Peneplains and tectonics in North-East Greenland after opening of the North-East Atlantic

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Abstract

Elevated plateaus with deeply incised valleys characterise elevated, passive continental margins (EPCMs) in all climate zones. These features are, however, a topic of debate regarding when and how the large-scale landscapes formed. We have investigated and mapped the partly glaciated landscape of North-East Greenland (70–78°N). The area consists of crystalline basement and Palaeozoic–Mesozoic rift basins, capped by Palaeogene basalts that erupted during the northeast Atlantic break-up. Our stratigraphic landscape analysis reveals a typical EPCM dominated by two elevated erosion surfaces, extending 200 km east–west and 900 km north–south. The low-relief Upper Planation Surface (UPS; *c.* 2 km above sea level) cuts across basement and Palaeogene basalts, indicating that it was graded to base level defined by the Atlantic Ocean in post-basalt times and subsequently uplifted. The UPS formed prior to the deposition of mid-Miocene lavas that rest on it, south of the study area. In the interior basement terrains, the Lower Planation Surface (LPS) forms fluvial valley benches at *c.* 1 km above sea level, incised below the UPS. The LPS is thus younger than the UPS, which implies that it formed post mid-Miocene. Towards the coast, the valley benches merge to form a coherent surface that defines flat-topped mountains. This shows that the LPS was graded to near sea level and was subsequently uplifted. Hence, both the UPS and the LPS formed as peneplains – erosion surfaces graded to base level. The fluvial valley benches associated with the LPS further indicates that full glacial conditions were only established after the uplift of the LPS in the early Pliocene (*c.* 5 Ma). The uplift of the LPS led to re-exposure of a Mesozoic etch surface. We conclude that episodes of late Neogene tectonic uplift shaped the stepped landscape and elevated topography in North-East Greenland.

1 Introduction

Elevated plateaus (or planation surfaces) that extend over wide areas are characteristic features of elevated, passive, continental margins (EPCM) (Jessen 1943; King 1967; Lidmar-Bergström *et al.* 2000; Japsen *et al.* 2012a; Green *et al.* 2013). They occur in all climate zones from the Arctic to tropical and along with Mesozoic and Palaeogene rift systems, along the margins of the Atlantic Ocean from South Africa and Brazil to Norway and Greenland. The formation of these surfaces, and when and how they reached their present elevation, is a topic of debate. Are the elevated plains remnants of pre-rift

landscapes that have remained largely unaffected by later processes (Ollier & Pain 1997)? Did they form during rifting or break-up and remain at high elevation (Gilchrist & Summerfield 1990; Gallagher *et al.* 1998; Bishop 2007; Braun 2018)? Did they form by glacial and periglacial processes at high elevation in Arctic regions (Steer *et al.* 2012; Egholm *et al.* 2017)? Or were they graded to the base level of the adjacent sea by fluvial erosion long after rifting and break-up, and were subsequently uplifted to their present elevation (Lidmar-Bergström *et al.* 2000, 2013, 2017; Bonow *et al.* 2006a, 2006b, 2014; Japsen *et al.* 2012a, 2019; Green *et al.* 2013)?

Bonow *et al*. (2014) used stratigraphic landscape analysis (Lidmar-Bergström *et al*. 2013, 2017) to identify and map two elevated planation surfaces, the Upper and Lower Planation Surface (UPS and LPS, respectively) in southern–East Greenland (68–71°N; here referred to as the Blosseville Kyst region, primarily south of Scoresby Sund). The bedrock of Blosseville Kyst is dominated by flood basalts that erupted around the Paleocene–Eocene transition during the break-up of the North-East Atlantic (Larsen *et al.* 1989; Pedersen *et al.* 1997; Gaina *et al.* 2017). As these planation surfaces cut across the Palaeogene basalts as well as the metamorphic basement, Bonow *et al.* (2014) inferred that they were graded towards the level of the newly formed North-East Atlantic. Consequently, the present elevation of the UPS and the LPS that reach 3 and 2 km
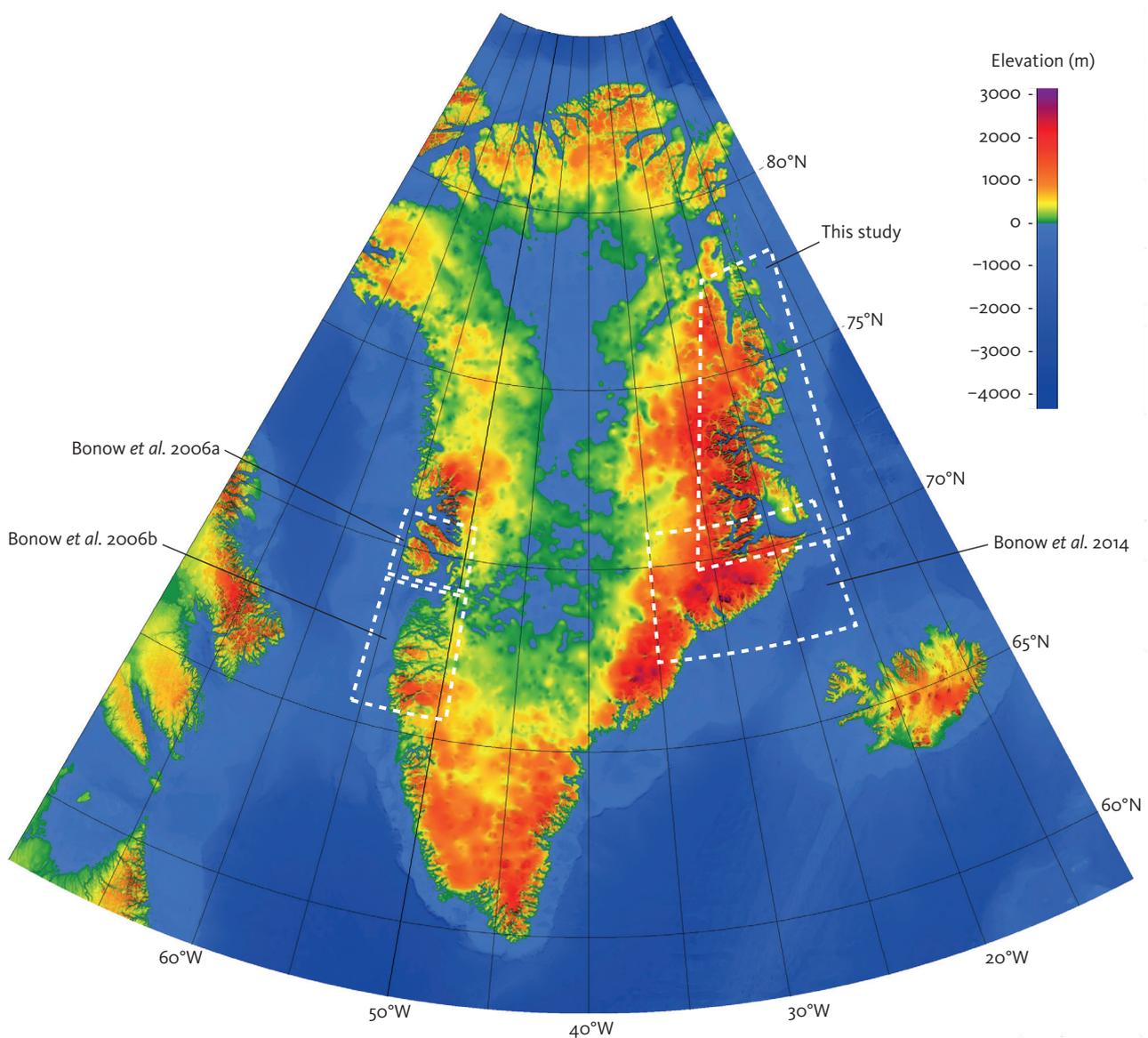
Fig. 1 Bedrock topography of Greenland: Areas investigated by stratigraphic landscape analysis are indicated (Bonow *et al.* 2006a, 2006b, 2014; and this study). The landscape of East Greenland is generally of higher elevation than West Greenland, where elevated areas are restricted to the coast. The load of the Greenland ice sheet causes up to 850 m subsidence of the bedrock topography in central Greenland. Peripheral bulging along the margins of Greenland, caused by this ice loading, has a negligible effect on elevation (Medvedev *et al.* 2013). Elevation data is from Amante & Eakins (2009).

above sea level (a.s.l.), respectively, in southern East Greenland, reflect uplift after their formation. Three major phases of uplift and erosion led to the formation and subsequent uplift of these surfaces in late Eocene, late Miocene and early Pliocene as estimated from apatite fission-track analysis (AFTA) data and landscape observations (Japsen *et al.* 2014). These results are further confirmed by AFTA data from North-East Greenland (Japsen *et al*. in press).

Here, we continue the work of Bonow *et al.* (2014) by presenting coherent maps and analyses of the large-scale landscape of North-East Greenland, north of Scoresby Sund (70–78°N; Fig. 1). Whereas the previous study focussed on the region dominated by the Palaeogene basalts, this study investigates the geomorphology along the late Palaeozoic – Mesozoic rift system of East Greenland (Surlyk 1977, 1978, 2003; Parsons *et al.* 2017). An important question is: does the large-scale landscape here mainly contain elements that are inherited from the time of rifting and break-up, or is the landscape instead dominated by younger features? For example, Swift *et al.* (2008) argued that the first-order topography in North-East Greenland had existed since at least the time of break-up, at *c.* 55 Ma.

We apply the stratigraphic landscape analysis to identify and map planation surfaces in North-East Greenland and produce a relative tectonic event chronology that defines the major phases of denudation and uplift that led to the formation of the present landscape. The results may thus provide further insight into highly debated topics in recent years, including:

1. The origin of elevated plateaus along passive continental margins (Lidmar-Bergström *et al*. 2000; Japsen *et al*. 2009, 2012a, 2012b, 2019; Hetzel *et al*. 2011; Green *et al*. 2013, 2018; Haider *et al.* 2013; Calvet *et al.* 2015; Braun 2018; da Silva *et al.* 2018; Guillocheau *et al.* 2018).
2. The development of the margins of the North-East Atlantic (Japsen & Chalmers 2000; Nielsen *et al.* 2009;

Chalmers *et al.* 2010; Pedersen *et al.* 2012; Japsen *et al.* 2013, 2014; Lidmar-Bergström *et al.* 2013, 2017; Bonow *et al.* 2014; Egholm *et al.* 2017).
3. The role of tectonics for triggering the formation of the Greenland ice sheet (Pedersen & Egholm 2013; Solgaard *et al.* 2013; Steinberger *et al.* 2015; Pérez *et al*. 2018).

2 Stratigraphic landscape analysis for mapping erosion surfaces in East Greenland

In this study, we apply the same technique for mapping erosion surfaces as Bonow *et al*. (2014), that is, stratigraphic landscape analysis (Green *et al*. 2013; Lidmar-Bergström *et al*. 2013). We define an erosion surface graded to base level as a peneplain, in agreement with the original idea of Davis (1899), who stressed the fundamental importance of a base level for the development of an eroding landscape. Thus, we use the term peneplain for any erosion surface graded to base level.

Stratigraphic landscape analysis is based on:

1. The relationship between peneplains in crystalline basement and their cover rocks of different ages.
2. The cross-cutting relationships between such re-exposed peneplains and epigene peneplains (peneplains that have never been covered by sedimentary rocks).
3. The occurrence of valleys incised below peneplains (Fig. 2).

Stratigraphic landscape analysis is thus a further development of a long tradition in geomorphology focussed on the study of large-scale landforms that contain information about long-term erosional processes and tectonic events (Davis 1899; Reusch 1901; Ahlmann 1919, 1941; Penck 1924; Baulig 1935; Jessen 1943; King 1967; Brunsden 1993; Ahnert 1998; Godard *et al.* 2001; Benito-Calvo & Pérez-González 2007; Peulvast *et al.* 2009, 2011; Hetzel
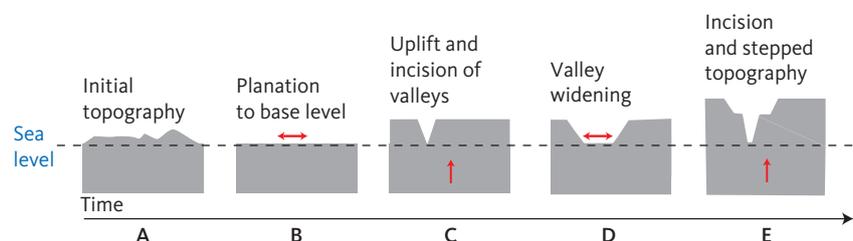
Fig. 2 Conceptual diagram illustrating the formation of peneplains through time: **A**: Initial topography. **B**: Formation of a first peneplain by planation of the landscape to base level (sea level) in a tectonically stable environment. **C**: Tectonic uplift or a significantly lowered base level results in valley incision below the peneplain. **D**: Erosion continues within the valleys resulting in valley widening and the formation of a second peneplain controlled by the new base level. Erosion primarily affects the older, elevated peneplain along its edges. **E**: Renewed uplift ends the formation of the second peneplain and valleys again grade the landscape to the new base level. The result is a landscape with distinct steps. At this scale and for the time span considered (*c.* 10 Myr), the downwearing of the peneplains is negligible (Fu *et al.* 2019).

et al. 2011; Haider et al. 2013; Li et al. 2014; Ma et al. 2020). Classical models of landscape development focus on the idea of continuous uplift, interrupted by periods of quiescence (Davis 1899; Baulig 1935; Fairbridge & Finkl 1980; Benito-Calvo & Pérez-González 2007). However, stratigraphic landscape analysis emphasises that the relationship between relief in basement and cover rocks provides information about both uplift and subsidence of a region (Lidmar-Bergström et al. 2013).

It is important to understand the relationship between the geology of the rocks into which a surface is eroded and the present appearance and extent of the surface. An extensive erosion surface across resistant rocks (such as crystalline basement) will require a long time to form, but once formed it will persist for a long time in the landscape. On the other hand, an erosion surface that forms across less resistant rocks (such as sediments) will form more quickly, and the surface will be dissected faster than a surface formed in crystalline basement (Simon-Coinçon et al. 1997; Fjellanger & Etzelmüller 2003; Bonow et al. 2009; Green et al. 2013). Another aspect that must be considered during the mapping of peneplains is the possible complications from structural control in terrains with flat-lying cover rocks, which are common in northeast Brazil (Peulvast & Bétard 2015) and also in parts of North-East Greenland.

The formation of regional, extensive erosional surfaces is likely to be governed by the common base level to which rivers erode, given time and sufficient tectonic stability. Thus, if an erosion surface loses its contact with the base level to which it formed, it is a palaeosurface, and it will begin to be dissected by incising valleys and the relief will rejuvenate. The valleys will eventually be widened, which results in a new erosion surface graded towards the base level (Ahnert 1998; Bonow 2004; Lidmar-Bergström et al. 2017). Such landscapes will thus be characterised by plateaus in distinct steps and deeply incised valleys (Fig. 2), similar to the landscapes in eastern Australia and southern Norway, the Shillong Plateau, India and West Greenland (Lidmar-Bergström et al. 2000; Bonow et al. 2006a; Biswas et al. 2007). The parsimonious explanation is that these plateaus are erosion surfaces that were graded to distinct base levels (Japsen et al. 2009). The next parsimonious explanation is that the base levels correspond to sea level at the time of erosion of the surface. Where a study area is known to have been near the sea at the time in question, and the surface is not defined by a resistant level, this is the obvious explanation.

An erosion surface may be buried after its formation and thus, be preserved below its cover. Such buried surfaces can be identified as unconformities in boreholes, on offshore seismic profiles and on exposed sections (e.g. Larsen et al. 1989; Bate 1997; Lassen & Thybo 2012; Parsons et al. 2017). However, uplift events may lead to re-exposure of previously buried surfaces (Lidmar-Bergström 1989; Bonow 2005; Peulvast et al. 2011). The characteristics of a re-exposed surface (e.g. relative relief outliers and saprolite types) often allow it to be followed along topographical profiles or identified away from its cover. If the re-exposed surface is tilted, its extension may at some point be cut-off by younger erosion that forms a new, more horizontal surface with low-angular unconformity. In such a setting, it can be inferred that the erosion responsible for the formation of the younger surface must have involved both erosion of former cover rocks and of the re-exposed surface (Fig. 3, Lidmar-Bergström et al. 2017).

The cross-cutting relationships between peneplains of different tilts and with different relief and cover provide information about the relative denudation chronology. A relative denudation chronology is a key input to studies of uplift and erosion along a passive margin, similar to other independent datasets, such as evidence from the stratigraphic record and thermochronological data. The chronology provides tectonic information during periods where little or no geological information is otherwise available. Such periods, with little or no
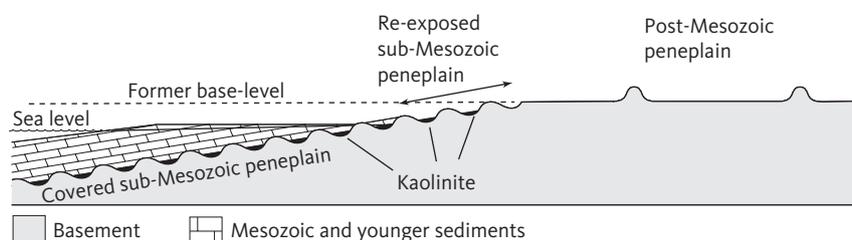
Fig. 3 Relationship between peneplains and cover rocks in southern Sweden: The presence of Mesozoic outliers and remnants of kaolinitic saprolites at a high position in the landscape, demonstrates that Mesozoic cover was once more extensive. The near-horizontal peneplain cut off the tilted sub-Mesozoic peneplain and is therefore younger. The geological constraints and the appearance of the two surfaces reveal a history of erosion (formation of the sub-Mesozoic peneplain), subsidence and deposition of the Mesozoic strata, followed by tilting and uplift (change from a near-horizontal surface to an inclined surface), erosion (removal of cover and formation of a new peneplain) and a late uplift phase that explains the landscape configuration. Based on Lidmar-Bergström (1982, 1988); Green et al. (2013); Lidmar-Bergström et al. (2013, 2017).

preserved geological record, often represent a larger timespan than that for which a stratigraphic record exists (e.g. Ager 1973; Green *et al*. 2013).

