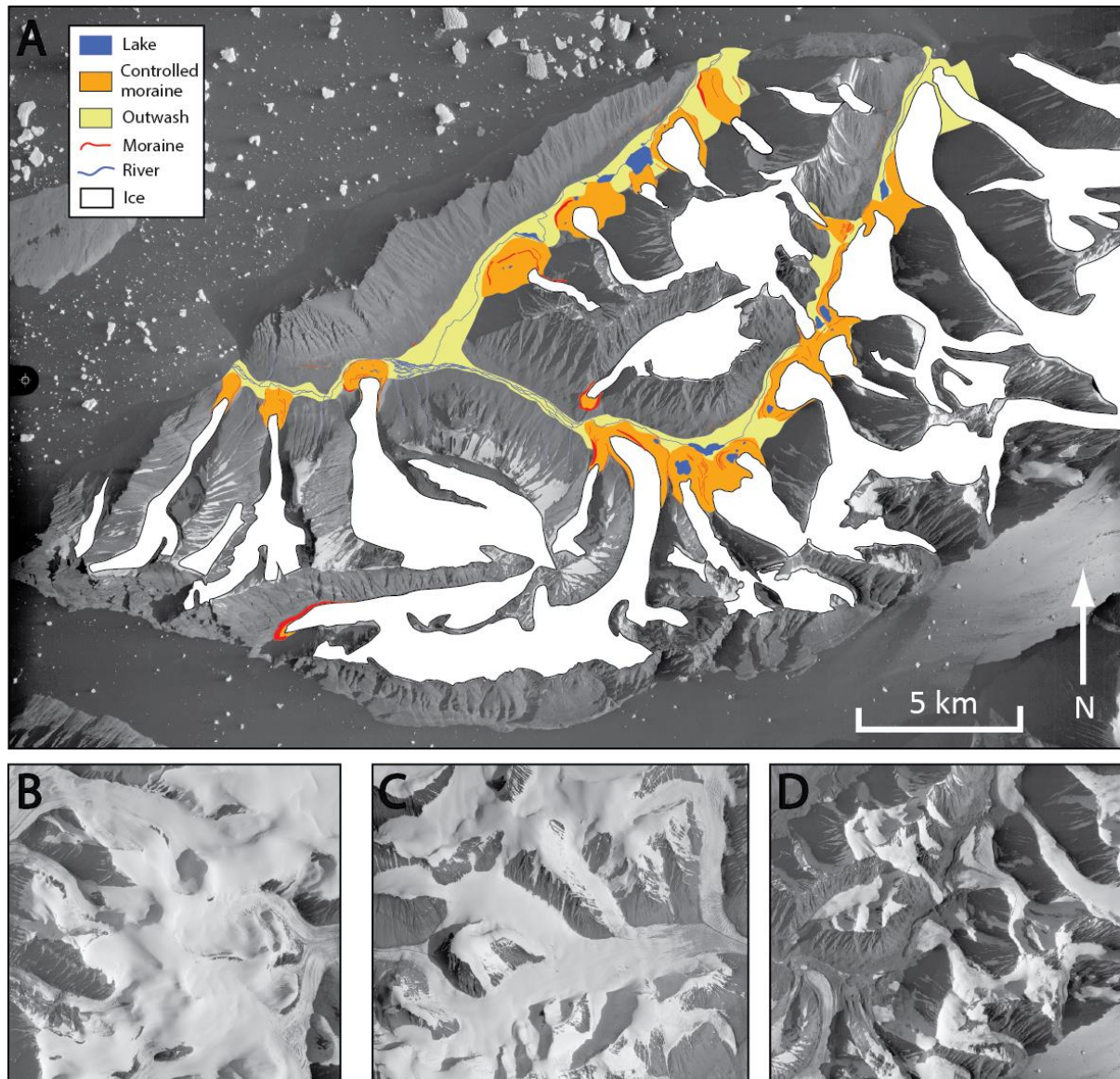
Fig. 4. A. Areally scoured topography from the southern Uummannaq region, with large lineations/macro-scale bedforms mapped. B. Areally scoured terrain from the northern Uummannaq region, with erosional bedforms mapped. C. Photograph of the areally scoured topography from the south of the Uummannaq region, showing classic knock and lochan topography. D. Photograph of areally scoured topography in the north of the Uummannaq region, with long, angular bedforms evident.
