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Earth and Planetary Science Letters 248 (2006) 315–324
EPSL
www.elsevier.com/locate/epsl

Elevated, passive continental margins: Long-term highs or Neogene uplifts? New evidence from West Greenland

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Received 23 December 2005; received in revised form 9 May 2006; accepted 12 May 2006
Available online 18 July 2006
Editor: S. King

Abstract

It is commonly assumed that elevated, passive continental margins have remained uplifted since the time of rifting. In many areas, e.g. Scandinavia, the timing and extent of uplift movements are difficult to determine because the uplifted area consists almost exclusively of ancient metamorphic rocks. However, the preserved Mesozoic–Cenozoic sedimentary and volcanic record of West Greenland makes this a key area for studying the uplift of passive continental margins.

We have combined apatite fission-track analysis data with landform analysis to investigate the development of West Greenland landscapes across areas with substantially different geology. We show that the present-day mountains of West Greenland (65–71°N) are the end result of three Cenozoic phases of uplift and erosion. The first phase that began between 36 and 30 Ma led to the formation of a planation surface during the Oligocene–Miocene. This surface was offset by reactivated faults, resulting in megablocks that were tilted and uplifted to present-day altitudes of up to 2 km in two phases that began between 11 and 10 and between 7 and 2 Ma. These late Neogene uplift phases postdate rifting by c. 50 million years and sea-floor spreading west of Greenland by c. 30 million years, while the first of these phases predates onset of glaciation in Greenland by c. 3 million years.

The similarity in morphology between West Greenland and other rifted continental margins suggests that uplift of rift flanks to present-day elevations may often post-date rifting significantly. The regional nature of the uplift movements along passive margins and their considerable distance from active plate boundaries suggest that the causal mechanisms must be located in the deep crust or the upper mantle where the thickness of the crust and lithosphere changes substantially over a short distance.

Keywords: passive margins; uplift; geomorphology; thermochronology; Greenland

1. Introduction

Many passive continental margins around the world are characterized by an elevated plateau, often separated from an adjacent coastal plain by a pronounced escarpment [1–3]; e.g. on both sides of the Atlantic, southeast Africa, western India and in eastern Australia.

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doi:10.1016/j.epsl.2006.05.036

There is a widespread assumption in the literature that such mountain areas bordering a rift were uplifted during or just after rifting and that they have remained elevated since rifting [4–6]. For example, uplift of the areas bordering the northern North Atlantic is commonly interpreted either as rift-margin uplift [6] or to be caused by isostatic uplift due to underplating during emplacement of the Arcto-British large igneous province [7]. If either assumption is true, most of the present relief must have formed during the Paleocene and/or early Eocene. On the other hand, evidence has been accumulating during recent years that a major component of the relief is of Neogene age [8].

In many areas, e.g. Scandinavia, the timing and extent of uplift movements are difficult to determine because the uplifted area consists almost exclusively of ancient metamorphic rocks. In West Greenland however, the 2-km high mountains on Nuussuaq and Disko expose a Cretaceous–Eocene sedimentary and volcanic record [9] that reveals two phases of extension and rift formation during the Early Cretaceous [10] and latest Maastrichtian–early Paleocene [9] (Fig. 1). The mountains also contain a detailed record of an uplift episode that occurred in the mid-Paleocene, probably in response to impact of the Iceland plume [11], immediately prior to rapid km-scale subsidence and infilling by sediments and volcanic rocks during later Paleocene and Eocene times [12]. Sea-floor spreading in the Labrador Sea took place simultaneously with this infilling of the Nuussuaq Basin [9,10]. Uplift during the Neogene [12,13] has taken Paleocene marine sediments to 1200 m above sea level (a.s.l.) [14] while deposits of equivalent age were buried below 3 km of sediments in the present-day offshore areas. Farther south, the rift is located offshore, parallel to the coast [10] and the mountainous hinterland onshore is composed of Precambrian basement [15].