3 Study area
3.1 Geologic and tectonic setting

The bedrock of North-East Greenland consists of Precambrian and Caledonian basement overlain by Palaeozoic, Mesozoic and Cenozoic cover rocks (Fig. 4, Henriksen *et al.* 2008, 2009). This geological setting is favourable for an analysis of the relationship between basement and cover rocks, because the minimum age of re-exposed basement surfaces can be constrained by the age of the cover rocks, and the maximum age of surfaces that were never covered (epigene surfaces) can be constrained by the age of the cover rocks that they

cut across. It is then possible to use such relationships to establish a chronology for the development of palaeosurfaces (e.g. Lidmar-Bergström 1988; Bonow 2005; Lidmar-Bergström *et al.* 2013).

The Caledonian orogeny lasted from 465 to 400 Ma (Middle Ordovician to early Devonian), and culminated in the collision between Laurentia and Baltica about 420 Ma (latest Silurian; Henriksen 2008). The Caledonian mountains collapsed between 400 and 355 Ma (early Devonian to earliest Carboniferous), and the sediments from the eroding Caledonides were deposited in sedimentary basins parallel to the present coast in central East Greenland (Larsen & Bengaard 1991; Higgins *et al.* 2008). The sea transgressed the eroded Caledonian basement in the late Permian (Haller 1971; Surlyk 1990). A series of Carboniferous–Mesozoic rift basins
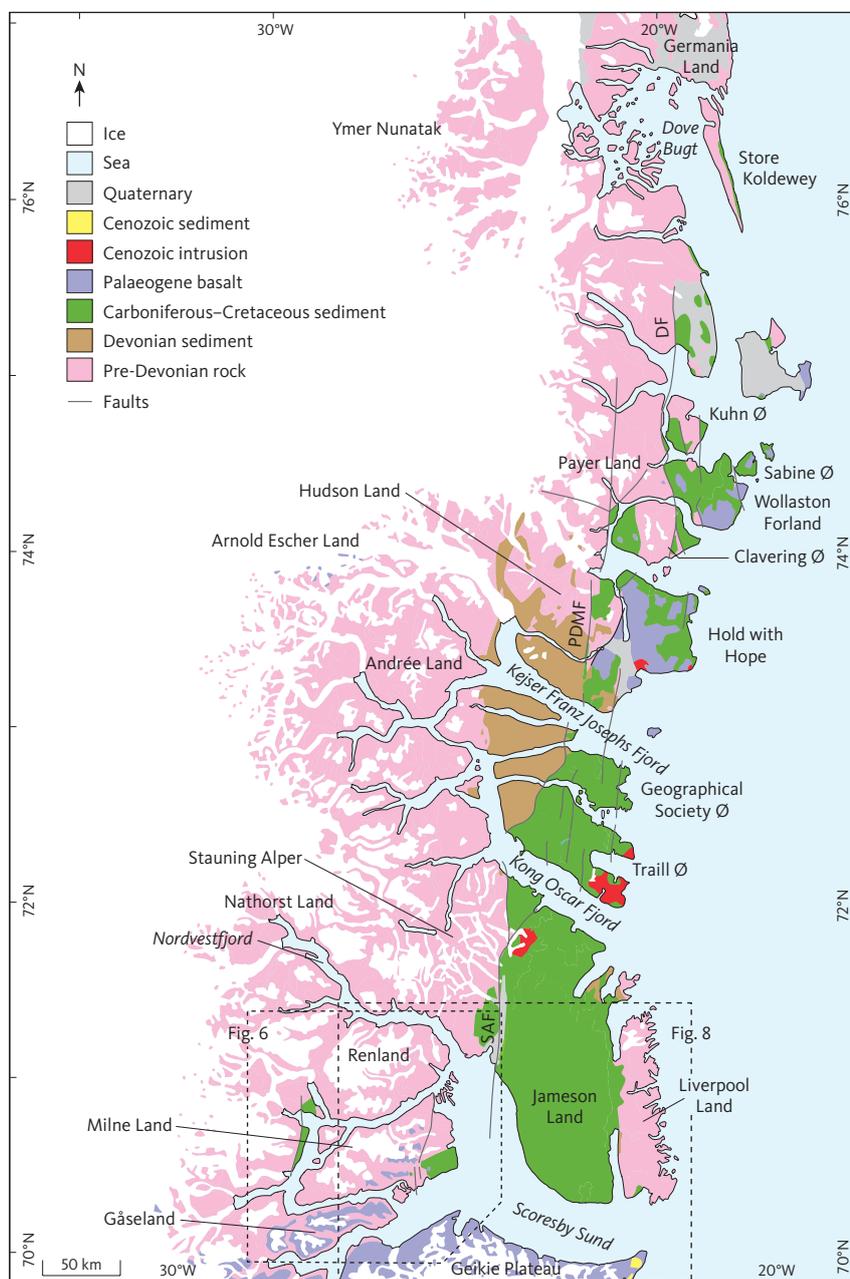
Fig. 4 Geology of the study area (70–78°N; location in Fig. 1): **DF**: Dombjerg Fault. **SAF**: Stauning Alper Fault. **PDMF**: Post-Devonian Main Fault. We refer to the PDMF and the SAF as the Post-Devonian Main Fault system. Crystalline basement (Precambrian and Caledonian) and Devonian rocks dominate west of the PDMF with Carboniferous–Cretaceous rift basins to the east. Palaeogene flood basalts dominate much of the southern part of the study area, but patches of basalt occur as far north as 75°N. Several Palaeogene intrusive centres occur along the coast. **Black dashed lines**: locations of Figs 6, 8.

developed in East Greenland, forming N–S-trending, coast-parallel depocentres located to the east of the so-called post-Devonian Main Fault (Vischer 1943) – a north–north-east-trending fault, which appears as a marked scarp in the terrain, defining the present-day western boundary of the sedimentary basins north of Kong Oscar Fjord. South of the fjord, it is termed the Stauning Alper Fault. We will refer to these two faults as the post-Devonian Main Fault system. Important phases of rifting took place during the early and late Carboniferous, late Permian, late Jurassic and Cretaceous, prior to the opening of the North-East Atlantic at the Paleocene–Eocene transition (Surlyk 1990, 2003; Stemmerik et al. 1993; Stemmerik 2000; Surlyk & Ineson 2003). Parsons et al. (2017) studied the geology of Traill Ø and Geographical Society Ø and identified three main rift phases during the Devonian–Triassic, Jurassic–Cretaceous and Palaeogene. The greatest amounts of faulting and block rotation occurred during Palaeogene rifting, which they related to the break-up at 56 Ma and to the plate reorganisation at 36 Ma.

Break-up in the North-East Atlantic was accompanied by extrusion of voluminous flood basalts that dominate the region south of Scoresby Sund, along Blosseville Kyst and its hinterland (68–70°N), where much of the lavas are referred to as the Main Basalts (Larsen et al. 1989; Brooks 2011). Palaeogene basalts are also present as far as 75°N (Larsen et al. 2014). The ages of the lava series near the coast in North-East Greenland range from 56 to 53 Ma, whereas the ages for lavas on inland nunataks in Arnold Escher Land range from 53 to 50 Ma (Larsen et al. 2014). For comparison, the Main Basalts along Blosseville Kyst erupted during a time span of only one million years (56–55 Ma; Brooks 2011). The flood basalts along Blosseville Kyst attained a total vertical thickness of up to 5.5 km, but subsidence kept pace with the thickness of extruded basalts. As such, individual lava flows can be traced over thousands of square kilometres, indicating a largely horizontal lava plain without significant relief (Larsen et al. 1989; Pedersen et al. 1997). Marine incursions onto the earliest and latest basalt flows along Blosseville Kyst show that the landscape was low-lying during the volcanic eruptions (Wager & Deer 1939; Nielsen et al. 1981; Larsen et al. 1989, 2013; Pedersen et al. 1997; Larsen & Tegner 2006; Brooks 2011). A phase of middle Miocene volcanism is documented by the presence of the lava flows of the Vindtop Formation (c. 14–13 Ma; Storey et al. 2004) that crop out on nunataks within a small area at 2.7–2.9 km a.s.l., just south of our study area (c. 69°N). Pliocene–Pleistocene deposits within our study area are reported from Jameson Land, Île de France (c. 78°N) and Store Koldewey (Freyling-Hansen et al. 1983; Bennike et al. 2002, 2010).

Interpretation of seismic data off East Greenland has provided evidence for distinct tectonic activity along the margin during the late Eocene – early Oligocene and mid-late Miocene (Larsen et al. 1994a; Hamann et al. 2005; Døssing et al. 2016; Petersen 2019).

3.2 Glacial history

Stratigraphically extensive, ice-rafted debris, including macroscopic drop stones, occur in late Eocene to early Oligocene sediments from the Norwegian–Greenland Sea, indicating sediment rafting by continental ice and East Greenland as the likely source (Eldrett et al. 2007). Eldrett et al. (2009) presented climate estimates for the Eocene–Oligocene based on spore and pollen assemblages in marine sediments from the Norwegian–Greenland Sea. The climate estimates indicated cooling across the Eocene–Oligocene transition, but also provide evidence for relatively warm summer temperatures at that time, and thus that continental ice on East Greenland was probably restricted to alpine outlet glaciers.

A phase of exhumation in East Greenland starting near the Eocene–Oligocene transition was defined from thermochronology data and was argued to have been caused by glacial erosion (Bernard et al. 2016). However, the timing is consistent with the late Eocene phase of uplift and erosion defined by AFTA data in West, South-East and North-East Greenland (Japsen et al. 2006, 2014, in press). This phase of exhumation in Greenland coincides with pronounced magmatic activity in East Greenland (Larsen et al. 2014), cessation of sea-floor spreading west of Greenland and with a major plate reorganisation in the North-East Atlantic (Gaina et al. 2009) and is thus likely to be of tectonic origin.

Studying ice-rafted debris from drill cores off South-East Greenland, Larsen et al. (1994a) concluded that full glacial conditions were established in South-East Greenland at 7 Ma. Similar evidence was identified in the borehole at Site 987 of the Ocean Drilling Program Leg 162 from the basin off Scoresby Sund. Here, upper Miocene – lower Pliocene sediments contain abundant ice-rafted debris and evidence for slumping and turbidity currents (Jansen et al. 1996; Channell et al. 1999).

Pérez et al. (2018) carried out seismo-stratigraphic analyses of Miocene to recent deposits on the continental shelf off Blosseville Kyst to Liverpool Land. Eight stratigraphic units were tied to the Ocean Drilling Program Site 987. The formation of the oldest sedimentary unit (unit 8, between the early Miocene oceanic crust and a 7.3 Ma discontinuity) was controlled by major tectonic events along the margin, notably the late Miocene uplift episode at c. 10 Ma, as defined by AFTA data in rock samples from the Blosseville Kyst region (Japsen et al. 2014). Pérez et al. (2018) explained the

high sediment input in this time interval by the presence of fluvial systems onshore. The subsequent, upper Miocene to lower Pliocene unit 7 (7.3–4.9 Ma) forms a widespread sedimentary body with isolated depocentres along the outer shelf, mostly off the major inland fjords. Pérez *et al.* (2018) inferred that cross-shelf glaciation began to influence the shelf during this interval at the time of the proposed onset of widespread glaciation in Greenland around 7 Ma, indicated by the occurrence of ice-rafted debris (Larsen *et al.* 1994a, 1994b; Jansen *et al.* 1996; Channell *et al.* 1999). Subsequently, two major phases of ice-sheet advance occurred across the shelf. First one was in the early Pliocene (unit 6), likely influenced by topographic forcing during early Pliocene uplift (Japsen *et al.* 2014). Second one was around the Pliocene–Pleistocene transition (unit 4). The deposits of the intervening phase (unit 5) reflect glacial retreat during the mid-Pliocene warm period (Raymo *et al.* 1996). Sedimentary successions from the Pleistocene to present (units 4–1) contain features that indicate that full-scale Greenland glaciation was established at 2.9 Ma (Sarnthein *et al.* 2009; Pérez *et al.* 2018).

Biomolecules from the silty section at the base of deep ice cores in central southern Greenland suggest that the region was forested sometime within the past million years (Willerslev *et al.* 2007). While measurements of cosmic-ray-produced isotopes in a bedrock core from central Greenland further indicate that Greenland was deglaciated for extended periods during the Pleistocene Epoch (2.6 Ma to 11.7 ka; Schaefer *et al.* 2016; see also Solgaard *et al.* 2013). The Greenland ice sheet that today has a thickness of up to 3 km, thus, appears to have had a discontinuous history.

3.3 Large-scale landscapes
Here, we briefly review previous work on the large-scale landscapes in East Greenland. Altitudes in North-East Greenland vary significantly from a relatively low-lying terrain along the coast, across the Carboniferous–Palaeogene basins, to the elevated plains across crystalline basement, Devonian sediments and Palaeogene basalts further inland (Fig. 4). Elevation in the coastal zone rarely exceeds 1 km a.s.l.; however, the plateaus in the hinterland are typically around 2 km a.s.l., although Stauning Alper has peaks of up to 2.8 km a.s.l. (Figs 4, 5). The plateaus are often covered by thin ice, but north of 74°N the ice sheet almost reaches the coast. The elevation contrast between the exhumed basins along the coast and the interior basement terrains is pronounced along the post-Devonian Main Fault system.

A peneplain overlain by upper Permian, shallow marine sediments, has been identified both west and east of Jameson Land (Haller 1971; Larsen 1988; Surlyk 1990; Vigran *et al.* 1999; Stemmerik 2000). Surlyk (1990)

concluded that the peneplain represents the latest Carboniferous to early Permian unconformity that marks the most profound change in tectonic style and overall depositional environment in the post-Caledonian development of East Greenland. This marks the transition from a long period of crustal extension to a period of subsidence governed mainly by thermal relaxation of the rifted crust.

A peneplain covered by Middle and Upper Jurassic sandstones of marine origin is exposed on Kuhn Ø and Milne Land (Surlyk 2003; Surlyk & Ineson 2003). Extensive denudation that started in the early Jurassic most likely led to the formation of this surface.

The landscape of the coastal areas of Jameson Land and Liverpool Land is the result of tertiary plateau uplift that resulted in partial denudation of the Mesozoic basins according to Peulvast (1988, 1991). Peulvast (1988) described a 10 km-wide westward-sloping plateau on Liverpool Land that he regarded as a sub-Triassic planation surface. Mapping showed that it disappeared to the west below the sediments on Jameson Land, while the surface was obliterated near the most uplifted parts on Liverpool Land. He regarded the westerly tilted surface on Jameson Land as mainly structural, although he speculated that some near-horizontal, post-Mesozoic peneplains might be present on Liverpool Land at 800–900 m a.s.l.

The unconformity between Palaeogene basalts and basement rocks on Milne Land and Gåseland was mapped by Larsen *et al.* (1989). They concluded that the basement formed a high ridge with irregular topography and large relative relief at the time of basalt eruptions, and that the basement acted as a barrier, directing various basalts flows. The saprolites encountered at the basement-basalt contact are kaolinitic (Birkelund & Perch-Nielsen 1976).

The fjord landscapes from Jameson Land to Hudson Land was studied by Swift *et al.* (2008) who defined the 'first-order topography' based on a map combining elevation and slope together with elevation profiles and geology. They identified three elevational areas reflecting the main aspects of the geology, separated by escarpments along major geological boundaries. These include:

1. Areas composed of Mesozoic strata to the east of the post-Devonian Main Fault system that are generally of low elevation with low to moderate relief and gently incised.
2. Areas west of the post-Devonian Main Fault where the landscape is more elevated and steeply incised by fjords.
3. Areas composed of Caledonian crystalline basement in the south and east that have the highest elevations and the deepest incision.
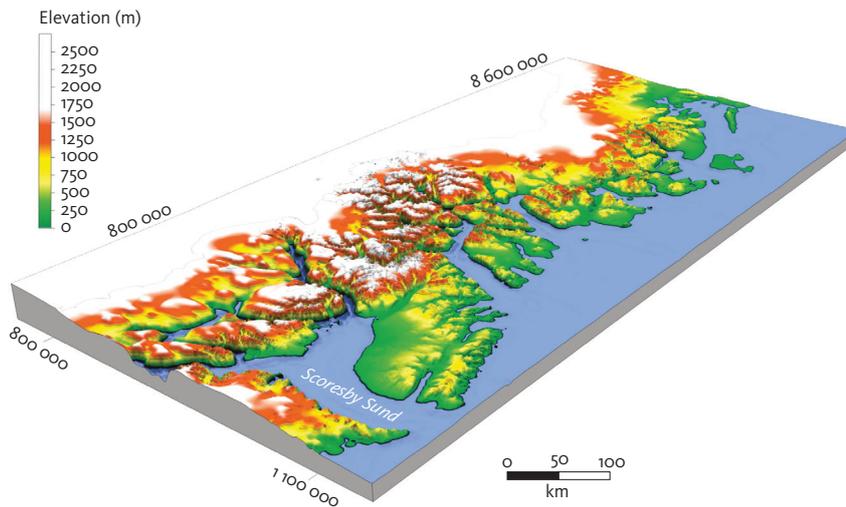
A strong link between elevation and lithology was noted. In particular, the Caledonian basement was shown to have formed a consistent, high-elevation, low-relief landscape at *c.* 2000 m a.s.l., locally incised by the fjord system. The presence of Palaeogene sediments beneath Palaeogene basalts (Jolley & Whitham 2004) indicated that the present-day first-order topography had existed prior to at least 55 Ma. The conclusions of Swift *et al.* (2008) were thus based on the configuration of the pre-basalt surface, and particularly on a contour map of that surface on Milne Land (Larsen *et al.* 1989), which they found to mirror the present topography. Finally, they found that glacial modification of the landscape is strongly influenced by first-order geology and hence lithological resistance to erosion.