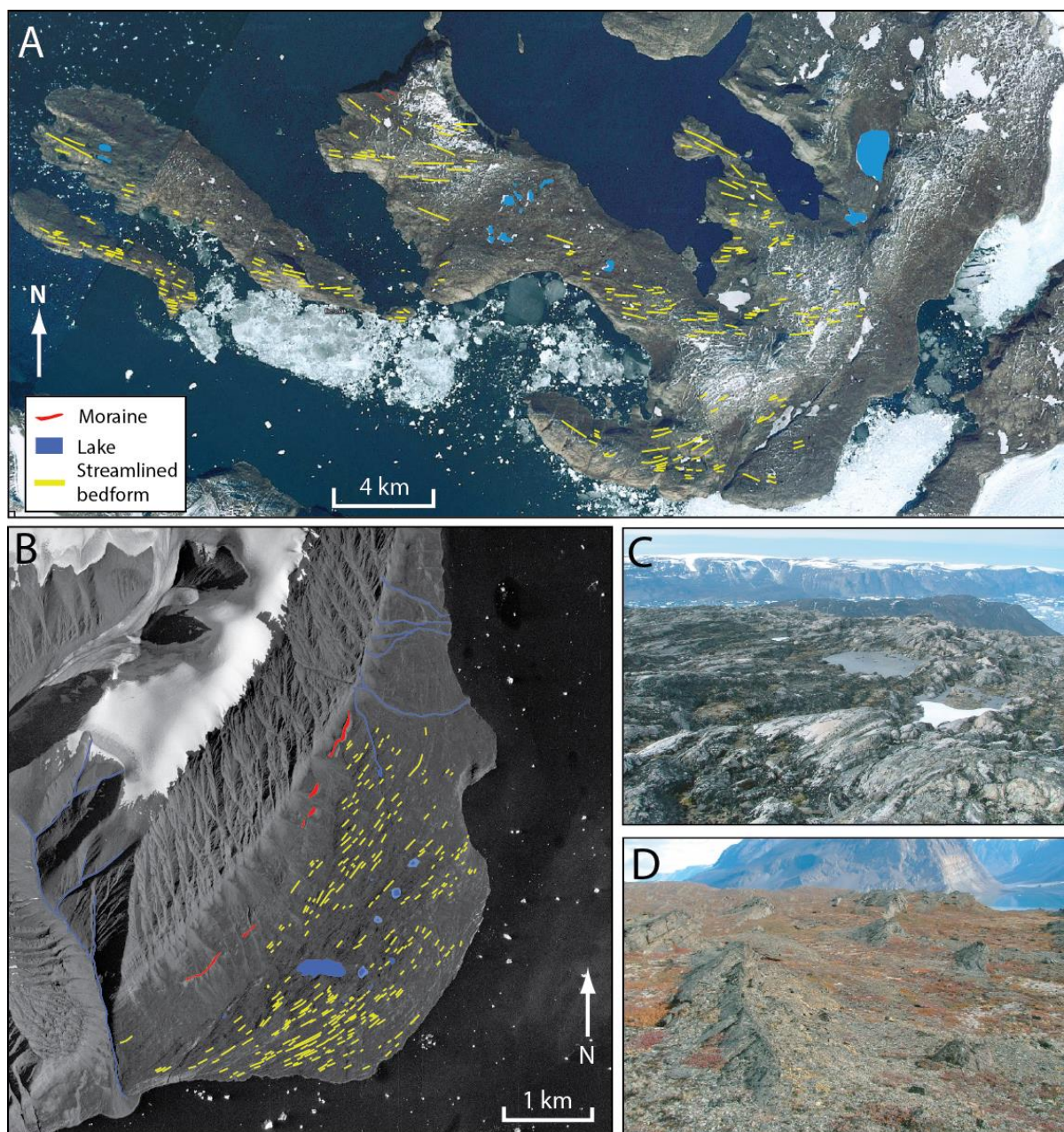
Fig. 5. Geomorphological maps overlain on aerial photographs showing areas of cirque glaciation (A) and valley glaciation from Svartenhuk (B).