We have earlier demonstrated Neogene uplift and denudation in West Greenland within the rifted Nuussuaq Basin based on unconformities in the offshore sedimentary record [16], apatite fission-track analysis [12] (AFTA [17]), and landform analysis of palaeosurfaces [13] (denudation surfaces formed under climatic or tectonic conditions different from the present [13,18]). Here we extend our studies to also include the basement areas landward of the rift farther south as well as the offshore areas. We do so by combining offshore seismic data and landform analysis of palaeosurfaces [13,19,20] with previously published [12] and new AFTA data from across central West Greenland (65° to 71° N).

Analysis of landforms and AFTA data complement each other (Fig. 2). If a palaeosurface was formed subsequent to the onset of cooling from a palaeothermal peak defined by AFTA data, the cooling of the subsurface must have involved exhumation rather than being the consequence of changes in heat flow. AFTA also gives the date of the onset of the erosional episode that leads to the formation of a palaeosurface, while the age for its final formation may be constrained by cover rocks or by the morphology of the palaeosurface that may indicate the environment at that time.

2. Methods

2.1. Apatite fission-track analysis

Apatite fission-track analysis supported by vitrinite reflectance data was carried out on 69 West Greenland samples from outcrops up to 1.7 km a.s.l. and from boreholes down to 3.0 km below sea level (the Gro-3 well [21]) (Fig. 1A). The fission track age range is 61–474 Ma for the outcrop samples and down to 2 Ma for the borehole samples; 35 samples are of Precambrian basement, 2 of a latest Proterozoic carbonatite intrusion and 32 of Cretaceous–Paleocene sandstone. All details of the new AFTA data for 55 samples are accessible as supplementary data online.

Thermal history constraints have been extracted from our AFTA data following the principles established in [12]. Data in individual samples typically define two (rarely three) discrete palaeo-thermal episodes. Synthesis of the timing constraints for individual cooling episodes identified in all samples suggests that at least six discrete episodes of cooling are required to explain all the AFTA results. The events date back to the latest Proterozoic, but here we focus on the late Mesozoic and Cenozoic development, with the AFTA data defining four dominant cooling episodes which began in the intervals 160 to 150 million years ago (Ma), 36 to 30 Ma, 11 to 10 Ma and 7 to 2 Ma (cooling episodes C1 to C4; see Fig. 2). Note that these time intervals represent the ranges of uncertainty for the time of onset of cooling in each episode, not the intervals during which all of the cooling took place. Results from two Disko samples indicate an cooling episode that began between 92 and 53 Ma (not shown in Fig. 2).

2.2. Landform analysis

Landform analysis was carried out in a digital elevation model with 250-metre grid. Palaeosurfaces