The large-scale landscapes of North-East Greenland (72–76°N) was studied by Ahlmann (1941) who demonstrated that topography could provide evidence of tectonic events in the past. His main conclusion is still important: '... the plateau and summit areas are the remains of what has once been a more or less uniform, high plateau rising towards the west'. He interpreted the elevated plateau there as the 'initial topography' from which the present relief had evolved by valley incision after uplift. Ahlmann argued that the landscape in North-East Greenland consisted of one plateau surface, dissected by valleys, and that the landscape was arched towards the present-day coastline. He observed that the plateau cuts across the basalt sequences and therefore concluded that it was an erosional surface that had formed after the extrusion of the volcanics. As the surface was incised by deep valleys, he deduced that the timing for the uplift to its present elevation was in the late Tertiary. Ahlmann's interpretation that the dominant topography is of post-basalt age is thus at odds with that of Swift *et al.* (2008), who considered it to be pre-basalt.

The regional post-basalt plateaus mapped by Ahlmann continue south of the study area, into the large-scale landscape between 68°N and 71°N, studied by Bonow *et al.* (2014). This led to the identification of two elevated, post-basalt erosion surfaces of regional extent – the UPS and LPS. Bonow *et al.* (2014) concluded that these surfaces were the result of significant erosion, a conclusion that was in agreement with studies of the zonation of zeolite minerals in the Palaeogene basalts (Larsen *et al.* 1989; Neuhoff *et al.* 1997). Collectively, these studies showed that up to 1200 m of basalts (and possibly younger rocks) have been removed since the extrusion of the volcanics in South-East Greenland. For example, at least 400 m was estimated to have been removed on Milne Land.

4 Methods

Fieldwork was conducted in the study area during the summer of 2008 and 2010, using a helicopter for reconnaissance field support and as a platform for obtaining oblique photographs. We mapped planation surfaces map between 70°N and 78°N, using the methods described by Bonow *et al.* (2014). We used the Global Land One-kilometre Base Elevation (GLOBE) digital elevation model for construction of a general 3D landscape model of the study area in East Greenland (Fig. 5) and we used the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM; *c.* 30 m resolution) for

1. construction of a map with 100 m contours (Supplementary files S1, S2; Fig. 6)
2. construction of topographical profiles (Supplementary file S3; Fig. 6)
3. construction of swath profiles (Supplementary file S3; Fig. 6).

The elevation data contain some artefacts, for example, zero-value data occur in near-vertical mountainsides along fjords, resulting in data gaps in the model. There

Maximum topography in swath
Topography along profile
Minimum topography in swath
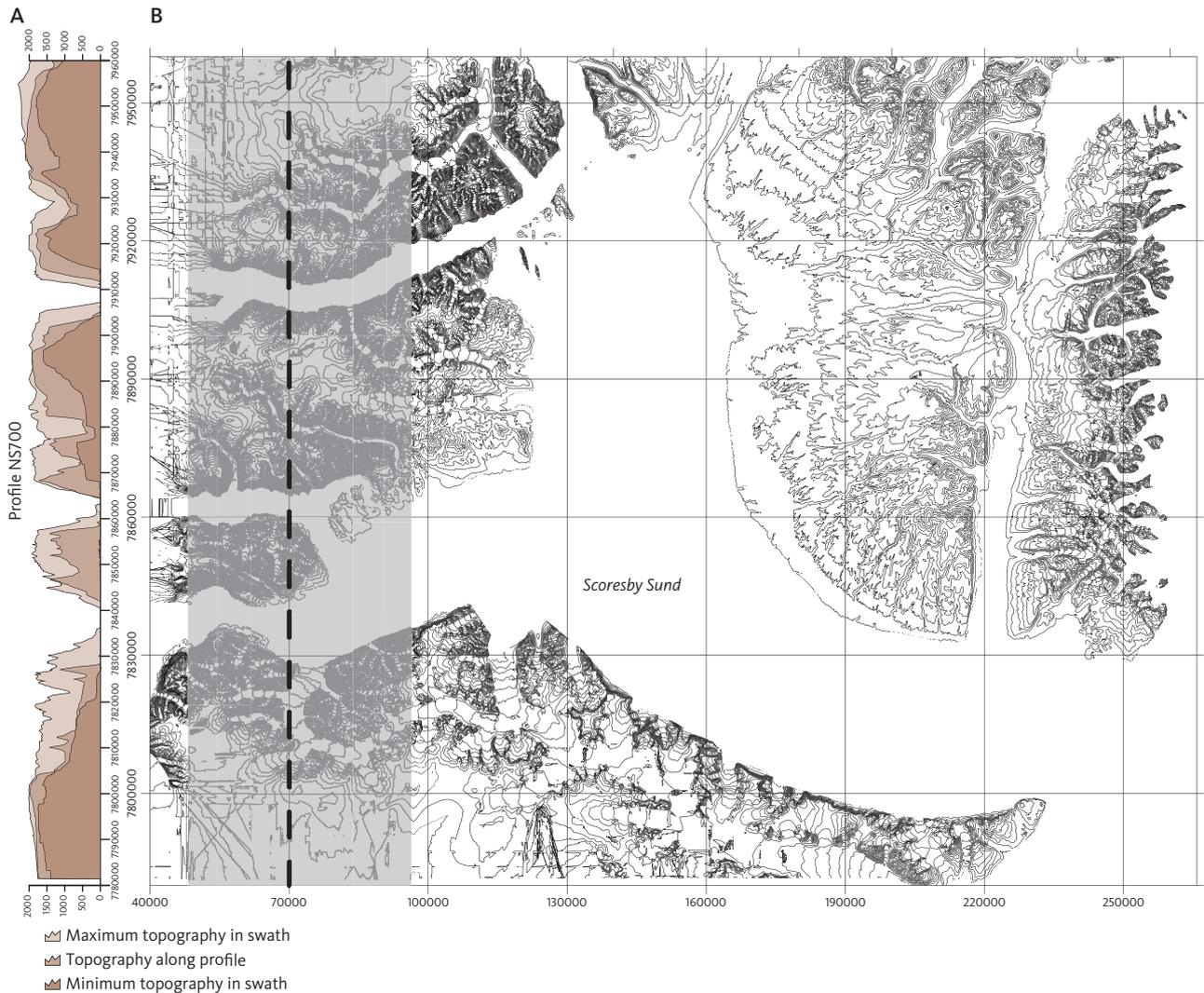
Fig. 6 Construction of topography profiles with minimum and maximum elevations within a swath: **A**: North–south profile with topography along the profile transect and with maximum and minimum elevations within the swath. X-axis: UTM northing (km). Y-axis: Elevation (km). Location in Fig. 4. **B**: The 100-m contour map constructed from ASTER data. These data are used in the surface mapping and to construct topography profiles. UTM coordinates indicated (km; UTM zone 27N). **Grey area**: 50-km wide swath used to calculate maximum and minimum elevation along the profile. **Black dashed line**: the actual topography along profile shown in panel A.

are also some extreme values that result in erroneous peaks in the model. Further, elevation data are rather poor in areas where small, melt-water lakes appear on the ice sheet surface.

Topographical profiles were extracted from the ASTER elevation data along a square grid, spaced 25 km apart. Maximum and minimum elevations along the topographical profiles were also extracted in a 50-km wide swath. The profiles were printed on paper strips to the same scale as the contour map (1:500 000). The topographical profiles in combination with the swath profiles were used to support the mapping (Fig. 6). We cross-analysed 58 profiles with a cumulative length equal to 20 000 km.

The mapping of the surfaces started in areas of low relative relief with only minor fluvial incision. We determined the edge of a surface where there was a rapid change of inclination as seen from closely-spaced contours on the contour map. In the low-relief areas, maximum elevation along the swath coincides with the topographical profile, and thus provides a means of expanding the surface mapping into the dissected areas. This method of combining profiles and a contour map is useful for identifying offsets and tilting within a surface (see Lidmar-Bergström 1988; Bonow *et al.* 2006b, 2014).

We cross-checked the interpretation made on the contour map from profile to profile to ascertain that the interpretation was consistent. We also compared the mapped surfaces with the geological maps (Bengaard *et al.* 2007, topographical maps (GEUS 2007) and oblique photographs from the archives of the Geological Survey of Denmark and Greenland (GEUS).

5 Results

This study overlaps with the mapping of Bonow *et al.* (2014) in the area between 70°N and 71°N, where we identify the same elevated landscape features – the UPS and LPS (Figs 7, 8). We see that these features extend across Northeast Greenland between 70°N and 78°N (Figs 5, 9), and so they are the focus of the mapping and analysis in the current study. We also report the mapping of an exhumed etch surface (ES) formed by deep weathering (Supplementary files S1, S2). High-resolution contour maps for the northern and southern parts of the study area, overlain with the outline of the erosion surfaces, are provided as Supplementary files S1 and S2, respectively. Topographic profiles are also provided as a Supplementary file S3.

5.1 Mapping of erosion surfaces
5.1.1 The deeply weathered basement

Around Milne Land and Gåseland, weathered basement rocks are exposed at their contact with both Palaeogene basalts (Fig. 10) and Jurassic sediments (Fig. 11). A detailed analysis of these sub-Palaeogene and sub-Jurassic, weathered surfaces is beyond the scope of this paper. However, these surfaces are important as they provide snapshots of the erosional and depositional pre-basalt history of the margin. For example, the presence of weathered basement that crops out below marine Jurassic sediments shows that after the period of weathering and erosion of the land surface, prior to the Jurassic, the landscape was buried during subsidence, resulting in deposition of the marine sediments. A later
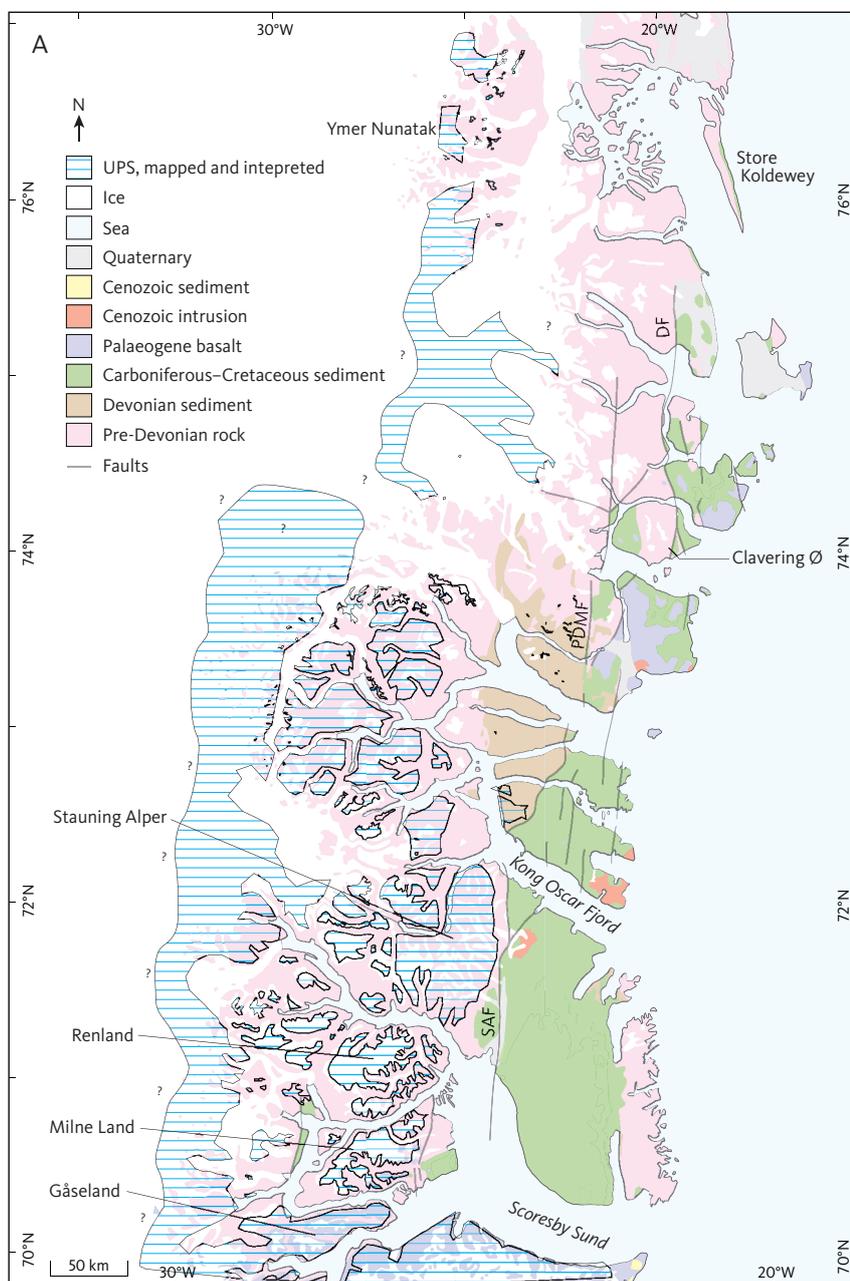
Fig. 7 Outlines of the Upper Planation Surface (**UPS**) and Lower Planation Surface (**LPS**) in North-East Greenland: **A**: UPS . **B**: LPS. See Fig. 4 for additional place names and supplementary files S1 and S2 for maps of these surfaces at 1:500 000 scale.

phase of uplift that must have occurred after the Jurassic raised the marine sediments to their present position in the landscape, which are now visible overlying the weathered basement. This is geological evidence of an episodic development of the landscape, in contrast to the frequent assumption of a progressive emergence of the bedrock (e.g. Pedersen *et al.* 2012).

The outline of the weathered basement is shown in Supplementary file S1, and some of the details of the weathered basement are discussed by Larsen *et al.* (1989). Where a bedrock surface is formed by deep weathering, its character does not depend on the age of the cover rocks, for example, Jurassic sediments or Paleocene basalts. For the purpose of this paper, which is to distinguish between the pre-basalt and the

post-basalt landscape development, we chose to refer to these different pre-basalt surfaces as a single ES, as this term describes the formation process, the characteristics of saprolites and the general hilly relief shape of the basement (e.g. Bonow 2005).

The ES can be mapped with high confidence close to cover rocks, but it is more difficult to identify in areas with no cover and further away from cover rocks. It is especially difficult to identify deeply weathered surfaces in formerly glaciated areas because classical roche moutonnée landscapes (e.g. Sugden 1974; Glasser & Warren 1990; Freire *et al.* 2015) are highly similar in shape to bedrock forms shaped by weathering (Lindström 1988; Sugden *et al.* 1992; André 2001, 2002; Migoń & Lidmar-Bergström 2001; Bonow 2005; Krabbendam &
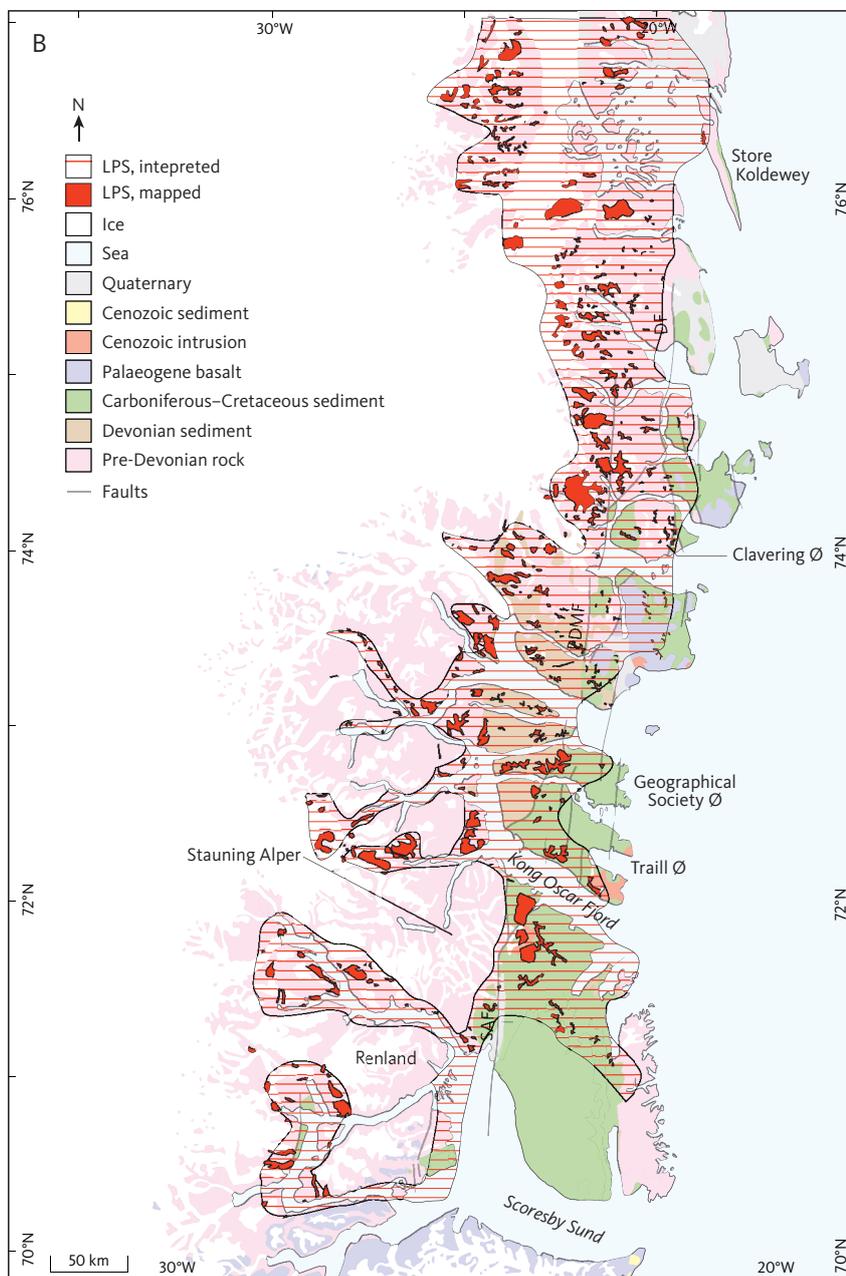
Fig. 7 (Continues) Outlines of the Upper Planation Surface (**UPS**) and Lower Planation Surface (**LPS**) in North-East Greenland: **A**: UPS . **B**: LPS. See Fig. 4 for additional place names and supplementary files S1 and S2 for maps of these surfaces at 1:500 000 scale.
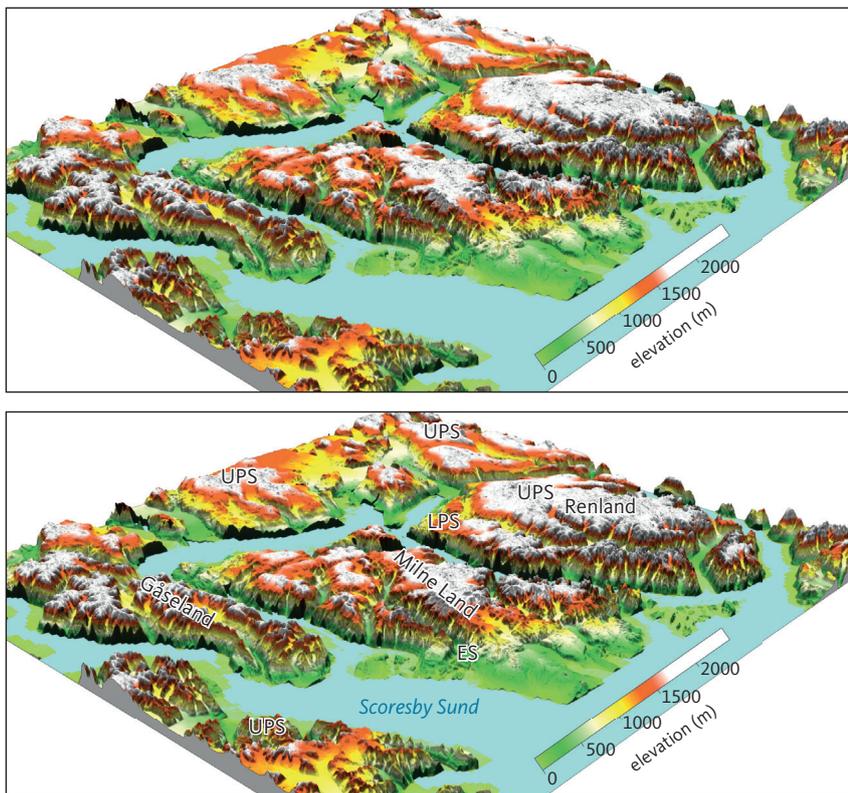
Fig. 8 3D model from ASTER data showing the characteristic landforms in the region around Gåseland, Milne Land and Renland: **A**: 3D model with no labels. **B**: The same 3D model with labels. The Upper Planation Surface (**UPS**) is well preserved, while the Lower Planation Surface (**LPS**) is mainly identified along the main valleys. The inclined Jurassic etch surface (**ES**) is identified in eastern Milne Land where it is cut off by the UPS. Location in Fig. 4.