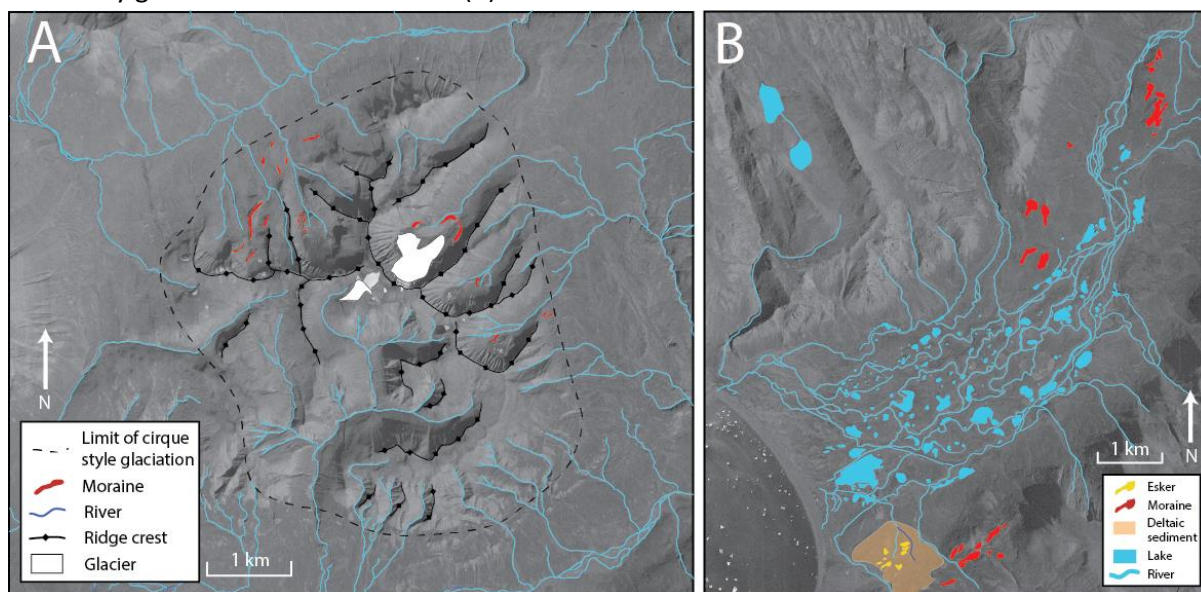
Fig. 6. Geomorphological maps of the 'lowland terrestrial deposition' landsystem identified in this study. Maps are overlain on aerial photos. These landsystems were limited in abundance, found on Ubekendt (A) and southern Nuussuaq (B).
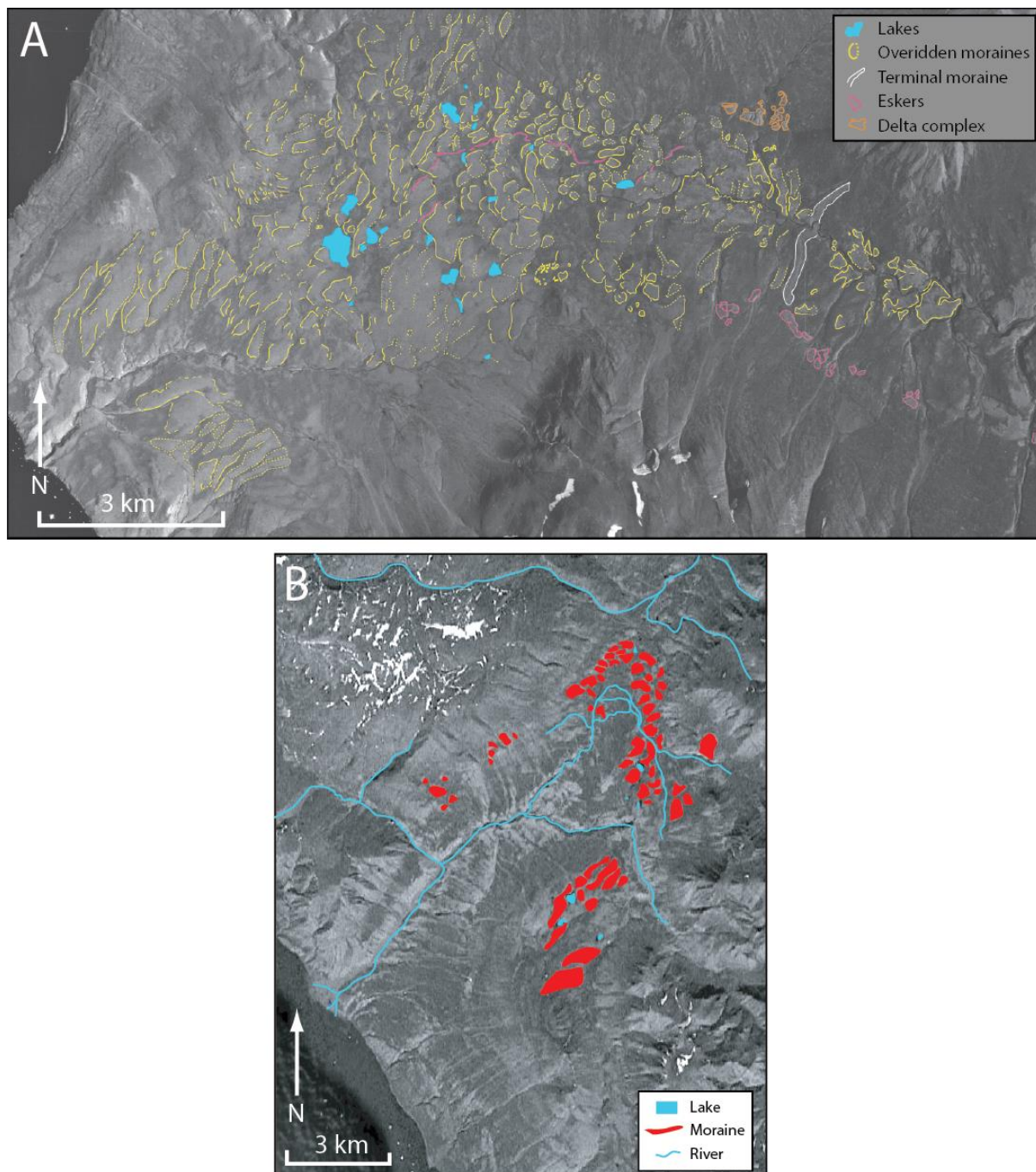
Fig. 7. Aerial photograph (A) and geomorphological map (B) of south-western Svartenhuk. The well-developed fluvial drainage system and extensive deposits of sediment are evident.
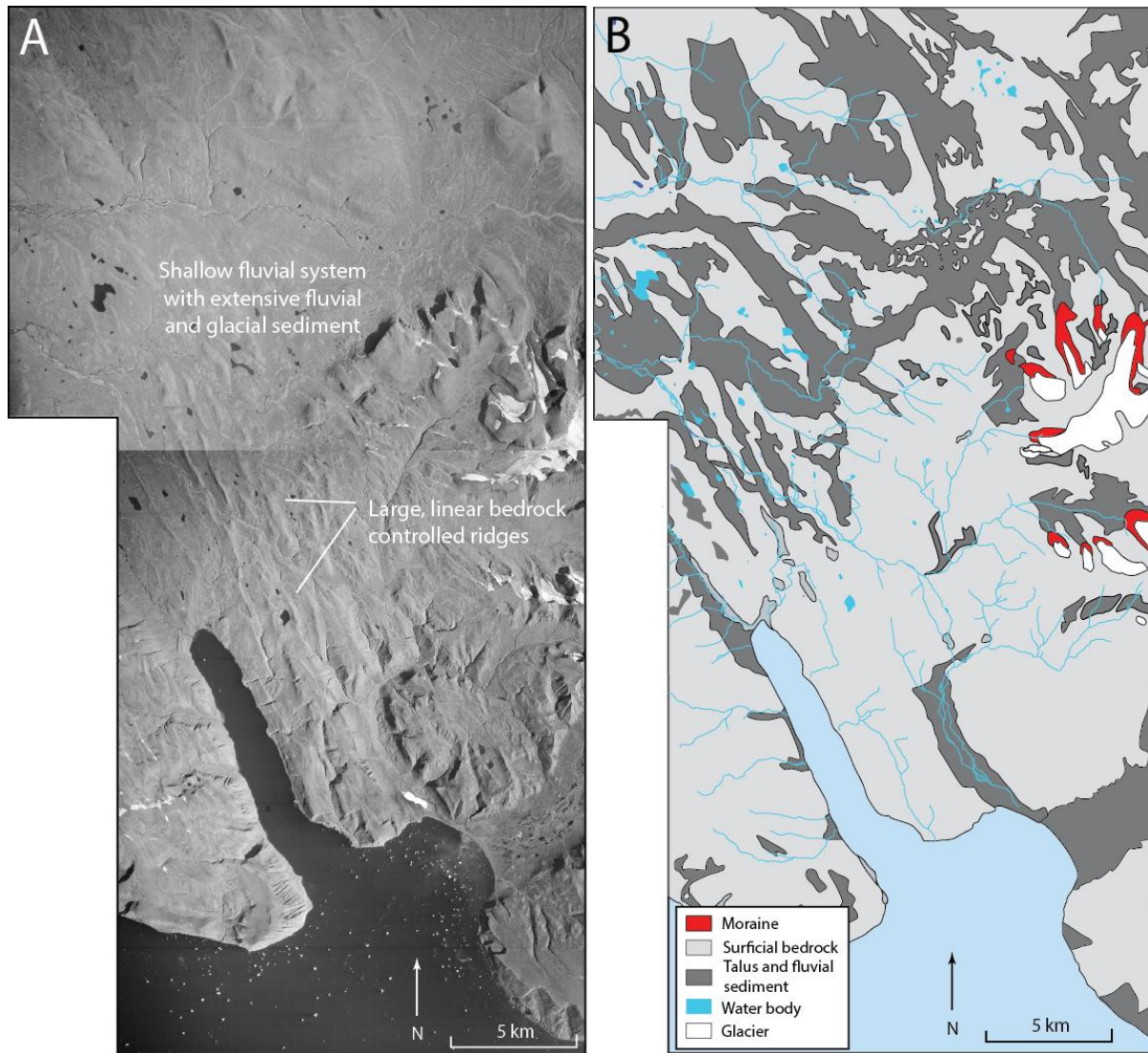