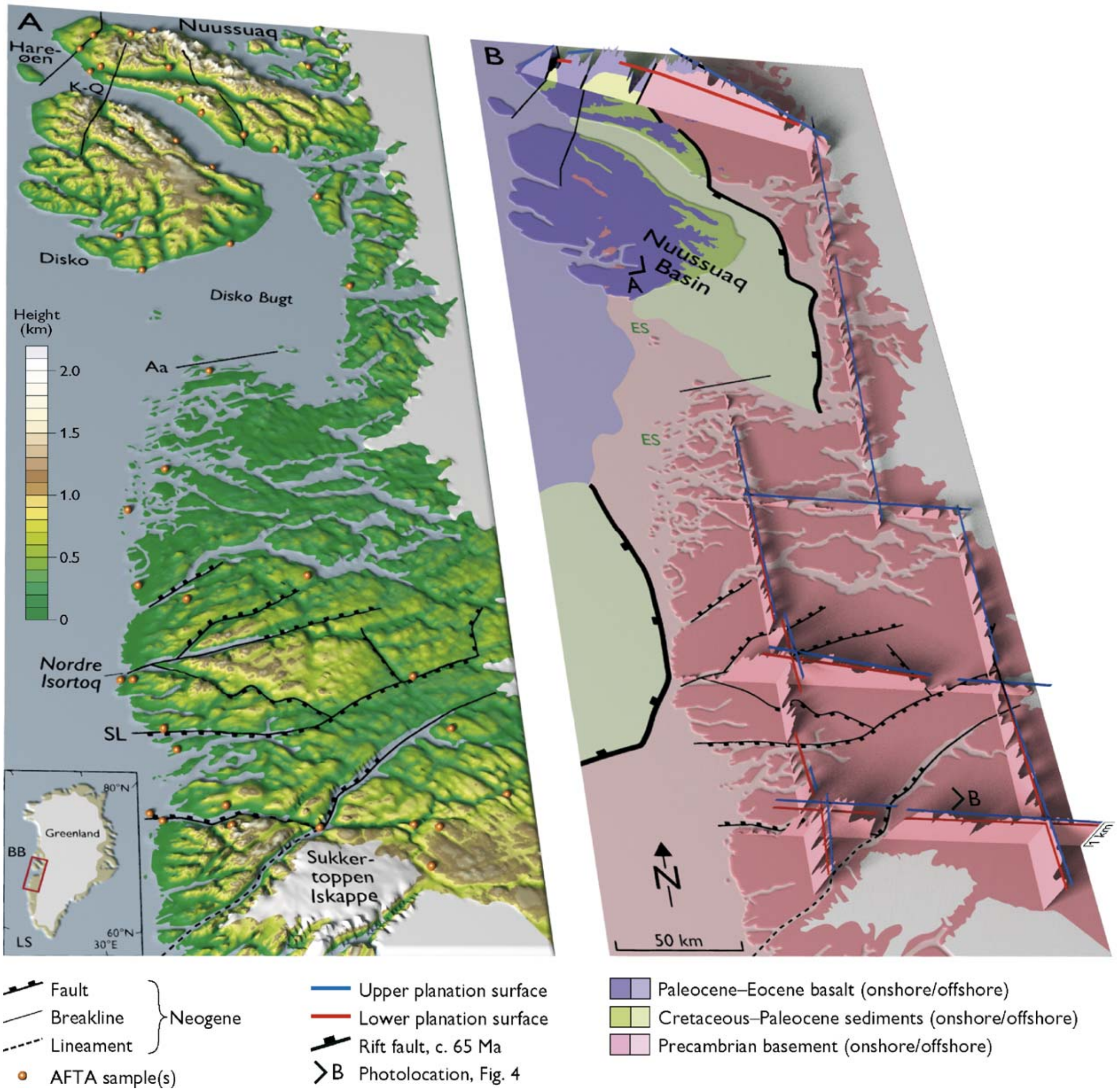


Fig. 1. Three-dimensional maps of the study area. (A) Topography. (B) Geology with topographical profiles [9,13,19,20]. An elevated plateau is defined by two planation surfaces (shown as red and blue lines) that cut across Precambrian basement and Palaeogene volcanic rocks. The formation of the planation surfaces was uniform across the study area and they must be younger than mid-Eocene basalts. The planation surfaces now dip in different directions and are offset by faults that displace them. Three significant faults and breaklines (changes in slope gradient) relative to the planation surfaces are (1) the north–south Kuugannguaq–Qunnilik (K–Q) fault on Disko and Nuussuaq, (2) an east–west fault just north of Aasiaat (Aa) where orthogneisses are separated from supracrustal rocks to the north [46]; this fault separates the south-dipping planation surface on Disko from the north-dipping surface south of Disko Bugt, and (3) the east–west Sisimiut Line [20] (SL) that coincides with the Precambrian Ikertôq thrust zone [15]. An etch surface (ES) has been re-exposed from below Cretaceous–Paleocene cover rocks on Nuussuaq, Disko and south of Disko Bugt. LS: Labrador Sea, BB: Baffin Bay.

were interpreted from cross-cutting topographical profiles and by analysis of the maximum topography of each profile within a 20-km wide corridor and were mapped on a contour map with 100-m contour interval [20]. On Nuussuaq and Disko the interpretation of palaeosurfaces is based on four topographical profiles across elevation maxima, combined with vertical geological sections and interpretation of