Bradwell 2014; Lidmar-Bergström *et al.* 2017; Hall *et al.* 2020). All parts of the identified ES in the study area are close to cover rocks and thus, we have high confidence in our mapping of its extent. On Milne Land, the tilted ES is cut off by the near-horizontal UPS that formed across both basement and basalts, which shows that the UPS formed after the ES (Figs 11, 12).

5.1.2 The Upper Planation Surface

The UPS dominates the landscape away from the coast, especially south of 74°N. The UPS is up to 200 km wide and extends across the study area for more than 900 km in north–south direction. Photographs provide further visual evidence of the continuity of the UPS across wide areas (Figs 11–14). North of 74°N, the UPS disappears below the Greenland ice sheet. The UPS is to a large extent covered by ice due to its high elevation at around 2 km a.s.l. The ice increases in thickness towards the west. In the northernmost part of the study area, the UPS occurs at slightly lower elevation, *c.* 1.5 km. South of Scoresby Sund the UPS becomes more elevated (above 3 km) in the Kangerlussuaq area (*c.* 400 km south of the study area; Bonow *et al.* 2014). In the south, a flat bedrock surface was observed in section and photographed along the rim of incised valleys, emerging from beneath the thin ice caps. These plateau rims are typically too small to be represented on the maps, but

these observations support the mapping and allowed us to interpret the bedrock surface as part of the UPS.

North of 74°N, the UPS is represented by minor, flattish remnants located where the Greenland ice sheet becomes coherent (Fig. 7A); for example, Ymer Nunatak in the northernmost part of the study area (Fig. 4). It is not possible to assess the relief of these surfaces as only the rim is exposed from below the ice cover, but the rims appear to be flat. The correlation between the well-developed UPS in the south and the remnants in the north is less well constrained because of the ice cover and the long distance between them. Thus, in this part of the study area, it is not always clear how to correlate the surface on the topographical profiles.

In the south, especially on Milne Land and Gåseland, the UPS is developed across rocks of different age and of different resistance (Fig. 7A). For example, on Milne Land the UPS developed across Palaeogene basalt (Fig. 15A) and crystalline basement rocks (Fig. 15B) just a few kilometres apart and at about the same elevation. On Gåseland, the UPS is about 700 m below the original top of the volcanic pile as estimated from zeolite stratigraphy (Larsen *et al.* 1989; Fig. 12), offering further evidence that the position of the UPS is not defined by structural control on a regional scale from flat-lying lava flows.

The UPS cuts across the Palaeogene basalts at about 2.2 km a.s.l. in Arnold Escher Land, located about 200 km from the coast and close to the ice sheet (74°N, 28°W;

Fig. 4). The UPS is thus mainly preserved in basalts and basement rocks in the southern part of the study area. However, the landscapes across the sedimentary basins near the coast are characterised by many ridges and minor flattish summits that reach the projected level for the UPS, even in areas such as Traill Ø with sedimentary rocks at 1800 m a.s.l.

Offsets of the UPS along the topographical profiles would indicate tectonic movements after the formation of the UPS. We could not identify any, but some movements cannot be ruled out as the ice covering the UPS obscures its precise identification in many places, and correlating the UPS across a fjord or a valley is occasionally problematic. Where there are offsets, however, they are only minor, indicating that the entire region where the UPS is preserved has been uplifted and appears to have acted as a single tectonic unit. A deviation from this pattern occurs in Stauning Alper where the summits reach an elevation of 2.8 km a.s.l. – the highest elevation within the study area. Even though no remnants of the UPS were identified in this area, it was possible to use the swath profiles to reconstruct the elevation of the UPS fairly well (Fig. 16). The contours of the UPS define a dome around Stauning Alper, whose highest area is above *c.* 2.3 km a.s.l. (Fig. 9A). The domal pattern of the UPS in this region indicates that a fairly localised, tectonic movement occurred after the formation of the UPS. South of the study area, in the Blosseville Kyst region, the elevation of the UPS increases and approaches 3.5 km a.s.l. near Gunnbjørn Fjeld, which at 3.7 km a.s.l. is the highest mountain in Greenland (Bonow *et al.* 2014).

The UPS is well defined across large areas, but less so where only a limited part of the UPS is preserved, including coastal areas with only a narrow ice-free landmass. Here, the precise extent and the correlation of the surface between profiles (especially in north–south direction) are uncertain. This is the case for the UPS across most of the sedimentary areas in the east and in the region north of 74°N. Another source of uncertainty is the presence of extensive ice caps that cover much of the surface. This problem cannot be solved completely, but the presence of minor remnants of flat surfaces or nunataks, supports the interpretation that the UPS is present below the ice. This is further supported by the occurrence of outliers of Palaeogene basalts on the inland nunataks in Arnold Escher Land that are equivalent to, but slightly younger than, the basalts on Milne Land (Fig. 4; Larsen *et al.* 2014).

In summary, the formation of the UPS must have been governed by the general base level at the time of formation, as the surface cuts across rocks of different age and resistance (Figs 11–13, 15). Therefore, the UPS is not a structural surface, such as the top of the last basalt flow, which an investigation of a minor area might suggest. Since the UPS developed after the extrusions of the Palaeogene basalts and the onset of sea-floor spreading in the North-East Atlantic, the general base level must have been the Atlantic Ocean. Hence, we can consider the UPS as a peneplain.

5.1.3 The Lower Planation Surface
The LPS typically occurs at *c.* 1 km a.s.l. and it extends across a 50 to 75 km wide zone (up to 100 km) inland from the coast (Fig. 7B). It also exists as wide-valley benches along some of the major fjords further inland (Figs 17, 18). In the areas where sedimentary rocks crop out, the LPS is defined by flat-topped summits that make up a coherent surface, while in areas with basement rocks, the LPS is more extensive and less dissected (Fig. 18). North of 74°N, the LPS dominates the ice-free areas of the upper-plateau landscape in near-coastal areas (Fig. 7B). However, south of 74°N, the LPS and the UPS co-exist, and the LPS can occasionally be followed as a wide-valley bench along some of the major valleys (Figs 9, 17). The LPS reaches an elevation of 2 km a.s.l. in the southern part of the Blosseville Kyst area (*c.* 68⁰N; Bonow *et al.* 2014), where it is continuous across different rock types with significantly different resistance to erosion. The difference in geology defines how developed the LPS is; that is, less developed in resistant rock and vice versa. The LPS is incised below the UPS, and therefore younger.

The LPS thus extends from valley benches in basement rocks in the interior to plateau remnants in sedimentary rock at the same elevation closer to the coast. This supports the finding that the formation of the LPS was controlled by the fluvial system and thus graded towards the new base level, which again must have been the Atlantic Ocean, and hence we can also consider the LPS to be a peneplain.

5.1.4 Escarpments and faults
The post-Devonian Main Fault system is a prominent feature that runs north–south through the study area (Fig. 4). East of the fault, where sediments are exposed, the UPS is not present, possibly because it has been destroyed. The LPS, however, is defined on both sides of the post-Devonian Main Fault at about the same elevation (Fig. 7B). West of the fault, the LPS is defined by wide-valley benches, and the surface continues at the same elevation east of the fault, where it is defined by flat-topped summits. The escarpment between the UPS and the LPS follows along the major valleys.

5.2 Relative denudation chronology and magnitude of uplift
5.2.1 Constraints on the timing for the formation of the UPS and LPS
The UPS post-dates the extrusion of the basalts in the Paleocene–Eocene transition (*c.* 56 Ma) as the surface truncates both the Palaeogene basalts and older
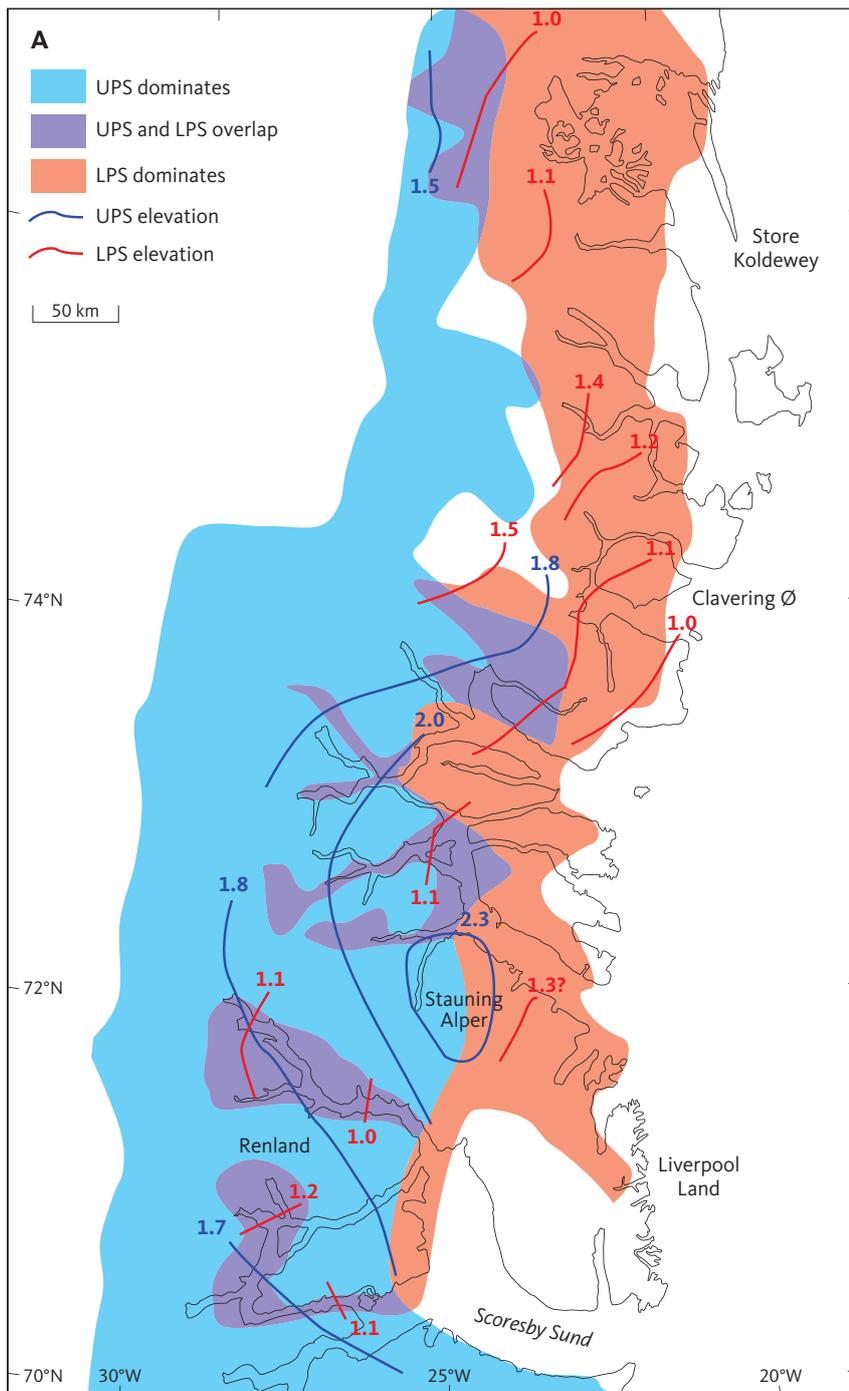
Fig. 9 Extent and elevation of the Upper and Lower Planation Surface (**UPS** and **LPS**): **A**: UPS and LPS shown with elevation contours. **B**: UPS and LPS annotated with the location and orientation of Figs 10–20. The UPS is typically 2 km a.s.l., identified mainly south of 74°N at some distance from the coast. North of 74°N, the UPS is identified only as small remnants close to the Greenland ice sheet. The LPS is typically 1 km a.s.l. and coalesces to form a coherent surface towards the coast. Note the dome structure of the UPS centred on Stauning Alper, which suggests tectonic doming after formation of the UPS.

rocks. The wide areal extent and low relative relief of the surface indicate long-term, tectonically stable conditions during its formation as, given enough time, resistant rocks will be denuded until all significant topographical expression has been removed (Fig. 2). This could take several million years, as was suggested for West Greenland (Bonow *et al.* 2006b, 2007a, 2007b; Japsen *et al.* 2009). We therefore find that the UPS represents a single erosional phase that affected East Greenland, at least between 68°N and 78°N as documented in this paper and by Bonow *et al.* (2014).

The presence of the mid-Miocene lava flows of the Vindtop Formation (14–13 Ma; Storey *et al.* 2004), south of our study area (69.18°N), provide further constraints on the timing of the formation of the UPS. The Vindtop Formation rests on the Palaeogene basalts in a small area between 2.7 and 2.9 km a.s.l. According to the mapping of Bonow *et al.* (2014), this unconformity corresponds to the UPS and this implies that the UPS had formed prior to the eruption of the mid-Miocene volcanics, well before the onset of the Plio–Pleistocene glaciations (*c.* 2.7 Ma; Shackleton *et al.* 1988). As the valley benches associated with the