Fig. 8. Topographic map of the Uummannaq region. Colour scheme is used to demonstrate hypothetical ice sheet basal temperature during the most recent period of glacial inundation. Blues indicating regions of frozen beds; reds showing areas of high basal temperature. Onshore topographic data are from ASTER GDEM, and offshore topography is from the IBCAO dataset (Jakobsson *et al.* 2012).
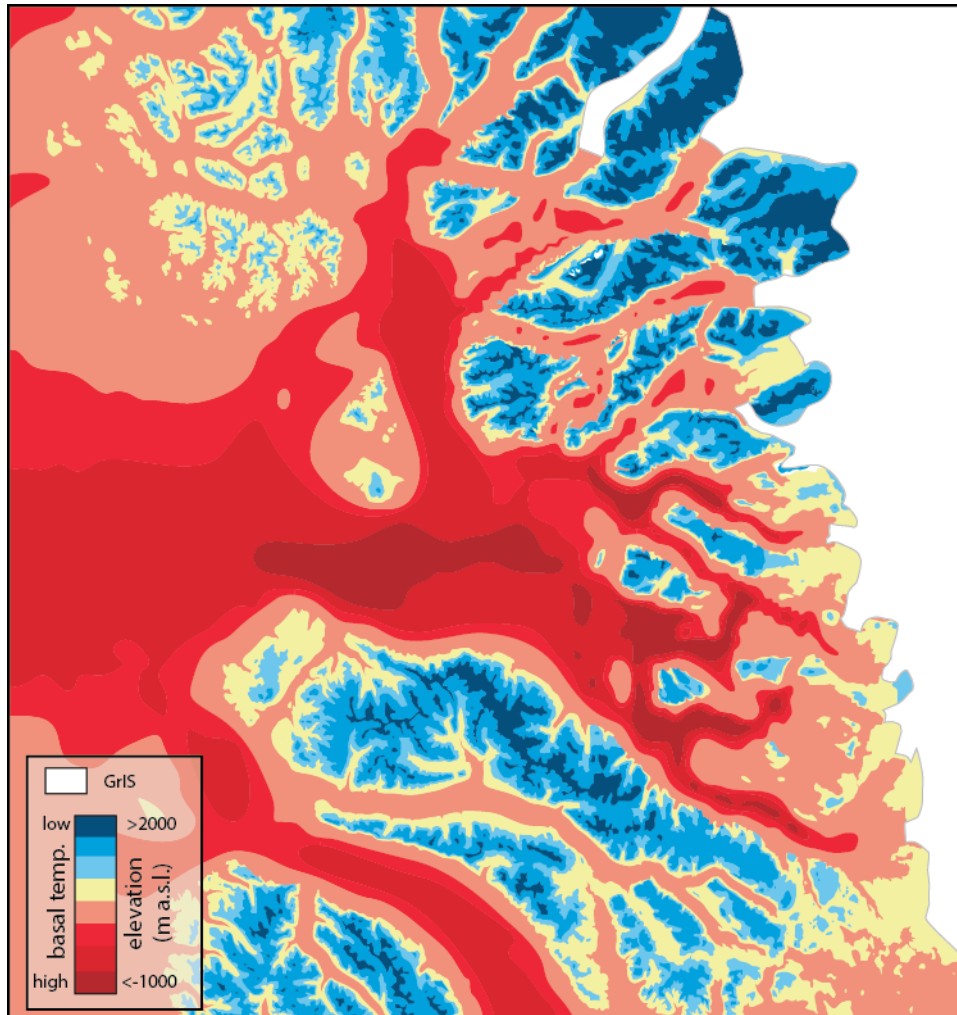
Fig. 9. Idealised profiles taken north-south through the Nuussuaq Basin in the Uummannaq region, illustrating the development of the UPS and LPS, and the re-exposure of the Precambrian etch surface (adapted from Japsen *et al.