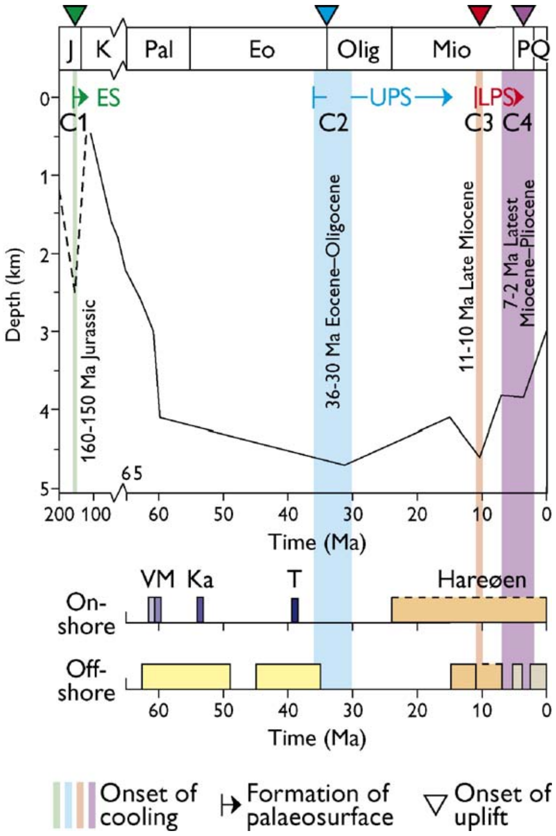


Fig. 2. Schematic event chronology. Relation between discrete episodes during which AFTA data indicate onset of cooling (C1 to C4), formation of palaeosurfaces and the most likely onset of uplift. Minimum burial is not constrained by AFTA, but supplementary information is derived from geomorphology that describes bedrock surfaces formed during periods of denudation [19,20]; ES: etch surface; UPS: upper planation surface; LPS: lower planation surface. The burial curve (full line) is for a hypothetical interface between basement and Cretaceous sediments now at 3-km depth (corresponding to the bottom of the Gro-3 well [12]; Fig. 3); arbitrary depth scale before 100 Ma (dashed line). J: Jurassic; K: Cretaceous; Pal: Paleocene; Eo: Eocene; Olig: Oligocene; Mio: Miocene; P: Pliocene; Q: Quaternary. Basalt–V: Vaigat Formation (c. 61 My old [22]), M: Maligât Formation (c. 60 My old [22]) and Ka: Kanisut Member (c. 53 My old [22]), T: Talerua Member (c. 39 My old [23]). Hareøen: Neogene–Quaternary deposits on Hareøen [21]. Offshore sedimentary units [26,27] see Fig. 3. Dotted lines: maximum age range of sediments.

oblique aerial photographs [13]. The hilly relief on southern Disko was studied from digital elevation models and aerial photographs [19]. Fieldwork was carried out in 2002, 2003 and 2005.

3. Palaeosurfaces in West Greenland

Three Mesozoic–Cenozoic palaeosurfaces have been identified both within the Nuussuaq Basin and over the extra-rift basement area as far south as Sukkertoppen Iskappe [13,19,20], viz (Figs. 1B, 3):

- a re-exposed etch surface (ES),
- an upper planation surface (UPS) and
- a partially developed, lower planation surface (LPS).

The ES, formed by deep weathering of basement rocks, has been re-exposed from below Cretaceous–Paleocene cover rocks [19]. This surface is characterized by an undulating topography with distinct hills up to 100 m high, and can be observed on Nuussuaq, Disko and in the coastal regions south of Disko Bugt.

In the extra-rift highlands around Nordre Isortoq and Sukkertoppen Iskappe, the two planation surfaces are clearly separated in elevation [20]. The UPS can be traced to above 1.5 km and the LPS to c. 1 km a.s.l. Both surfaces are tilted towards Disko Bugt, and the surfaces merge and only the UPS can be identified below c. 500 m a.s.l. The UPS cuts off the more steeply inclined ES and must therefore have formed during the Cenozoic.