B

- UPS dominates
- UPS and LPS overlap
- LPS dominates

76°N

50 km

74°N

72°N

70°N

30°W 25°W 20°W

Store Koldewey

18B

Dr. Margrethe II Land

Payer Land

Tyrolerfjord

18A

Clavering Ø

Andrée Land

Kejser Franz Josephs Fjord

14C

Furesø

13D

Stauning Alper

14A

Nordvestfjord

Nathorst Land

16C

Hinks Land

13C

16A 16B

20 13A

14B Flyverfjord

13B

Th. Sørensen Land

Renland

Milne Land

Øfjord

Liverpool Land

15 B A

11A

10 14D

11B

Fønfjord

Gåseland

12

Gåsefjord

12C

Scoresby Sund

Geikie Plateau

Fig. 9 (Continues) Extent and elevation of the Upper and Lower Planation Surface (**UPS** and **LPS**): **A**: UPS and LPS shown with elevation contours. **B**: UPS and LPS annotated with the location and orientation of Figs 10–20. The UPS is typically 2 km a.s.l., identified mainly south of 74°N at some distance from the coast. North of 74°N, the UPS is identified only as small remnants close to the Greenland ice sheet. The LPS is typically 1 km a.s.l. and coalesces to form a coherent surface towards the coast. Note the dome structure of the UPS centred on Stauning Alper, which suggests tectonic doming after formation of the UPS.
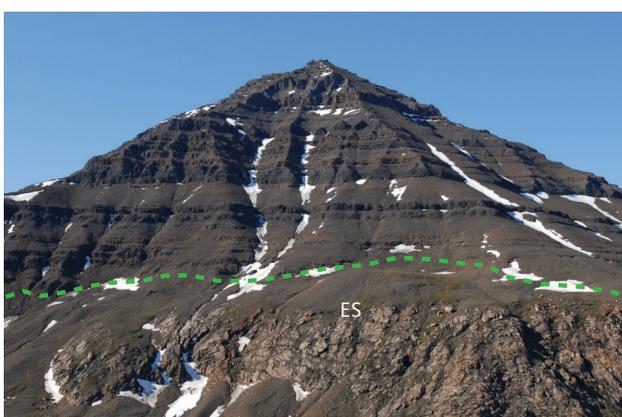
Fig. 10 The contact between Palaeogene basalt and crystalline basement is the re-exposed etch surface (**ES**), Milne Land: The basement is weathered and kaolinitic saprolites are found at the contact (e.g. Larsen *et al.* 1989). Photo location in Fig. 9.
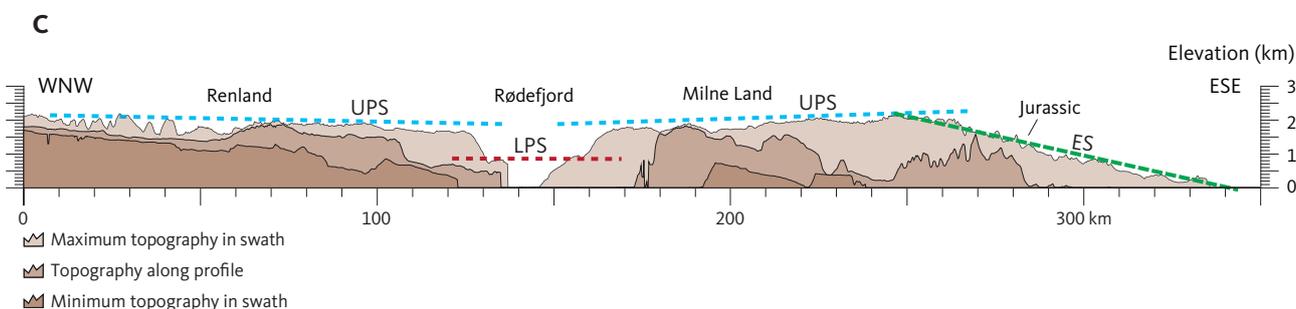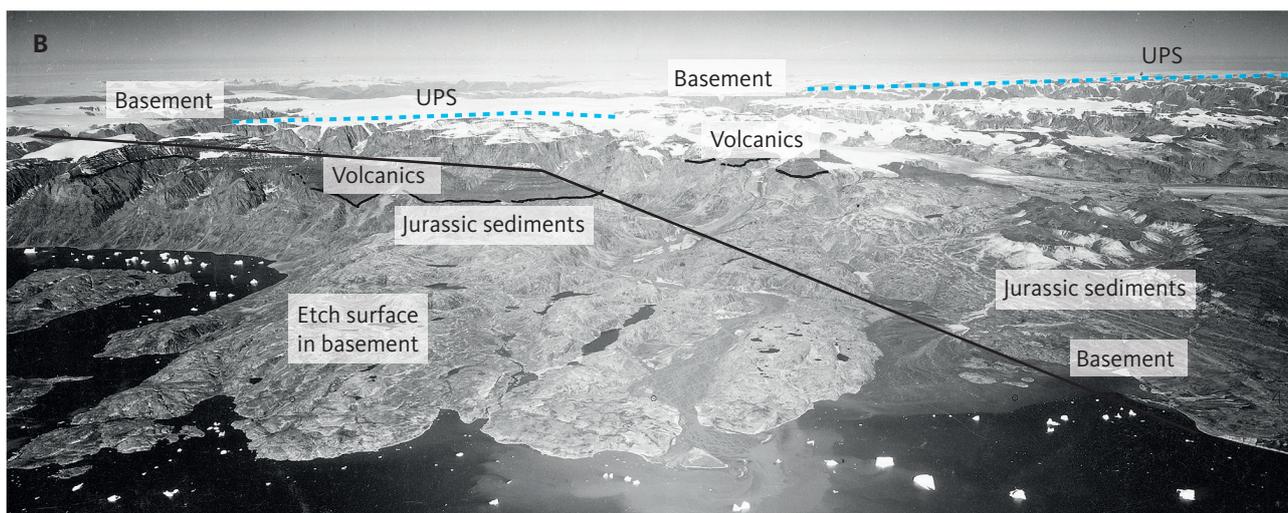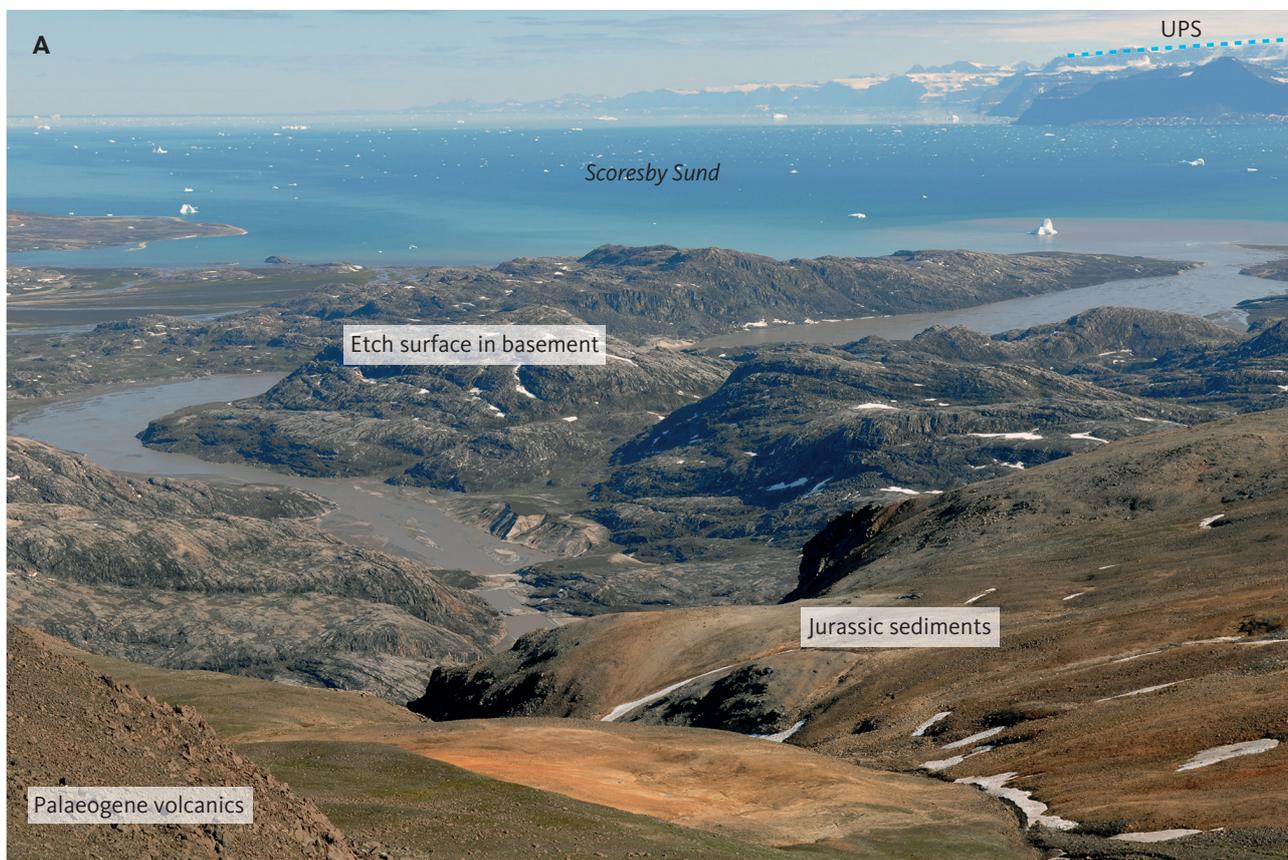
Fig. 11 The relationship between the deeply weathered basement (etch surface, **ES**) overlain by the Middle Jurassic Charcot Bugt Formation and Palaeogene basalts on southern Milne Land. The Upper Planation Surface (**UPS**) truncates the sub-Jurassic ES and the basalts. Location of photographs and profile are shown in Fig. 9. **A**: View from southern Milne Land across Scoresby Sund towards the Geikie Plateau where the UPS cuts across the basalts. The tilted ES of sub-Jurassic age is characterised by distinct hills defined by intensively weathered fracture systems prior to the deposition of the cover rocks. Jurassic sediments rest on the ES, which therefore constrains the final formation age of this surface. **B**: View of a tilted ES on southern Milne Land looking northwest. The extensive UPS is developed across Renland and beyond. The UPS truncates both the basement and the volcanics, which constrains the UPS as younger than the Palaeogene basalts (see also Fig. 15). Note that Jurassic sediments cover the ES, but also that valleys within the ES have been filled by basalt flows. This means that the Jurassic ES surface had been re-exposed prior to eruption of the Palaeogene basalts. **Black line**: Approximate location between the 210 and 340 km marks of the profile in C. Photo: Kort & Matrikelstyrelsen, Denmark. **C**: Swath profile illustrates the relationship between three surfaces: ES, UPS and the Lower Planation Surface (**LPS**).
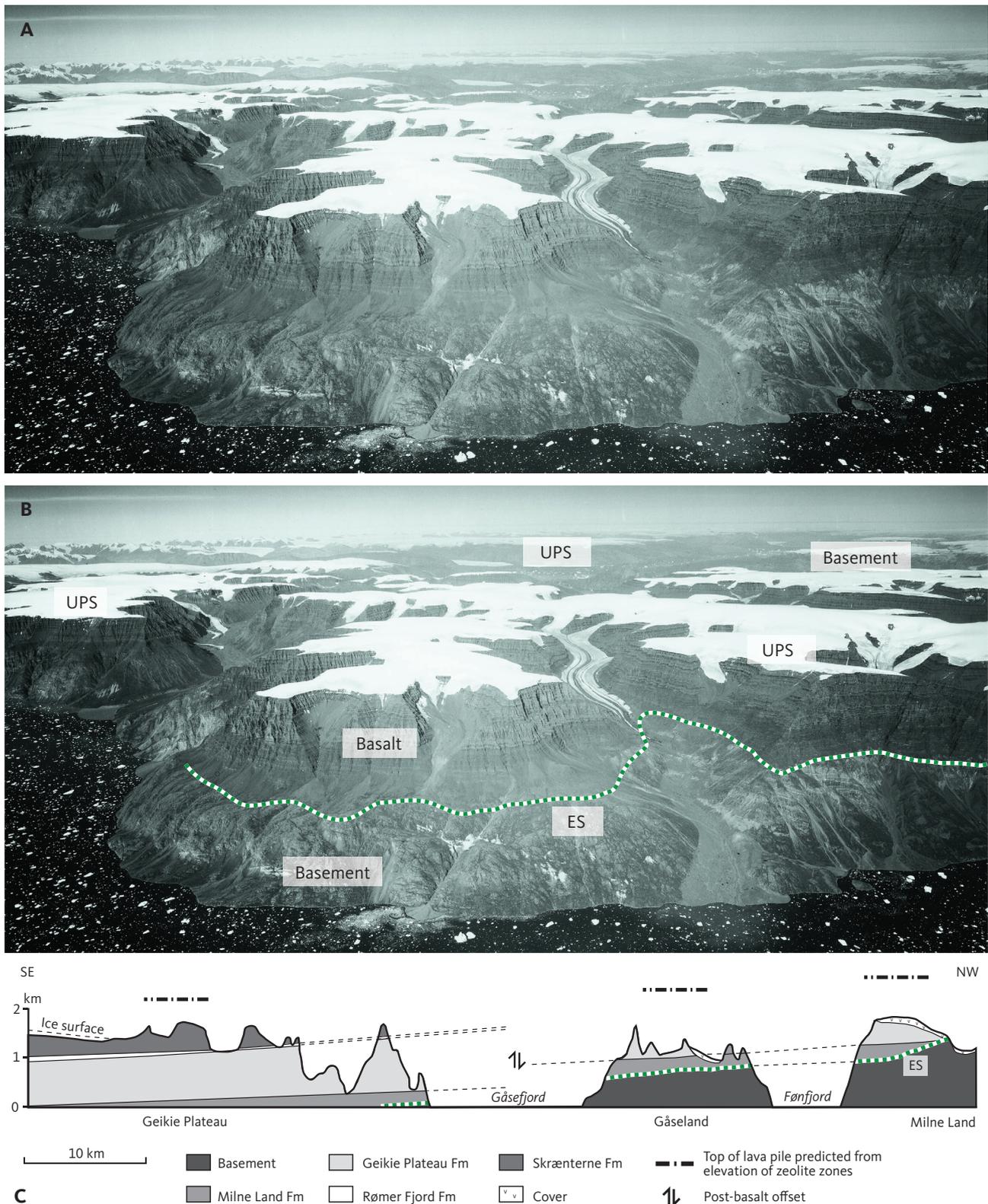
Fig. 12 The Upper Planation Surface (**UPS**) at an elevation of about 1800 m a.sl. developed across Palaeogene basalts on Gåseland. The UPS was likely formed by erosion after the extrusion of the volcanics. Locations shown in Fig. 9. **A**: View to the north-west across the inner part of Gåsefjord **B:** The volcanic strata are tilted south-east and about 700 m of basalt have been removed from above Gåseland (Larsen *et al.* 1989). The etch surface (**ES**) defines the base of the basalts. Photo: Kort & Matrikelstyrelsen, Denmark. **C**: Topography profile showing the inclined and truncated strata of the Main Basalts and the original top of the lava pile estimated from the elevation of zeolite zones across Milne Land, Gåseland and Geikie Plateau. The present-day lava surface is consequently an erosional feature and the tilt and offset of the basalt formations are post-basalt features. The UPS on Gåseland shown in panel B is thus about 700 m below the original top of the volcanic pile. Note the tilt of four formations of the Main Basalts, Geikie Plateau Fm, Skrænterne Fm, Milne Land Fm and Rømer Fjord Fm. Based on Larsen *et al*. (1989) and Bonow *et al*. (2014).
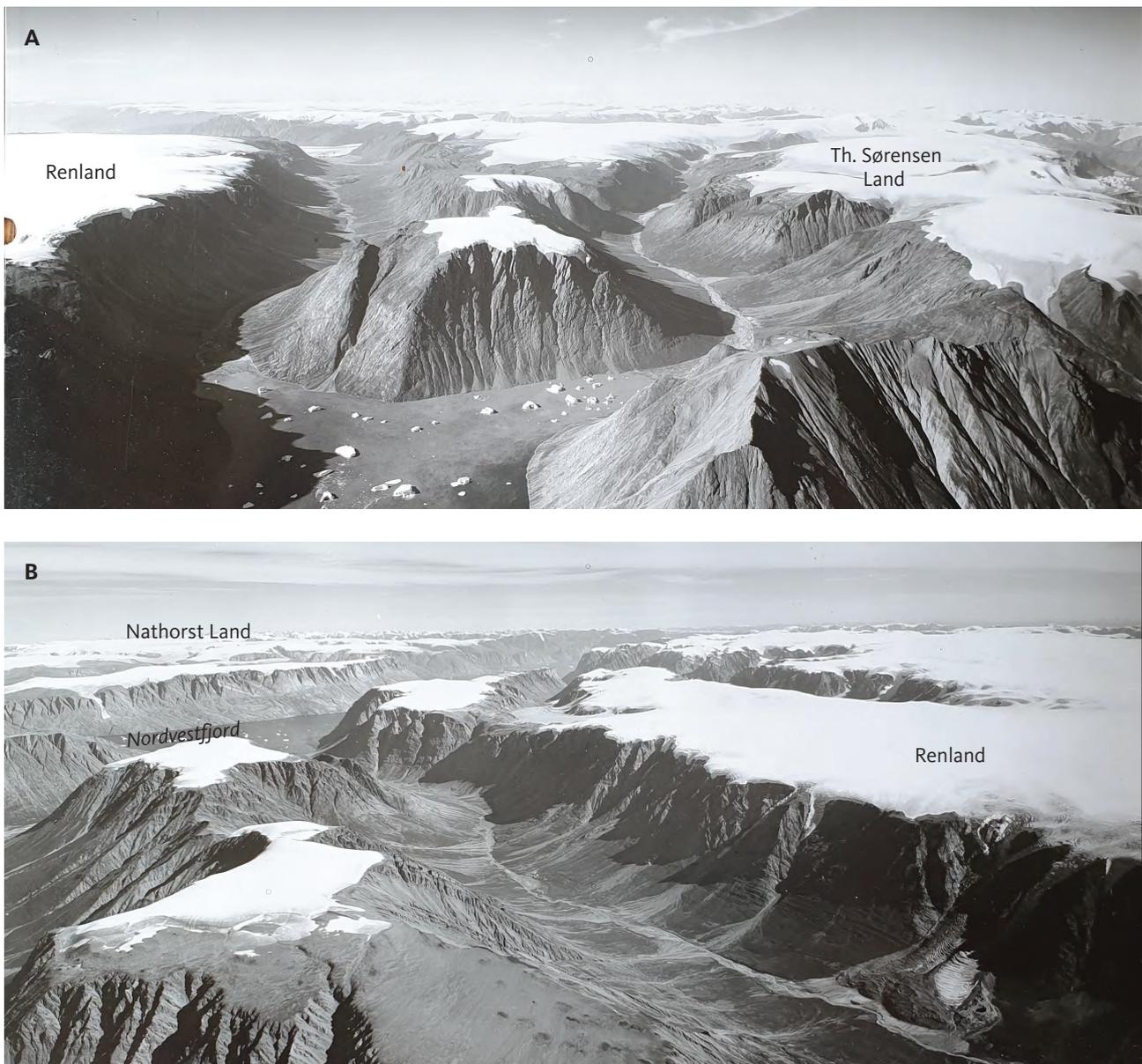
Fig. 13 The Upper Planation Surface (UPS) developed across basement rocks in the south-western interior of North-East Greenland: **A**: Looking south-west of Th. Sørensen Land and Renland across Nordvestfjord. **B**: Looking north-east from Renland towards Nordvestfjord and Nathorst Land. **C**: Looking south-west across the southern part of Stauning Alper towards Nordvestfjord and Renland. **D**: Looking south of Nathorst Land towards Furesø. Photo locations in Fig 9. Photo: Kort & Matrikelstyrelsen, Denmark.

LPS are fluvial in origin, this also suggests that the LPS was completed prior to the onset of the major, late Cenozoic glaciations at *c.* 2.7 Ma. The incision of the LPS below the UPS and the wide areal extent of the LPS in the north suggest: (1) a change of base-level (uplift) after the formation of the UPS and (2) re-establishment of relatively stable tectonic conditions so that the planation surface could develop across a large area. This cycle of events was repeated as the LPS is also uplifted. The LPS must have formed during the late Neogene as it is younger than the UPS that had formed by mid-Miocene times.