* 2009). The timing of the onset of glaciation and selective linear erosion in the region is shown within the context of uplift. Valleys were incised in two stages as a response to different phases of uplift (C3 and C4). Present day valleys are deeply incised to >1000 m b.s.l.
A-B: Uplift and erosion to a new base level produces the UPS (uplift event C2; Japsen et al., 2009). C-D: Regional uplift of the UPS to ~1000m a.s.l. (uplift event C3; Japsen et al., 2009). Erosion (predominantely fluvial) cuts to the new base-level, producing the LPS. Onset of glacial erosion at 4 Ma, having little impact upon the UPS. E: Regional uplift of the UPS and LPS (uplift event C4; Japsen et al., 2009) to ~2000 and ~ 1000 m a.s.l. respectively. Intense glacial erosion (selective linear erosion) to below the present-day landsurface.
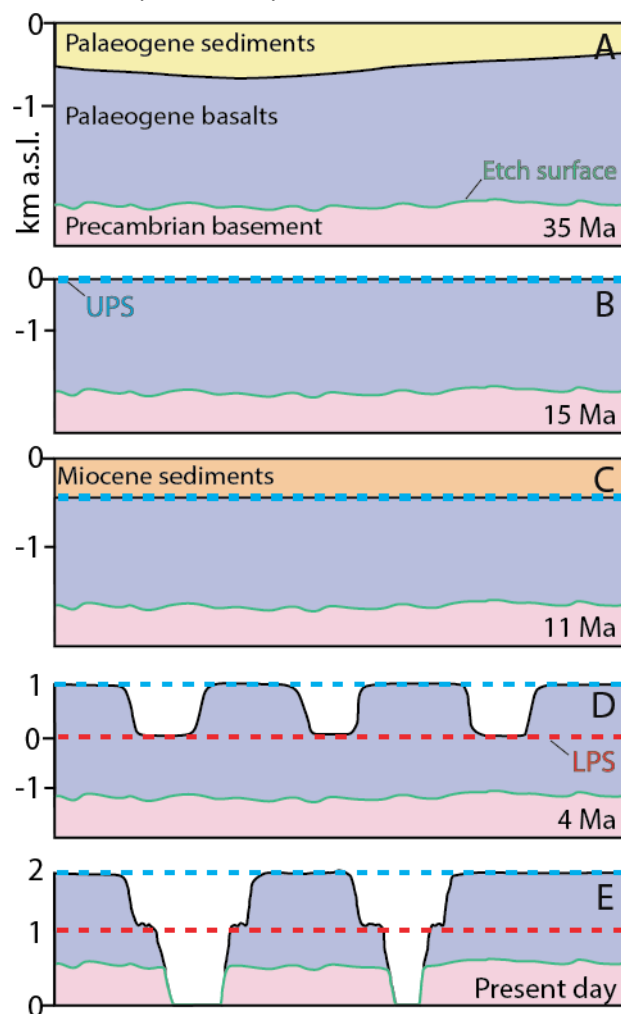
Fig. 10. Schematic diagram illustrating the hypothesised landsurfaces present throughout the Uummannaq region, their relationship to regional glacial history, and the resulting landscapes of erosion and deposition this forms. The landsurfaces are the result of the region's uplift histories (Bonow *et al.* 2006a; Japsen *et al.* 2006; Green *et al.* 2011).