In the Nuussuaq Basin, the UPS and LPS are similarly separated in elevation as in the extra-rift highlands to the south, but here they cut across Palaeogene basalts and older rocks [13]. The UPS cuts across lower Eocene basalts [22] in western Nuussuaq and middle Eocene basalts [23] on Hareøen, and the surface must thus have formed during post-mid-Eocene times. The two surfaces on western Nuussuaq and on Disko are comparable to those in the extra-rift area around Nordre Isortoq and Sukkertoppen Iskappe (Fig. 4). We correlate the UPS from north to south (Fig. 1B), and conclude that the formation of the two surfaces occurred uniformly across the entire study area.

The similar development of the UPS and LPS across different geology shows that they must have formed sub-horizontally over a considerable time period, because even a slight tilting will cause fluvial systems to incise [24] and consequently a tilted area will be graded towards the regional base-level [20]. The UPS currently forms the summits of crustal blocks that have been uplifted and tilted by different amounts, indicating a tectonic element in the uplift [13,20]. The variation in altitude of the UPS, about 1.75 km, must therefore represent the minimum surface uplift since the final formation of the surface that must have occurred after the mid-Eocene in the entire study area. The occurrence of marine Paleocene sediments 1200 m a.s.l. close to the UPS on western Nuussuaq ('m' on Fig. 3) is consistent with the elevation of the UPS being a measure of the amount of rock uplift at this location.

A first phase of uplift raised the UPS by a maximum of 1 km in western Nuussuaq and less further south (compare profiles A′A″ and B′B″ in Fig. 3). This phase triggered new fluvial valley incision that ultimately led to the formation of the partly developed LPS. A second phase of uplift interrupted the development of the LPS, and valley widening thus only occurred in restricted areas [13,20]. The LPS was raised to its present elevation of about 1 km a.s.l. around Sukkertoppen Iskappe, Nordre Isortoq, western Nuussuaq and Disko, and the UPS to its present-day maximum elevation of *c.* 2 km in western Nuussuaq. Removal of cover rocks after this second phase resulted in re-exposure of the ES around Disko Bugt.

4. Episodes of exhumation in West Greenland

AFTA data from most samples from the basement areas indicate onset of a cooling episode (C1) during the Late Jurassic, between 160 and 150 Ma (Fig. 2). The event preceded the onset of known rifting offshore and in the Nuussuaq Basin [10], and it affected rocks as far as 175 km away from the Cretaceous rift; consequently it may reflect crustal doming prior to rifting [25]. Palaeotemperatures estimated for rocks at present-day outcrop for this episode increase to above 100 °C towards the present-day coast. The ES is the probable end-result of the C1 cooling episode, which thus must have involved exhumation (Fig. 3).

A cooling episode (C2) that began at the Eocene–Oligocene transition between 36 and 30 Ma is recognized in AFTA results from almost every sample, both within the Nuussuaq Basin and in the extra-rift area. Peak palaeotemperatures during this C2 episode reached c. 100 °C at present-day sea level in western Nuussuaq at the location of the Gro-3 well, where they define a palaeogeothermal gradient of 39–44 °C/km, corresponding to additional burial of 1750–2100 m [12] (see Fig. 3). The samples recording the C2 event are distributed across an area similar in extent to the UPS that, as described above, has been dated independently to be post-mid-Eocene (Fig. 1). It is therefore a reasonable conjecture that both the UPS and the C2 cooling event are evidence of the same episode of uplift and erosion. Offshore, middle Miocene sediments lie directly on Eocene sediments [26,27] above an unconformity that correlates with the timing for the formation of the UPS onshore and thus indicates that the formation of the UPS continued for c. 20 million years (My) into the Miocene. Thermal history reconstructions from AFTA show that this Oligocene–Miocene exhumation was most likely followed by reburial to reach a new peak in palaeotemperatures at c. 10 Ma [12], after which renewed cooling began.