5.2.2 Amount of uplift

We have shown that the UPS and the LPS were formed as erosion surfaces graded to former base level and therefore, their present elevation and the difference in elevation between them can be used to estimate the amount of uplift since their formation (Fig. 19). The vertical distance between these two surfaces represents the magnitude of the first post-UPS uplift event, allowing for subsequent erosion. The distance from the LPS to the present sea level represents the second post-UPS uplift event. This means that after the UPS was graded to base level, an uplift phase raised it to about 1 km
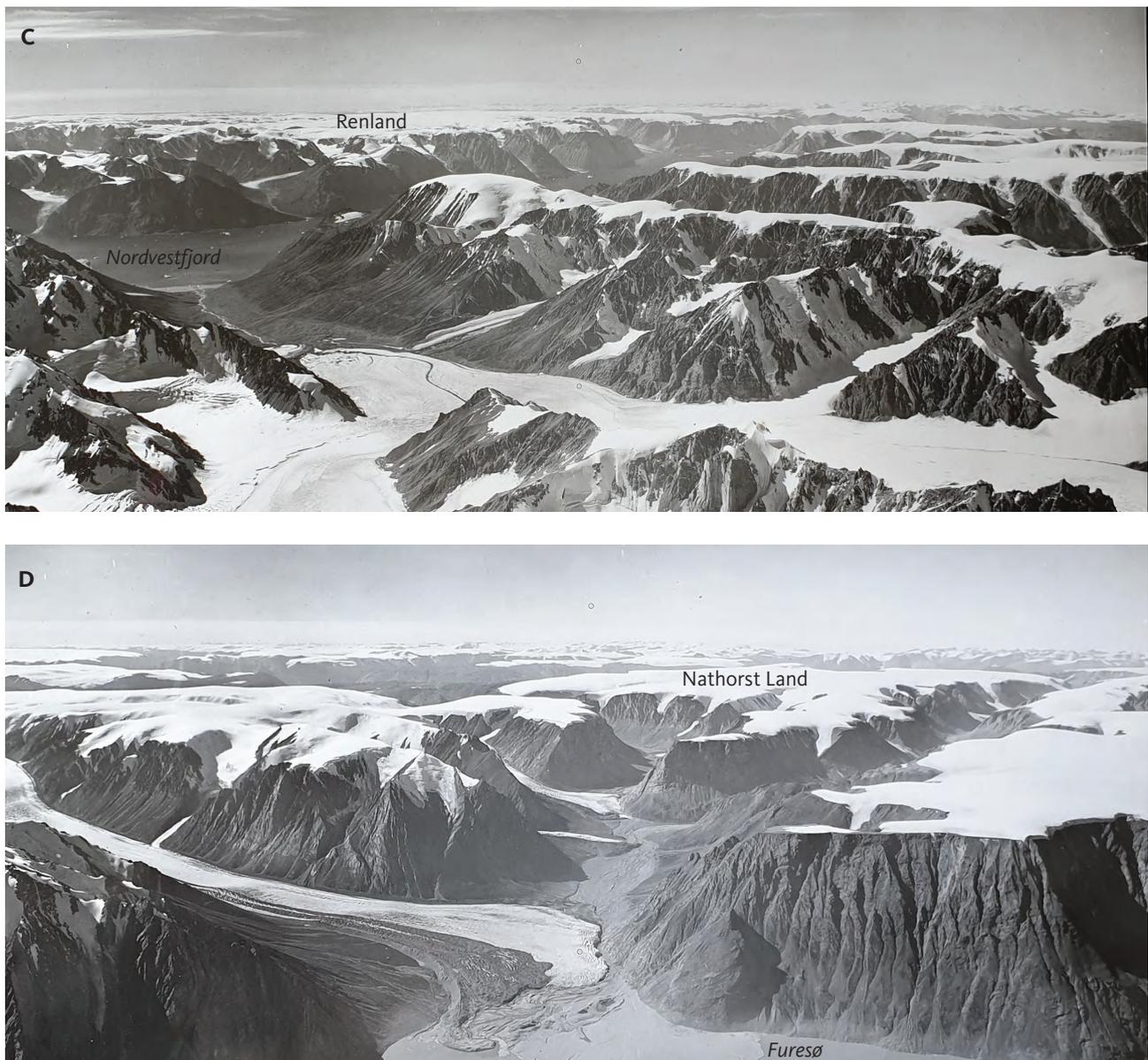
Fig. 13 (Continues) The Upper Planation Surface (UPS) developed across basement rocks in the south-western interior of North-East Greenland: **A**: Looking south-west of Th. Sørensen Land and Renland across Nordvestfjord. **B**: Looking north-east from Renland towards Nordvestfjord and Nathorst Land. **C**: Looking south-west across the southern part of Stauning Alper towards Nordvestfjord and Renland. **D**: Looking south of Nathorst Land towards Furesø. Photo locations in Fig 9. Photo: Kort & Matrikelstyrelsen, Denmark.

a.s.l., leading to incision that graded the LPS to sea level. A subsequent uplift phase of *c.* 1 km raised the whole landscape, leaving the LPS at about 1 km a.s.l. However, in the northernmost parts of the study area the LPS did not reach such heights, for example, 600 m on Germania Land. These two uplift events define the main appearance of the present-day topography in North-East Greenland.

5.2.3 Relative denudation chronology

Based on the mapping of the planation surfaces and the identification of re-exposed surfaces combined with the geological record, we propose the following relative denudation chronology for North-East Greenland.

Denudation and weathering of the basement in pre-Middle Jurassic and pre-Eocene times led to the formation of deeply weathered basement surfaces characterised by a hilly relief. The extrusion of Palaeogene basalts during the break-up of the North-East Atlantic was accompanied by rapid subsidence (e.g. Brooks 1985, 2011; Larsen *et al*. 1989).

The first uplift phase in post-basalt times was accompanied by erosion to the new base level, resulting in the formation of the UPS as a regional denudation surface that cuts across the Palaeogene basalts and older rocks. This phase most likely happened around the Eocene–Oligocene transition when uplift of the inner margin of South-East Greenland triggered a sudden and strong

Fig. 14 Thin ice covers the Upper Planation Surface (UPS) in many locations in North-East Greenland: **A**: View along Nordvestfjord towards the south-east. **B**: The east–west-trending Flyverfjord. North is to the left of the image. **C**: Looking west along the inner part of Kejser Franz Joseph Fjord towards Andrée Land. **D**: View from Milne Land towards the south across Scoresby Sund where the UPS defines the top of the basalts on Geikie Plateau. Photo locations in Fig. 9. Photos A–C: GEUS archive.
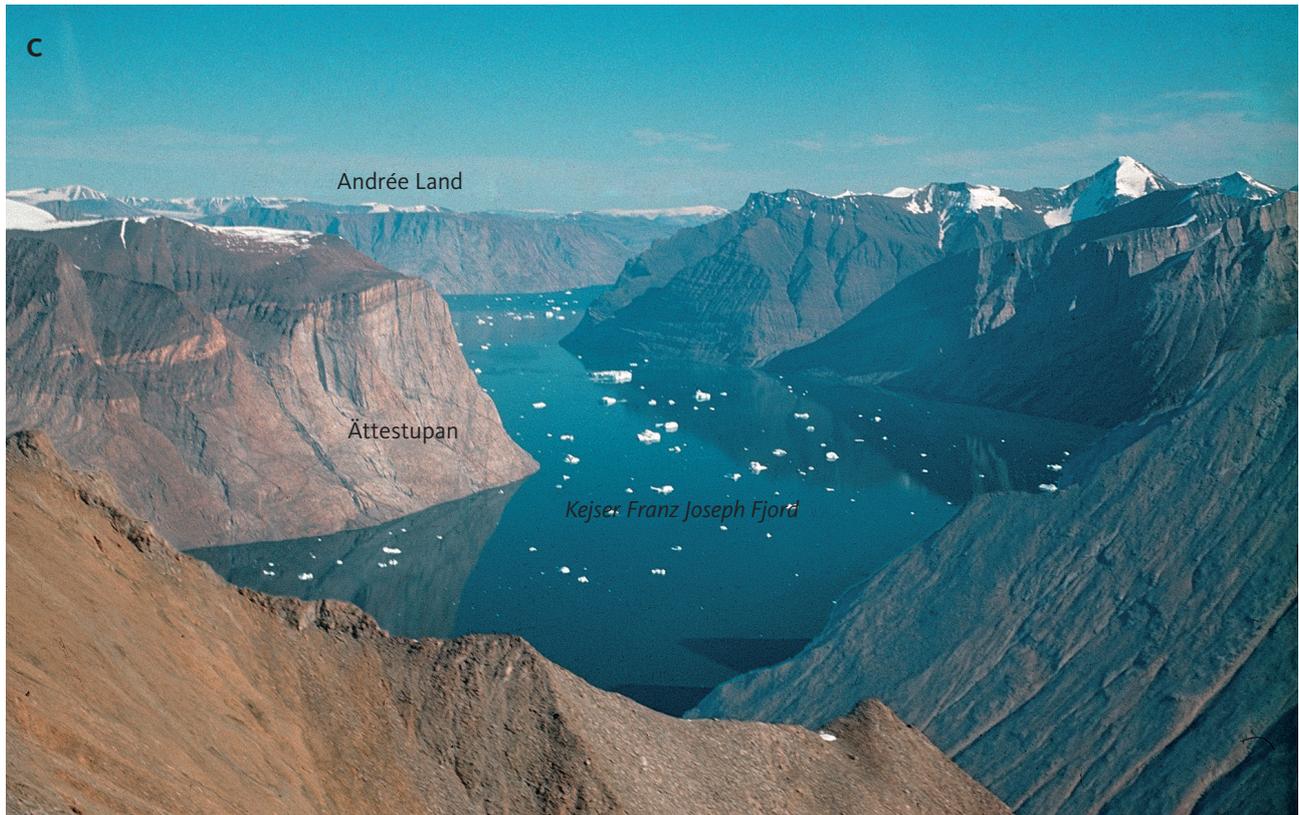
Fig. 14 (Continues) Thin ice covers the Upper Planation Surface (UPS) in many locations in North-East Greenland: **A**: View along Nordvestfjord towards the south-east. **B**: The east–west-trending Flyverfjord. North is to the left of the image. **C**: Looking west along the inner part of Kejser Franz Joseph Fjord towards Andrée Land. **D**: View from Milne Land towards the south across Scoresby Sund where the UPS defines the top of the basalts on Geikie Plateau. Photo locations in Fig. 9. Photos A–C: GEUS archive.
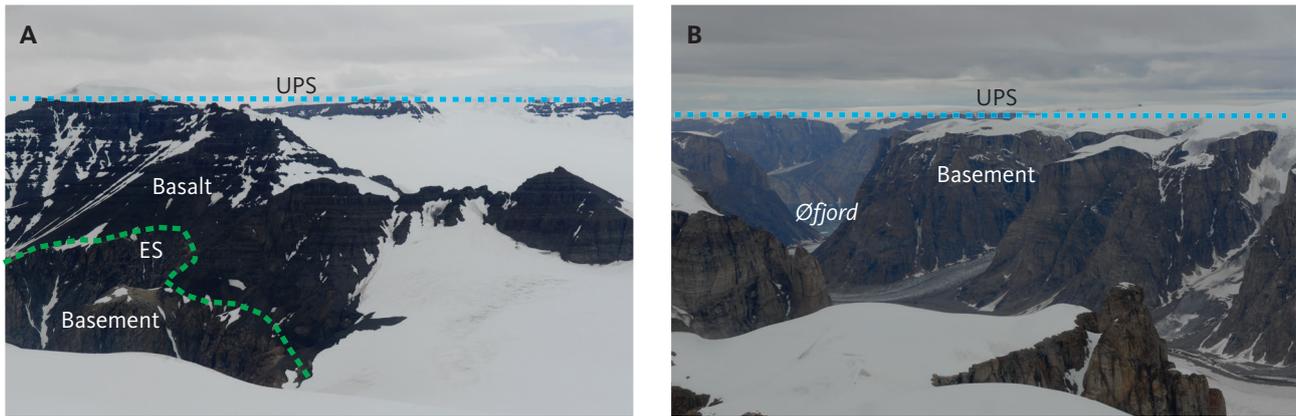
Fig. 15 The Upper Planation Surface (**UPS**) developed at an elevation of about 1800 a.s.l. across Palaeogene basalt and basement on Milne Land, constraining the age of the UPS to be younger than the Palaeogene basalts. **A**: UPS cutting across the basalt. **ES**: etch surface. **B**: UPS cutting across basement, note Øfjord in the background. There are only a few kilometres between the two locations. Photo locations in Fig. 9.
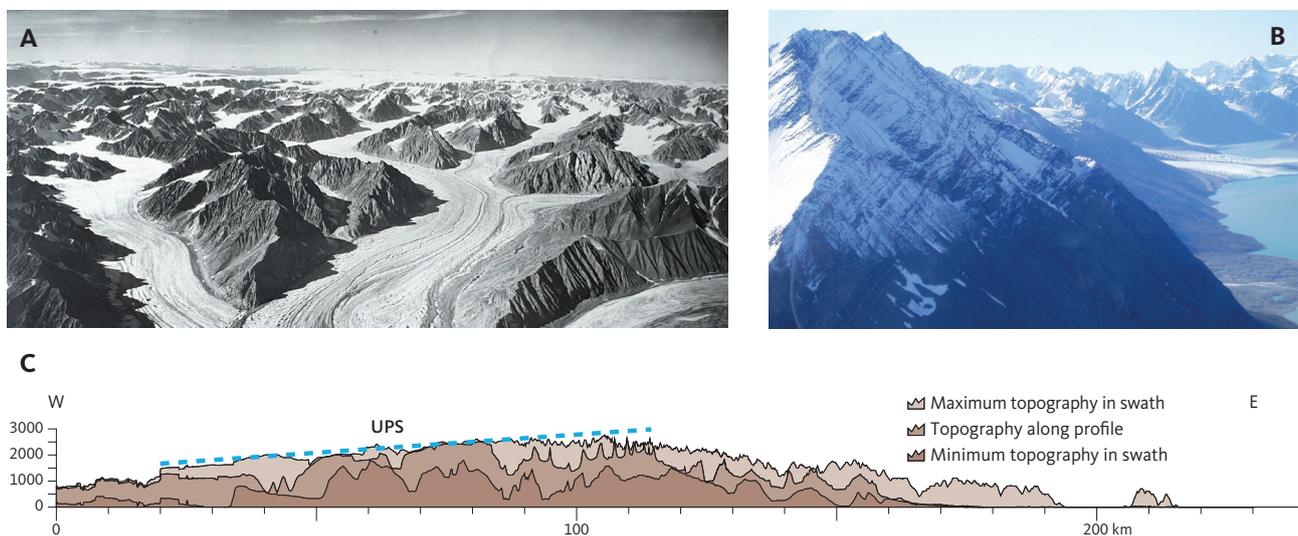
Fig. 16 Topography across Stauning Alper: **A**, **B**: Landscape with alpine relief and no remnants of the Upper Planation Surface (**UPS**) across Stauning Alper. Note that the UPS is present towards the north-west in the background of panel A. Photo A: GEUS archive. Photo B: Mette Olivarius. **C**: W–E profile illustrating that the peaks of the alpine relief can be projected to a surface (**blue dashed line**) that is coherent in the west. X-axis: UTM easting (km). Y-axis: Elevation (m). Locations in Fig. 9.

influx of coarse, clastic turbidites offshore. These turbidites overlay fine-grained lower Eocene sediments (Larsen *et al*. 1994b; Bonow *et al*. 2014). When this planation surface had finally formed, it had a low topographical expression in the landscape, graded to near the base level at that time, which must have been the adjacent Atlantic Ocean. The presence of the mid-Miocene Vindtop Formation above the Palaeogene basalts just south of our study area, implies that the UPS had formed by mid-Miocene times and thus well before the onset of glaciation (Bonow *et al*. 2014). Glacial cirques and valleys cutting into the UPS also support this observation.

The development of the UPS was terminated by a second, post-basalt uplift phase that raised the landscape by about 1 km. This led to incision of valleys below the uplifted UPS and to the development of a new surface, the LPS, during the late Neogene as it is younger than the UPS that had formed by mid-Miocene times.

The development of the LPS was terminated by a third base level change in post-basalt time, due to uplift of the landscape by about 1 km, which then led to dissection of the LPS. The further destruction of both the UPS and LPS was partly glacial and occurred during the late Cenozoic glaciations.

6 Discussion
6.1 Does present-day topography reflect the pre-break-up landscape?
New mapping of Traill Ø and Geographical Society Ø indicates three main rift phases during the Devonian–Triassic,
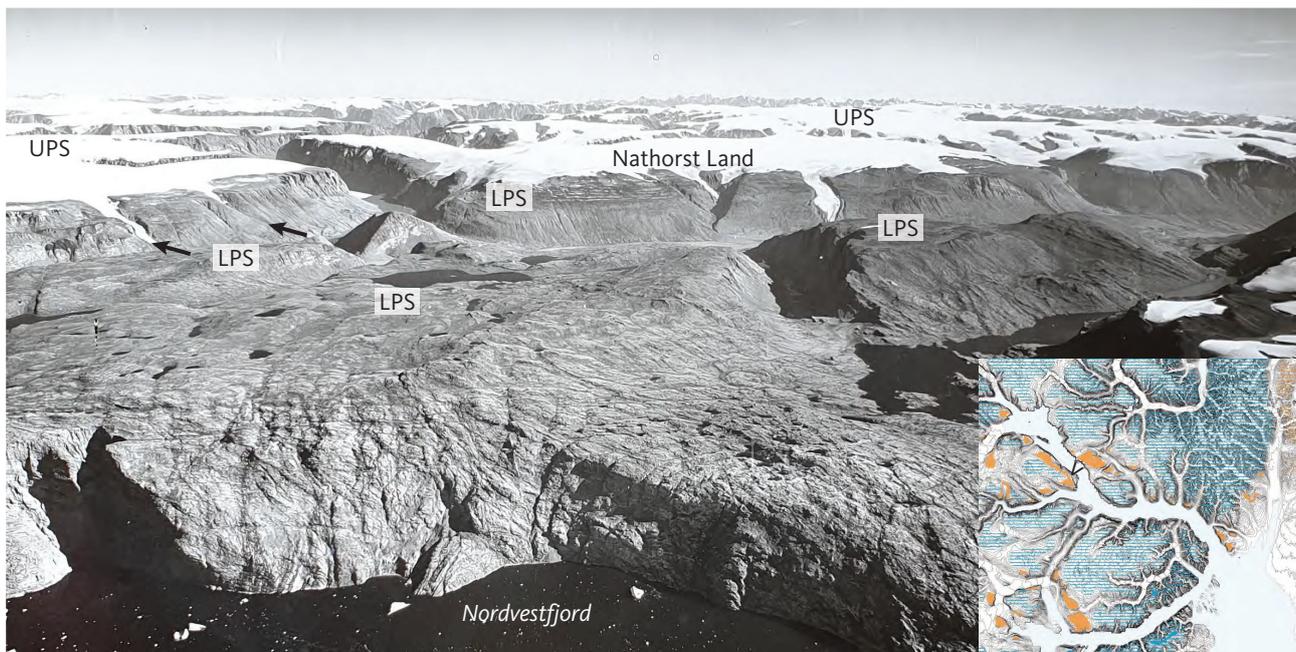
Fig. 17 Relationship between the Upper and Lower Planation Surface (**UPS** and the **LPS**, respectively) along the north side of Nord-vestfjord: LPS is well developed on the north side of Nordvestfjord and there is a distinct escarpment towards the UPS that is well developed across Nathorst Land. Note the consistent level of the LPS and that minor valleys often stop incising at that valley bench (**black arrows**). The **inset map** shows the photo location and the detailed mapping of the UPS (**blue**) and the LPS (**orange**) in the area, see supplementary file S1. Photo: Kort & Matrikelstyrelsen, Denmark.