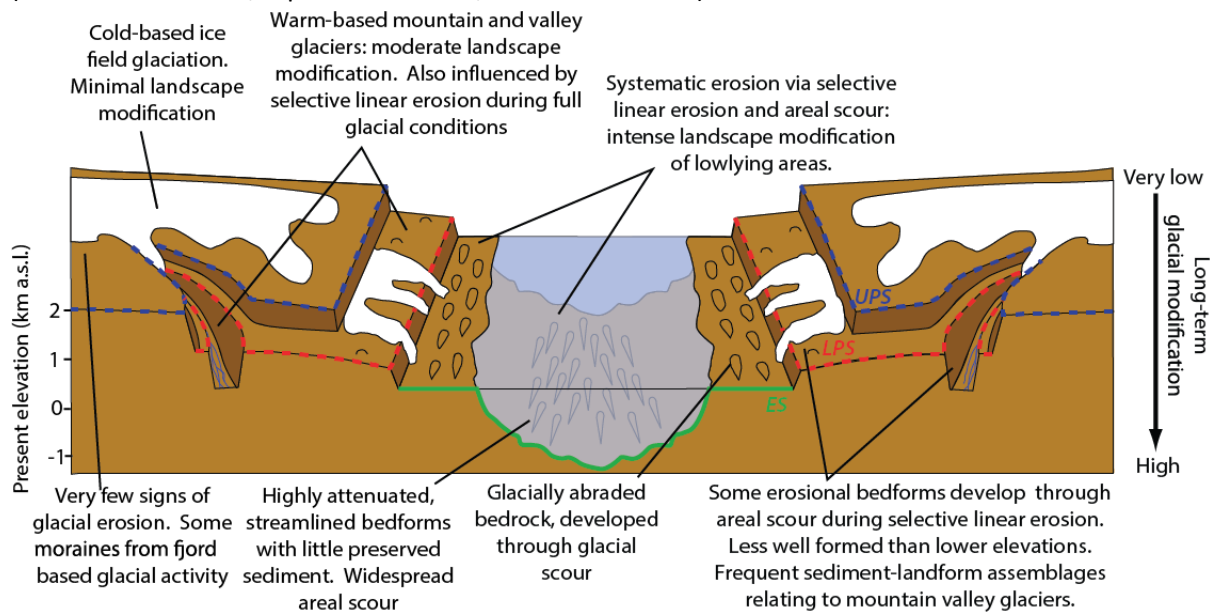

Table 1. Properties of fjords from the Uummannaq region, broadly grouped into northern and southern.

Fjord Name	Mouth location	Snout location	Azimuth (°)	Length (km)	Width at S.L. (km)	Ave. plateau height (m a.s.l.)	Max. water depth (m)[a]	Max ice flux (km^3 a^{-1})[b]
Northern fjords								
Ingia Fjord	71.73° N 53.32° W	72.00° N 52.70° W	213.4	38.5	4.5	1450	No data	1.1
Rinks-Karrat Fjord	71.40° N 53.07° W	71.73° N 53.65° W	238.1	63.6	6.2	1800	1100	18.8
Kangerdlugssuaq	71.38° N 53.00° W	71.45° N 51.83° W	263.2	61.7	4.2	1900	550	2.9
Southern fjords								
Kangerdluarssuk	71.13° N 52.30° W	71.25° N 51.52° W	245.0	34.9	5.7	1650	750	0.3
Perdlerjiup Kangerdlua	71.05° N 52.00° W	70.98° N 50.95° W	282.0	42.5	5.5	1400	1250	1.0
Itivdliarssup Kangerdlua	70.98° N 51.97° W	70.80° N 51.00° W	302.1	42.5	5.6	1300	900	7.6
Sermigdlip Kangerdlua	70.7° N 51.52° W	70.62° N 50.63° W	291.5	38.2	4.5	1200	1300	2.6
Qarajaqs Isfjord	70.68° N 52.28° W	70.37° N 50.60° W	302.7	75.4	6.9	1300	1000	17.8

[a]Data from GEBCO_08 Grid and Hareø-Prøven bathymetric charts.
[b]Data from Bauer *et al*. (1968) and Carbonnell and Bauer (1968).