Two late Neogene cooling episodes (C3 and C4) are recognized from AFTA, mainly in samples of Cretaceous–Paleocene rocks from the Nuussuaq Basin. The C3 episode began between 11 and 10 Ma (late Miocene) and the C4 episode between 7 and 2 Ma (latest Miocene–Pliocene) [12]. A section of c. 1 km was removed from above the location of the Gro-3 well during the C4 episode, assuming that the palaeogeothermal gradient had declined to a value close to the present value of c. 30 °C/km [12]. This amount of removed section is similar to the depth of incision of the present-day valley in which the well was drilled, and where the local summit level is close to the elevation of the LPS. Consequently, the C4 cooling episode is interpreted as representing the incision of the present-day valley below the LPS. The uplift of the LPS thus took place during the C4 episode while its formation was a result of both valley incision and widening during C3. Both the UPS and LPS are displaced vertically by up to 500 m across faults that must therefore have been active during the C4 phase (Fig. 1B).

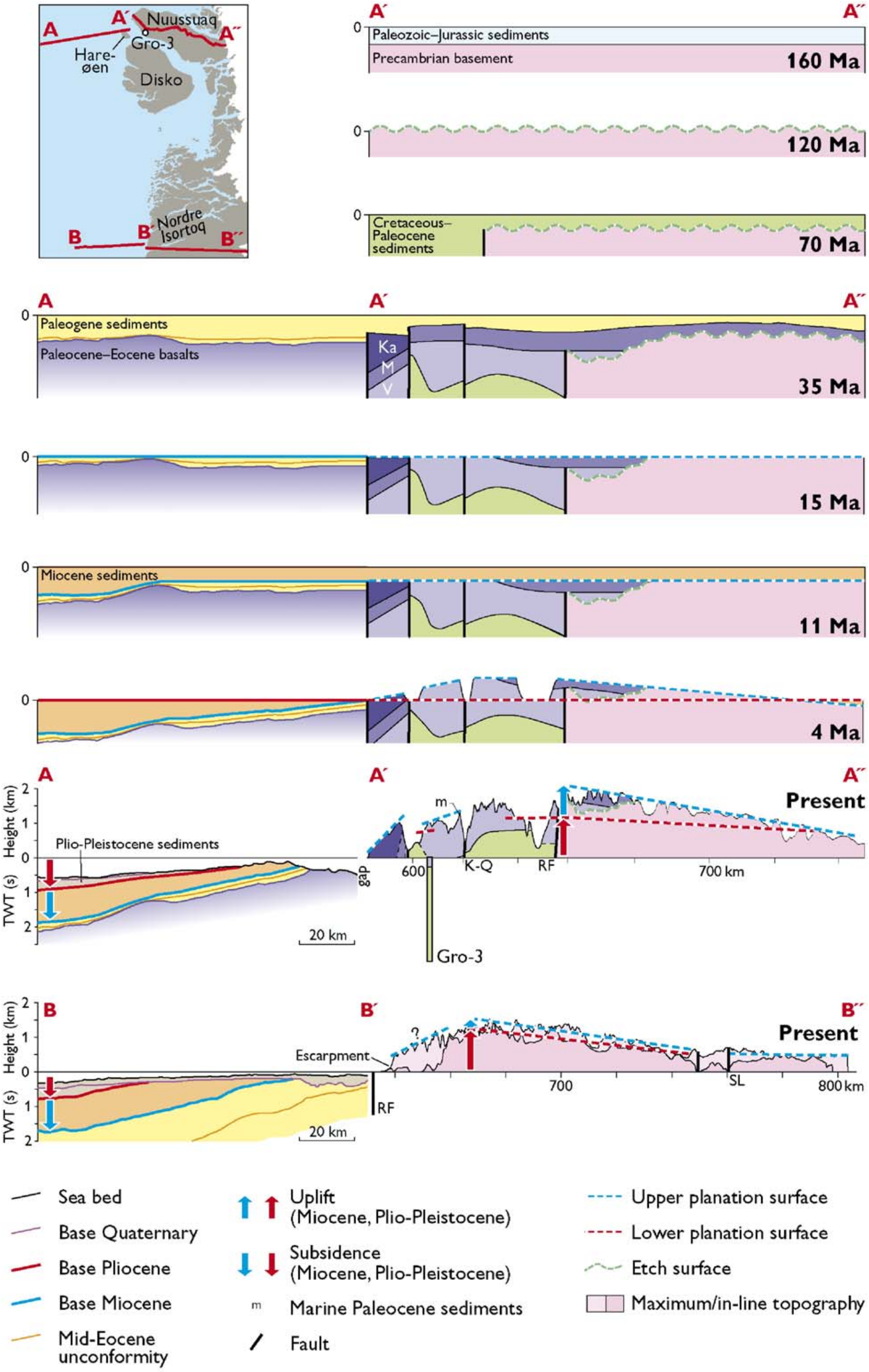
5. Onshore–offshore correlation

Three sedimentary sequences of post-Eocene age have been recognized offshore southern West Greenland [27] (Fig. 2): mid to late Miocene, early Pliocene and late Pliocene to Pleistocene, separated by hiatuses of late Miocene and early Pliocene age. If we correlate these two hiatuses with the two episodes of late Neogene uplift, then the late Miocene hiatus reflects the C3 uplift at c. 10 Ma, while the early Pliocene hiatus provides a more precise timing for the onset of the C4 uplift phase at c. 4 Ma.

The Neogene vertical motions along the coast can thus be defined by the depth/altitude of the base Miocene offshore and the UPS onshore (Fig. 3). The UPS defines asymmetric, domal structures that culminate near the coast and are more than 100 km wide in the east–west direction. Offshore, the base of the Miocene deposits may be correlated with a tentative reconstruction of the UPS along a 20 km wide corridor defining maximum topography for the Nordre Isortoq profile (Fig. 3, BB′B″). The UPS on western Nuussuaq dips more steeply than the base of the Miocene sediments offshore (Fig. 3, AA′A″). This observation and a magnetic anomaly west of Nuussuaq indicate that a fault must be located offshore along the coast of western Nuussuaq.

6. Discussion and conclusions