Jurassic–Cretaceous and Palaeogene with the greatest amounts of faulting and block rotation occurring during the latter phase related to break-up of the North Atlantic *c.* 56 Ma and to the plate reorganisation *c.* 36 Ma (Parsons *et al.* 2017). The cross sections published by Parsons *et al.* (2017; fig. 10) show no correlation between the present-day landscape and the underlying Mesozoic sediments and the fault systems that offset them. This lack of correlation agrees well with our identification of the LPS in the summits over large parts of Traill Ø and Geographical Society Ø (Fig. 7B). As argued in Section 5.2.1, the LPS was likely graded to the base level in the late Neogene, and it is therefore significantly younger than the dominant Palaeogene phase of block rotation. Consequently, faulting prior to, during, or after break-up has left few traces in the present-day landscape.

Swift *et al.* (2008) found the first-order topography in North-East Greenland to be closely related to the main aspects of the regional geology, in particular, controlled by escarpments along major geological boundaries. They also used the configuration of the pre-basalt surface from a small area in Milne Land in relation to the post-Devonian Main Fault system to argue that the present first-order topography had existed since at least the time of break-up, *c.* 55 Ma. Swift *et al.* (2008) did not, however, consider Ahlmann's (1941) conclusion that the first-order topography must have developed in post-basalt time, following the observation that planation had occurred across both Palaeogene basalts and basement rocks to

form the continuous erosion surface on a regional scale, which is now present as an elevated plateau (the UPS). The detailed mapping presented here also shows that there is no change in the separation between the UPS and LPS across the post-Devonian Main Fault system, so the fault does not control the development of the first-order topography. Instead, the step (escarpment) between the two surfaces winds along the main valleys that cut across the fault system (Fig. 7B). Geological evidence from the Blosseville Kyst region (Nielsen *et al.* 1981) further shows that the flood basalts were extruded near sea level and the kilometre-scale subsidence kept pace with the extrusion of the basalts (see Bonow *et al.* 2014 and references therein). The presence of late Paleocene to earliest Eocene marine strata at elevations up to 700 m a.s.l. on Wollaston Forland, Hold with Hope and Sabine Ø (Nøhr-Hansen *et al.* 2011), demonstrates that the present-day landscape and topography is very different from the landscape at the time of continental break-up. Furthermore, these observations document that post break-up rock-uplift was at least 700 m, which is in agreement with the elevation of the LPS in this region of about 1 km. However, possible post-rift burial of the marine sediments would lead to a bigger magnitude of their vertical movement since maximum burial.

Pedersen *et al.* (2012) presented a different view on the origin of the present-day mountains in North-East Greenland. They suggested that the mountains represent remnants of the original Caledonian topography
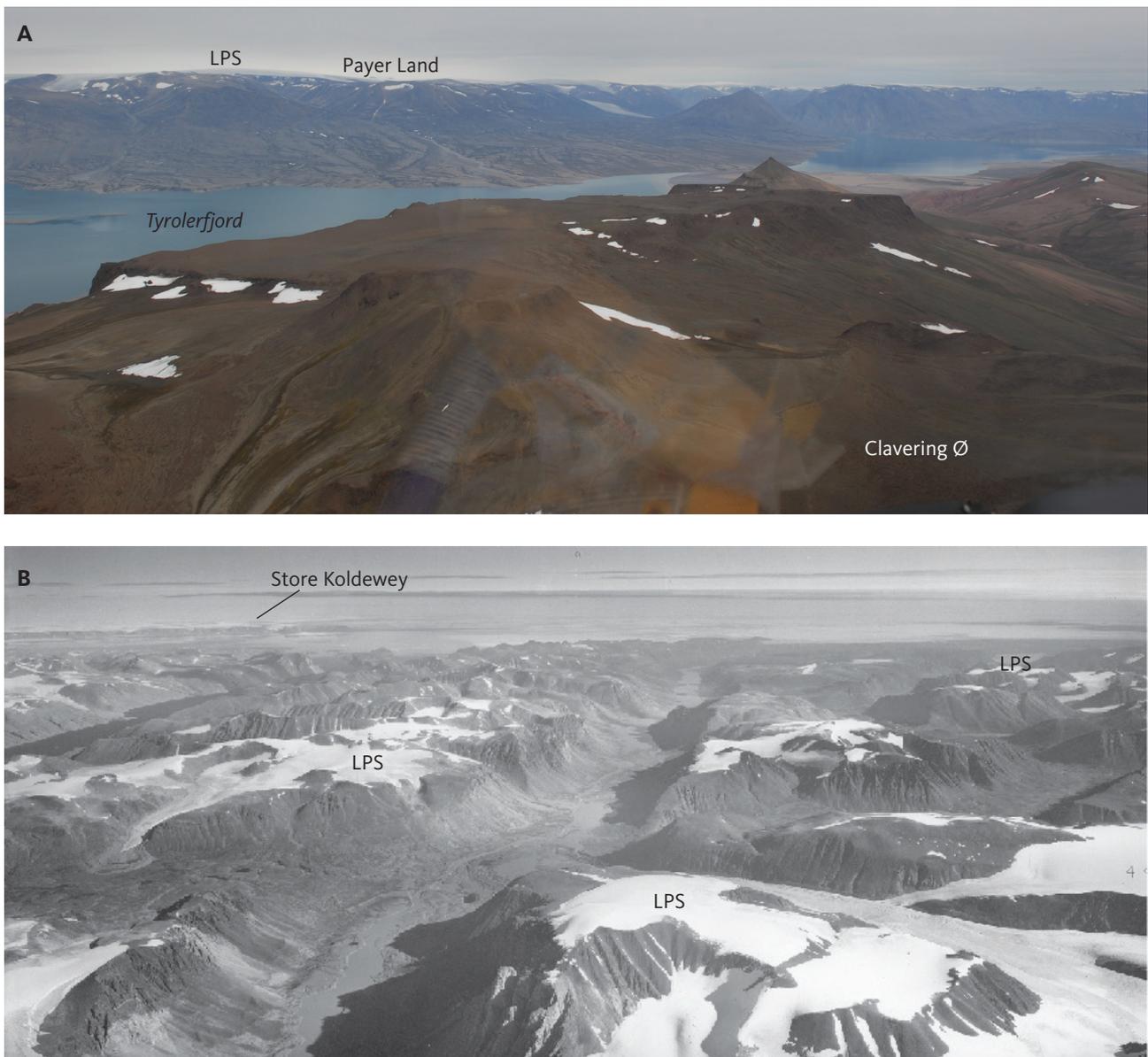
Fig. 18 The Lower Planation Surface (**LPS**) in the northern part of the study area: **A**: View of the LPS at *c*. 1300 m a.s.l. on Payer Land seen from Clavering Ø towards the north-west across Tyrolerfjord. Minor remnants of flattish land in the foreground are interpreted as the LPS developed in sedimentary cover rocks. The extensive surface in the background formed across crystalline basement. Photo: GEUS archive. **B**: View east, overlooking basement terrain in Dronning Margrethe II Land with Store Koldewey in the background. The flat summits are interpreted to be part of the LPS and are *c*. 1 km a.s.l. Photo: Kort & Matrikelstyrelsen, Denmark. Photo locations in Fig. 9.

modified during early rifting and that the area has undergone slow, steady exhumation since *c*. 250 Ma. They based this hypothesis on inverse modelling calibrated by AFTA data from samples of exposed Caledonian basement. However, AFTA data on their own register only episodes of cooling and must be integrated with geological evidence to reveal episodes of reheating that reflect re-burial. The modelling results of Pedersen *et al.* (2012) are at odds with the observations presented here that show two elevated plateaus, formed and uplifted after break-up, dominate

the landscape of North-East Greenland. Japsen *et al.* (2013) described how the well-documented geological record of North-East Greenland (e.g. Surlyk 1990) shows that the Caledonian mountains were obliterated as topographic features during the late Palaeozoic. The presence of outliers of both Upper Carboniferous and Middle Jurassic sediments resting on the basement in the study area of Pedersen *et al.* (2012) also provides evidence of a history involving episodic, post-Caledonian exhumation and re-burial. Japsen *et al.* (2013) concluded that the geological record in East Greenland is
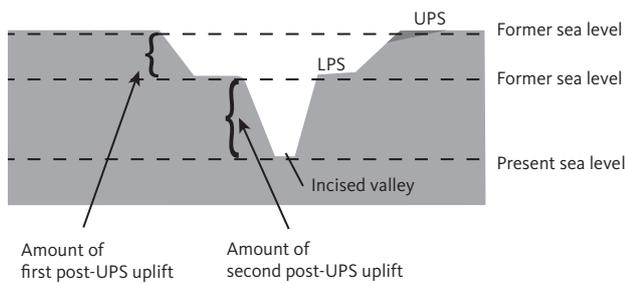
Fig. 19 Conceptual model that demonstrates how to estimate the amount of uplift based on the elevation of peneplains and their relationship to the base level. **UPS**: Upper Planation Surface. **LPS**: Lower Planation Surface.

incompatible with the idea of slow, steady exhumation since the Caledonian orogeny.

6.2 Formation and preservation of surfaces

The characteristic basement hills, separated by minor valleys, which frequently appear below the Palaeogene basalts, are the result of erosion during different weathering episodes in the Mesozoic (Larsen *et al*. 1989). At that time, the basement was exposed on the Earth's surface and became deeply weathered, forming saprolites, under warm, humid conditions. Stripping of saprolites occurred during drier conditions. After its formation and until recently, this weathered basement surface (ES) and the saprolites must have been protected from erosion by a cover of sediments or basalts, as seen in the area around Milne Land. Whereas the basement areas at high elevation are planated and typically form part of the UPS, the characteristic hilly relief of the ES occurs only at low elevation. The ES must have been covered when the planation occurred, otherwise this relief would have been obliterated by the planation (Figs 3, 11), which suggests a recent episode of exhumation due to late uplift. A similar history with Mesozoic deep weathering, followed by burial and late Cenozoic exhumation, has also been documented in West Greenland (Bonow 2005), southern Greenland (Peulvast *et al.* 2011) and Scandinavia (Lidmar-Bergström 1988, 1989; Lidmar-Bergström *et al*. 2017).

The UPS is preserved mainly in areas with resistant rocks such as crystalline basement and Palaeogene basalts (e.g. on Gåseland and Milne Land; Fig. 12). There are only minor remnants of the UPS in coastal areas underlain by sedimentary sequences, for example on Traill Ø. Prior to the first uplift of the UPS, the surface most likely extended across a much wider area towards the coast, across the sedimentary basins on Jameson Land, for example.

Independent lines of evidence support the suggestion that the UPS once covered a much wider area towards the coast. Palaeogene volcanics are present offshore between 72°N and 76°N (Henriksen *et al.*

2009), and it is thus likely that a thick cover of basalts was present in the coastal zone of the study area, where the basalts occur as outliers today (Fig. 4), and across Jameson Land (Mathiesen *et al*. 2000). By inference, it is likely that the UPS developed across this now-lost, basalt cover. Similarly, a late Palaeogene unconformity mapped on seismic sections across the Jan Mayen micro-continent (around 68°N, 12°W), has been suggested as an equivalent of the UPS onshore in East Greenland (Blischke *et al.* 2019).

While the UPS is preserved mainly in resistant rocks, the preservation pattern of the LPS is different (Fig. 7B). In the south, the LPS is mostly preserved as a coherent surface in areas with sedimentary rocks. In areas with crystalline basement, in the south-western part of the study area, for example, the LPS is identified as valley shoulders within the major valleys below the UPS. In the north, the LPS is developed as a coherent surface across a crystalline basement around Dove Bugt, for example. The LPS thus appears to have developed across the entire study area as an extensive plain in coastal areas and as the floor of fluvial valleys incised below the UPS in the hinterland.

The preservation pattern thus indicates that both the UPS and the LPS were destroyed quickly when formed across the sedimentary basin, but they have been preserved to a large degree where they formed across basement rocks, or basalts. We thus conclude that, once a large-scale surface has formed across resistant rocks like crystalline basement, it will persist and dominate the topography for a long time and is not easily reshaped (Brunsden 1993). The primary destruction of a peneplain thus occurs along the edge of valleys that were formed after uplift of the peneplain. This erosional pattern is observed in other uplifted areas (Liu *et al*. 2019).

The effect of glacial erosion on elevated plateaus covered by cold-based ice is limited, while significant erosion occurs in the deeply incised valleys (e.g. Sugden 1974; Bonow *et al.* 2006b; Swift *et al*. 2008; Hall *et al.* 2013a; Cook *et al.* 2020). Consequently, glacial erosion will lead to an increased relative relief between the comparatively unaffected pre-glacial peneplains and the glacial incision focussed in the valleys (Johansson *et al.* 2001; Hall *et al.* 2013a), whereas isostatic rebound due to fluvial and glacial erosion will increase the overall elevation of uplifted landscapes (Medvedev *et al.* 2013).

6.3 Two-stepped surfaces or one arched surface?

The geomorphological work by Ahlmann (1941) was a major achievement based as it was, on poor maps, limited fieldwork and some aerial photographs. Ahlmann (1941) was of the opinion that the landscape in North-East Greenland consisted of just one erosion surface (the
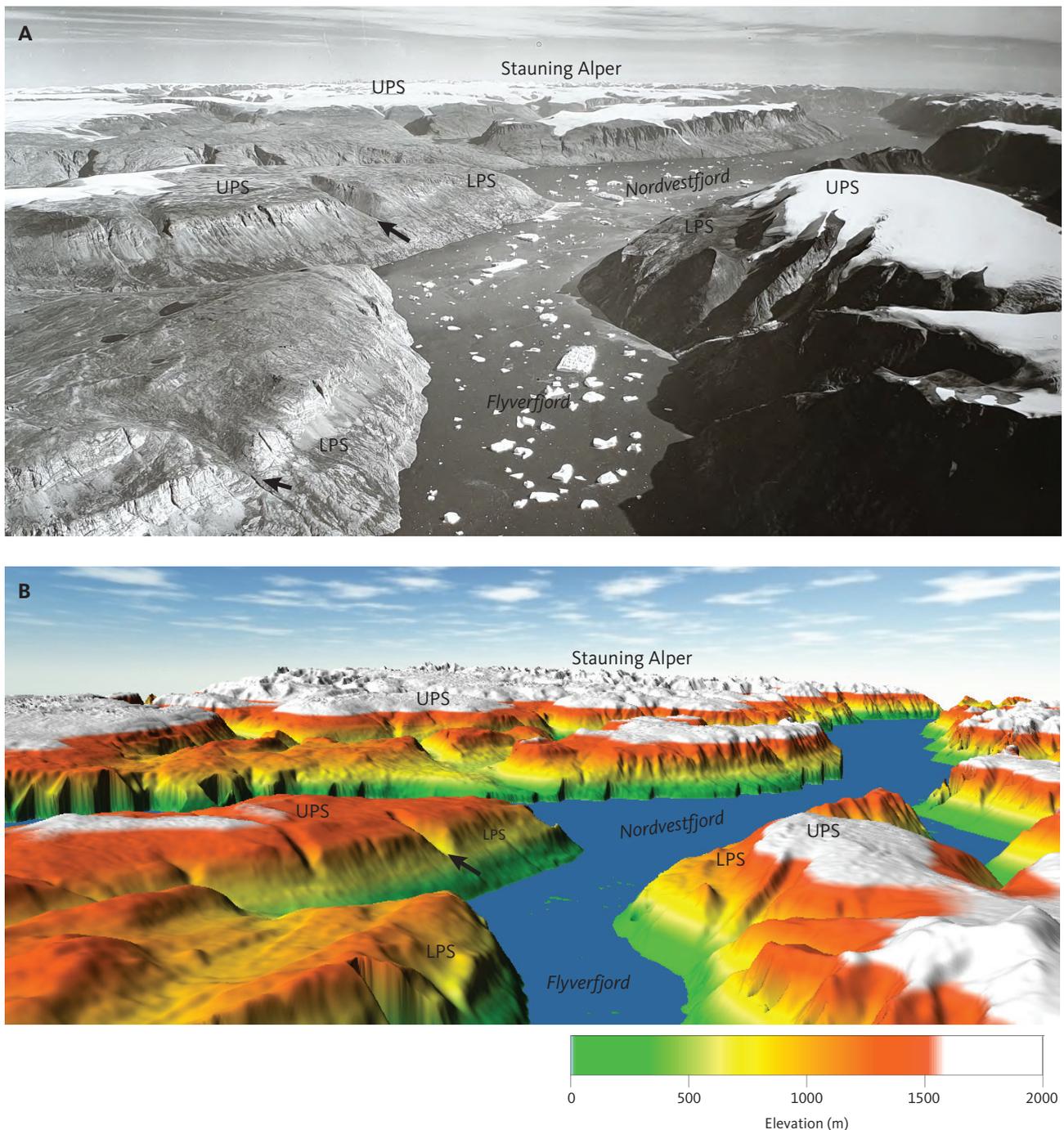
Fig. 20 The incision of the **LPS** into the **UPS** as a valley bench along Nordvestfjord (Lower and Upper Planation Surface, respectively): **A**: LPS along Flyverfjord and Nordvestfjord; view north-east across Th. Sørensen Land towards Nathorst Land (UPS) and Stauning Alper. **B**: 3D elevation model from ASTER data in approximately the same area. The LPS is developed as valley benches along the main fjords. Minor valleys connect the UPS with the LPS (**black arrows**). Map location in Fig. 9.