Our interpretation indicates that prior to 10 Ma there was no relief available to be eroded, so an isostatic response to erosion due to climate deterioration could not have initiated the late Neogene uplift; a tectonic trigger was required. The onset of the C3 uplift at c. 10 Ma precedes the first indications of glaciation in Greenland at 7 Ma [28], and the development of the LPS to a common fluvial base level shows that the area was not covered with ice [13,20]. However, by c. 4 Ma parts of the UPS had been lifted to c. 1 km a.s.l. and this relief, combined with climate deterioration, may have initiated mountain glaciation [29]. The C4 uplift event overlaps or even postdates the early



Pliocene warm period in NE Greenland, and apparently predates the late Pliocene glacial maximum [30]. This event, together with similar uplift in East Greenland [31], may thus have had a triggering role in the formation of the Greenland ice sheets. These arguments also demonstrate that the late Neogene uplift was not caused by glacial loading in central Greenland, as a peripheral bulge along the Inland Ice nor by post-glacial isostatic rebound [13].

The geological record of West Greenland can be combined with AFTA and landform analyses to reveal how three main phases of uplift punctuated by episodes of subsidence and tectonic stability have shaped the post-rift landscape:

1. Regional uplift occurred prior to magmatic activity in the mid-Paleocene (c. 61 Ma) [11] and the onset of sea-floor spreading in the Labrador Sea [10]. Amounts of section removed at this time were small compared to what happened subsequently and left no trace in the AFTA data at most locations. This episode of uplift was followed by kilometre-scale subsidence that lasted until Eocene times [12].
2. Another period of uplift started in the mid-Cenozoic between 36 and 30 Ma (the C2 event) subsequent to the cessation of sea-floor spreading in the Labrador Sea [10]. Cenozoic maximum palaeotemperatures were achieved during this event that was followed by protracted denudation until mid-Miocene times leading to formation of the UPS. What caused this episode is unknown. There is no evidence of rifting at this time.
3. The final uplift occurred in two phases during the late Neogene; the C3 event that started between 11 and 10 Ma and the C4 event that started between 7 and 2 Ma. The C3 event lifted the UPS and re-exposed it from under any Miocene cover rocks and initiated the formation of the LPS, while the C4 event lifted both surfaces to their present heights. Again, the C3 and C4 episodes are not associated with known rifting.