'initial topography' as he referred to it, which generally corresponds to the UPS of the current study). He regarded this surface to be arched towards the present-day coast.

In contrast, we find that the large-scale landscape in North-East Greenland consists of two distinct surfaces with a distinct step between them and not the single arched surface that Ahlmann described. Where the UPS and LPS overlap, there is a step between them.

This step is not formed by a fault or fracture system (e.g. the Post-Devonian Main Fault system); rather, it occurs where the sides of the valleys incised to form the LPS. This provides further evidence that the step is erosional. Stepped surface landscapes with similar forms are also present along other passive margins in central West Greenland (Bonow *et al.* 2006b), Norway (Lidmar-Bergström *et al.* 2000; Bonow *et al.* 2003),

Brazil (Peulvast & Claudino Sales 2004), southern Africa (King 1967; Green *et al*. 2017) and Ethiopia (Coltorti *et al*. 2007).

6.4 The domal structure of the UPS around Stauning Alper

Ahlmann (1941) identified a dome structure for the 'initial topography' with the highest elevation occurring around Stauning Alper. This feature corresponds to the anticlinal structure of the UPS identified on profiles for the area in this study (Fig. 16). Stauning Alper exhibits a significant alpine relief and is one of the most dissected areas in North-East Greenland. This type of relief is probably not due to a specific rock type because similar crystalline rocks occur in nearby areas at lower elevation where the UPS is very well preserved (e.g. Renland, Milne Land; Figs 13, 20). It thus seems likely that Stauning Alper has a tectonic history that deviates from the regional pattern after the formation of the UPS because the area experienced more uplift and perhaps, earlier uplift than the surrounding areas. Such development would inevitably lead to valley incision and relief rejuvenation, and possibly more erosion by cirque and valley glaciers, which would obliterate the UPS.

6.5 Comparison with erosion surfaces in West Greenland

The landscape of central West Greenland shares characteristics with that of North-East Greenland. A weathered basement surface has been identified in and around the Nuussuaq Basin (Pulvertaft & Larsen 2002; Bonow 2005). This surface is of Cretaceous to Paleocene age and is characterised by distinct hills and kaolinitic saprolites (Bonow 2005). Bonow *et al*. (2006b) mapped the weathered basement surface south of the Nuussuaq Basin and demonstrated that it is cut off by a post-basalt planation surface (also labelled UPS). The final formation age for the weathered surface in West Greenland is similar to the Palaeogene, sub-basalt, ES in North-East Greenland, which indicates that the weathering reflects a large-scale erosion event.

The main, post-basalt peneplain (the UPS) in central West Greenland has similar characteristics to the UPS in North-East Greenland (Bonow *et al*. 2006a, 2006b). However, whereas the UPS in North-East Greenland is also preserved in areas with less resistant basalts (e.g. Milne Land), the equivalent UPS in West Greenland is mainly preserved in basement rocks and is deeply dissected in the basalt areas on Nuussuaq and Disko (Bonow *et al*. 2006a). The UPS in North-East Greenland is located at a significantly higher elevation and is less tilted than that in West Greenland. The West Greenland UPS is also divided into several tectonic blocks that dip in different directions, while the North-East Greenland UPS is folded only around Stauning Alper. The high elevation together with less tilting and rotation might explain why the UPS is better preserved and thus of a wider extent in North-East Greenland.

The LPS in North-East Greenland is present across a significantly wider area than the equivalent surface in West Greenland, where it forms only a partially developed surface along a few valleys (Bonow *et al*. 2006b). One possible explanation could be that block movements and tilting have disrupted surface development in West Greenland (Bonow *et al*. 2006b), while the uplifts in North-East Greenland apparently have a more regional character. The LPS in West Greenland was also probably developed across Cretaceous sediments and Palaeogene basalts in the Nuussuaq Basin, where the surface was later obliterated by erosion.

6.6 The formation of the LPS and the onset of glacial conditions in Greenland

There is evidence of glacial activity from *c*. 7 Ma off East Greenland in the form of ice-rafted debris in Ocean Drilling Program (ODP) boreholes, which suggest that full glacial conditions were established in South-East Greenland by that time (*c*. 63°N and 70.5°N; Larsen *et al*. 1994b; Jansen *et al*. 1996; Channell *et al*. 1999). Recently, Pérez *et al*. (2018) inferred that cross-shelf glaciation off Blosseville Kyst and Liverpool Land began to influence the shelf during the deposition of upper Miocene to lower Pliocene sediments (7.3–4.9 Ma) based on seismic data tied to ODP borehole 987, off Scoresby Sund. For example, they attributed the prograding character of this succession, as well as the shift in depocentre configurations from inner to middle and outer shelf, to ice advancing across the shelf off Blosseville Kyst. In particular, they attributed outward-bulges in the depositional pattern to active ice streams crossing the continental shelf, in contrast to a previous study that inferred dominantly hemipelagic origin of late Miocene deposits off Scoresby Sund (Butt *et al.* 2001). However, according to Pérez *et al.* (2018), the two major phases of ice-sheet advance occurred after the Miocene – in the early Pliocene and around the Pliocene–Pleistocene transition (at *c*. 5 Ma and between 2.9 and 2.3 Ma, respectively).

Further insight into the glacial history of East Greenland may be obtained from the stratigraphic landscape analysis in East Greenland (68–78°N) presented here, and by Bonow *et al*. (2014). The formation of the LPS by incision below the UPS is thought to be controlled by the fluvial system because the LPS extends at the same elevation from the valley benches in the interior to the plateau remnants across the sedimentary basins closer to the coast (Figs 7B, 9A, 20). This observation implies that full glacial conditions were not established during

the formation of the LPS. The LPS must have formed during the late Neogene because it is younger than the UPS, which had been formed by the mid-Miocene. This interpretation is supported by the integration of stratigraphic landscape analysis with AFTA data in southern East Greenland, which led to the following conclusions (Japsen *et al*. 2014):

1. Late Miocene uplift (*c*. 10 Ma) led to the onset of incision of the LPS below the UPS
2. Early Pliocene uplift (*c*. 5 Ma) led to the incision of valleys and fjords below the LPS.

This timeframe is further supported by AFTA data in North-East Greenland (Japsen *et al*. in press). The LPS was thus established by the fluvial system in the interval between 10 and 5 Ma; thus, it is unlikely that full glacial conditions were established in East Greenland at this time.

We therefore suggest that the fluvial system led to the expansion of the shelf during the late Miocene; for example, along Blosseville Kyst. We note that over-deepened troughs were not observed across the shelf in the corresponding succession (unit 7) on the seismic lines presented by Pérez *et al*. (2018), whereas major ice streams would have created such troughs. This indicates that glacial action prior to the Pliocene was restricted to valley glaciers, which led to deposition of ice-rafted debris offshore, similar to the valley glaciers of Greenland reaching the sea today. The prograding character of the upper Miocene succession, as well as the shift in depocentre configuration off Blosseville Kyst at this time, may be the result of glacio-fluvial deposition. The major phases of ice-sheet advance and full glacial conditions thus only occurred after the Miocene (Solgaard *et al*. 2013; Pérez *et al*. 2018), in agreement with our conclusion that the final phase of uplift took place in the early Pliocene (Japsen *et al.* 2014).

6.7 Plateau landscapes are not related to glaciation

The presence of mid-Miocene volcanics on the UPS just south of the study area demonstrates that the UPS was formed prior to the onset of large-scale Neogene glaciations in Greenland (Larsen *et al.* 1994b; Storey *et al.* 2004; Bonow *et al.* 2014). As discussed in the previous section, the LPS is the result of late Neogene fluvial incision to below the UPS. The incision likely occurred prior to uplift in the early Pliocene and was followed by the major phases of ice-sheet advance and full glacial conditions. The UPS and the LPS are therefore not considered glacial surfaces, but their destruction was partly glacial as illustrated by the glacial forms that cut into them.

Our results agree with the well-established observation that old landscapes, sometime called 'relict surfaces'

are preserved beneath non-erosive, cold-based ice (Kleman 1994; Kleman & Hättestrand 1999; Sugden *et al*. 2005; Kleman 2008; Ebert & Hättestrand 2010; Hall *et al*. 2013a, 2013b). However, in terrains of selective linear glacial erosion, wet-based ice behaves differently. In hilly relief terrain, wet-based glaciers exploit and enhance the pre-glacial relief (e.g. Sugden 1974) while flat surfaces (e.g. planated surfaces) are not significantly altered (Lidmar-Bergström 1997; Johansson *et al*. 2001). In North-East Greenland, the elevated and flat terrain has facilitated the formation of cold-based ice, even in coastal areas on Store Koldewey, for example, where the flat basement summits are unscoured (Håkansson *et al*. 2007). Alpine relief mainly developed along the coast at Stauning Alper, for example. Similar patterns have been observed in the Blosseville Kyst region (Bonow *et al*. 2014).

Braun (2018) argued for the apparent longevity of high-elevation passive margins based on numerical modelling. Based on computational experiments, Egholm *et al.* (2017) proposed that plateau landscapes on glaciated margins reflected glacial and periglacial smoothing of an already elevated terrain prior to the inception of glaciers. Conclusions from such calculations and modelling are at odds with the results presented here, which document that the extensive plains in East Greenland were graded to sea level prior to the glaciations. The suggestion that glaciers produce smooth landscapes at high elevation is also at odds with modern understanding of glacial dynamics (e.g. Kleman *et al*. 2008; Hall & Kleman 2014; Cook *et al*. 2020). Finally, the presence of two regional peneplains separated by a major step in the landscape is not explained by the models of Egholm *et al*. (2017). A part of the youngest uplift that produced the second major step in the landscape between the LPS and present-day sea level can be explained by glacial processes (Medvedev *et al*. 2013), but isostatic rebound caused by glacial carving cannot produce a two-stepped landscape. We therefore interpret these steps as manifestations of episodes of tectonic uplift that affected North-East Greenland during the late Neogene. High-level plateaus and deeply incised valleys are characteristic of EPCM around the world in both tropical and Arctic climates (Jessen 1943; King 1967; Japsen *et al*. 2012a; Green *et al*. 2013, 2018). Lidmar-Bergström *et al*. (2000) showed that major landscape features such as high plateaus, a great escarpment and a coastal plain are similar in character in both southern Norway and eastern Australia. Thus, the formation of elevated plateaus along passive continental margins is not necessarily related to glacial action.

The evidence presented here for the origin and age of the large-scale landscape in North-East Greenland is therefore a typical example of the development of an EPCM.

6.8 Neogene uplift and the formation of the Greenland ice sheet

Solgaard *et al.* (2013) investigated the effects of two phases of Neogene uplift in both West and East Greenland, on ice sheet initiation using an ice sheet model in combination with a climate model. The uplift scenario tested in that study is similar to that defined by the presence of a landscape in two steps in North-East Greenland but put into an absolute timeframe based on AFTA data from West and East Greenland (Japsen *et al.* 2006, 2014). The scenario supposes that the landscape was at a low level prior to the late Miocene, after which two phases of kilometre-scale uplift in the late Miocene and latest Miocene – Pliocene (beginning *c*. 10 and 5 Ma, respectively) initiated the formation of the present-day mountains. The landscape model of Solgaard *et al.* (2013) was based on stratigraphic landscape analysis in West and South-East Greenland (Bonow *et al.* 2006a, 2006b). The new results from North-East Greenland presented in this paper provide further support that the model is valid for Greenland in general.

The modelling results of Solgaard *et al.* (2013) showed that no ice could build up on the low-lying and almost flat landscape (defined by the UPS) prior to the first uplift (*c*. 10 Ma). However, the models demonstrated significant ice expansion in response to increased precipitation and cooling due to the two phases of uplift that raised the UPS to its present elevation. Large amounts of ice could have formed after the first uplift event (leading to formation of the LPS), but the model showed that the ice sheet is sensitive to changes in climate. The second phase of uplift (*c*. 5 Ma, which led to the uplift of the LPS) facilitated the ice-sheet build-up and increased the stability of the ice sheet in the models. However, they also suggested a Föhn effect that inhibited ice-sheet expansion into the interior of Greenland and thus shifted the threshold of formation of the ice sheet towards colder temperatures. Under conditions that are colder than the present, the ice could overcome the Föhn effect flow into the interior and form a coherent ice sheet. The results thus indicated that the present-day Greenland ice sheet is a relict formed under colder conditions. Solgaard *et al.* (2013) concluded that the late Cenozoic mountain building in Greenland augmented the effects of the climatic deterioration leading to the Northern Hemisphere glaciations, and that without the second phase of uplift the Greenland ice sheet would have been more sensitive to the changes in climate over the past millions of years.

The modelling of Solgaard *et al.* (2013) is consistent with the observed climatic variability superimposed on the general cooling trend in the late Cenozoic, specifically the presence of ice-rafted debris in late Miocene deposits off South-East Greenland and evidence for mid-Pliocene warmth (Larsen *et al.* 1994a; Dowsett *et al.*

2010). The results are also consistent with the observation that large-scale glaciation in the circum-Atlantic region only occurred in the late Pliocene, and that the increase in land-ice volume occurred slowly and stepwise over the period from *c*. 3.5 Ma to 2.4 Ma (Thiede *et al.* 1998; Mudelsee & Raymo 2005; Pérez *et al.* 2018).

Pedersen *et al.* (2019) used the concept of geophysical relief (Small & Anderson 1998) to estimate fjord erosion and the subsequent flexural isostatic response to erosional unloading in North-East and North Greenland between Scoresby Sund (70°N) and Independence Fjord (82°N). They constrained the timing of erosion and isostatic uplift by marine sediments of late Pliocene – early Pleistocene age that are now exposed on land between 24 and 230 m a.s.l. (Feyling-Hanssen *et al.* 1983; Funder *et al.* 2001; Bennike *et al.* 2002, 2010). In this way, Pedersen *et al.* (2019) found that the Independence Fjord system formed since *c*. 2.5 Ma. In contrast, their results indicated that fjord formation in the outer parts of Scoresby Sund commenced before the Pleistocene, most likely in the late Miocene and continued throughout the Pleistocene by progressive, inland fjord formation. The results of Pedersen *et al.* (2019) demonstrate that the inception of the Greenland ice sheet began in the central parts of North-East Greenland before the Pleistocene and spread to North Greenland only at the onset of the Pleistocene and are thus in accordance with the model of Solgaard *et al.* (2013).

7 Conclusions

The large-scale landscape of North-East Greenland is similar to EPCM worldwide, characterised by upland plateaus dissected by deep valleys. The detailed mapping presented in this study reveals a landscape dominated by two regional erosion surfaces, the UPS and LPS at *c*. 2 and 1 km a.s.l., respectively, cut by deeply incised valleys. The UPS is a major surface at some distance from the coast, up to 200 km wide. In large areas north of 74°N, the UPS disappears below the ice sheet. Maximum elevation of the UPS is found in Stauning Alper, where the surface is dome shaped.

The UPS has a low relative relief, a regional extent and cuts across bedrock of variable age and resistance, including crystalline basement and Palaeogene basalts that erupted during break-up of the north-East Atlantic. This shows that the UPS was graded to base level, and the most likely base level was the Atlantic Ocean after the cessation of the volcanic eruptions. Hence, the UPS is a post-basalt peneplain. Further, the UPS must have formed prior to the eruption of the mid-Miocene lavas that rest on the UPS just south of our study area.

A significant change of base level (uplift) terminated the development of the UPS, leading to fluvial incision of valleys and to rejuvenation of the relief. The change

of base level must have been followed by a period of more stable base-level conditions, because the valleys widened and eventually formed a coastal plain near the base level at that time. Consequently, a new regional, low-relief peneplain – the LPS – formed. The LPS is readily identified in the interior parts of the study area, where it forms fluvial valley benches below the UPS at present day elevations of *c*. 1 km a.s.l. The presence of these well-developed valley benches shows that the LPS had formed prior to the onset of late Cenozoic glaciations. Towards the coast, the valley benches of the UPS merge to form a more coherent surface that extends across a 100-km wide zone. Where sedimentary rocks crop out, the LPS is only defined by flat-topped summits, while in the areas of crystalline basement rocks the LPS is more extensive and less dissected. North of 74°N, the LPS dominates the ice-free areas of the elevated plateau landscape in near-coastal areas, while the UPS further west is covered by the Greenland ice sheet.

A second phase of base-level lowering (uplift) caused the LPS to lose contact with the former base level, and thus the LPS was dissected by a new phase of valley incision and relief rejuvenation. The result was a landscape with distinct levels, manifested by a winding escarpment between the UPS and LPS. This stepped landscape later became glaciated and further eroded.

The LPS is defined on both sides of the post-Devonian Main Fault system at about the same elevation, and this further supports that the LPS was formed by the fluvial system. The escarpment between the UPS and the LPS does not coincide with the fault system, which appears as a marked scarp in the terrain, defining the western boundary of the sedimentary basin system.

Each of the uplift events that affected the region after the UPS was graded to sea level, were in the order of 1 km and the UPS is now at an elevation of *c.* 2 km a.s.l. The most recent uplift event also resulted in re-exposure of a pre-basalt erosion surface with etch characteristics, resulting from deep weathering in a warm, humid climate. Towards the north (Germania Land and Store Koldewey) the LPS reaches *c*. 600 m a.s.l., only.

The relative denudation chronology established here shows that the topography in North-East Greenland was not related to a break-up in the northeast Atlantic but developed much later. The denudation chronology for the elevated plateaus in North-East Greenland is similar to that previously established for southern East Greenland and central West Greenland. In these areas, absolute dating from AFTA documented three events of uplift in the late Eocene, late Miocene and early Pliocene that led to the formation of the UPS, the LPS and finally to their rise to their present-day elevation.

The dramatic change of the East Greenland topography since Miocene times was an important precondition for the establishment of the Greenland ice sheet, and the formation of the LPS by the fluvial system shows that full glacial conditions were likely only established after uplift of the LPS in the early Pliocene. In summary, the UPS and the LPS provide a visual manifestation of multiple episodes of tectonic uplift that affected North-East Greenland in late Neogene times.

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