The late Neogene uplift of West Greenland thus took place along a continental margin that was rifted during the Cretaceous–Paleocene, and the present coastline and onshore areas are defined by this late Neogene uplift.

The results from West Greenland demonstrate that lack of Mesozoic and Cenozoic cover rocks cannot be interpreted as evidence that this margin has remained elevated since the last episode of rifting. We have shown that the western margin of the West Greenland craton has experienced repeated cycles of burial and exhumation since Jurassic times (indeed since the latest Proterozoic; see the supplementary data online) and the geological/geomorphological record combined with the fission-track data show that the area has been neither stable nor has cooled slowly. Our analysis also underlines the significance of the planation surfaces that define elevated plateaux along many passive margins: a proper assessment of when these surfaces were formed is just as important for understanding the landscape development as estimating when they were uplifted to their present elevations.

The West Greenland margin resembles passive margins around the Earth that are characterized by an elevated plateau landward of a rift and by thick Cenozoic deposits offshore that are truncated towards the landmass [8]. However, the West Greenland example shows that, despite the apparent similarity with the topography of a rift shoulder [6], the formation of the present relief in West Greenland took place long after any rifting. We suggest that the development of similar margins, for instance around the Atlantic, southern Africa, western India and in eastern Australia, all of which are located onshore of ancient rifts, may similarly post-date the original rifting in those areas. Indeed a delay between rifting and the formation of the present topography has been reported [32–34], although the timing of uplift remain highly disputed and estimates may vary by many tens of millions of years [34–36].

The results presented here and other studies around the northern North Atlantic indicate that uplift and erosion took place broadly simultaneously at the Eocene–Oligocene transition and in the Pliocene and affected both present-day onshore and offshore areas [8,37,38]. One way of explaining this synchronicity is that the uplift episodes are the delayed response to the same rift events and happen where the thickness of the lithosphere changes over a relatively short distance. The contrast between the properties of the stretched and non-stretched lithosphere

Fig. 3. Onshore–offshore correlation. Present-day profiles across Nuussuaq (AA′A″) and Nordre Isortoq (BB′B″) (two lowest sections) reveal uplift of the upper planation surface onshore and subsidence offshore during the Neogene. Note that late Cenozoic erosion along the coast near Nordre Isortoq has resulted in a c. 500 m high escarpment. Suggested development along the Nuussuaq profile [12,13,47]: 160 Ma, Jurassic maximum burial before Late Jurassic–Cretaceous uplift (cooling episodes C1 from AFTA data, see Fig. 2). 120 Ma, Cretaceous etch surface (ES). 70 Ma, Late Cretaceous burial after first rifting episode that extended west of the profile. 35 Ma, Palaeogene maximum burial after second rifting and volcanism, before Eocene–Oligocene uplift (C2). 15 Ma, Oligocene–Miocene upper planation surface (UPS) onshore and truncation of Palaeogene strata offshore. 11 Ma, Neogene maximum burial before late Miocene uplift (C3). 4 Ma, late Neogene lower planation surface (LPS) onshore and truncation of Miocene strata offshore before latest Miocene–Pliocene uplift (C4). Basalt formations, see Fig. 2 (shaded violet: undifferentiated basalts). Location of Gro-3 well on index map. UTM easting co-ordinates along land profiles. Interpretation of seismic lines AA′: GGU95-15, BB′: GGU92-13 (C. Andersen personal communication). K–Q: Kuugannguaq–Qunnilik fault. RF: Rift fault (c. 65 Ma). SL: Sisimiut Line. TWT: Two-way traveltime (1 s ≈ 1 km).

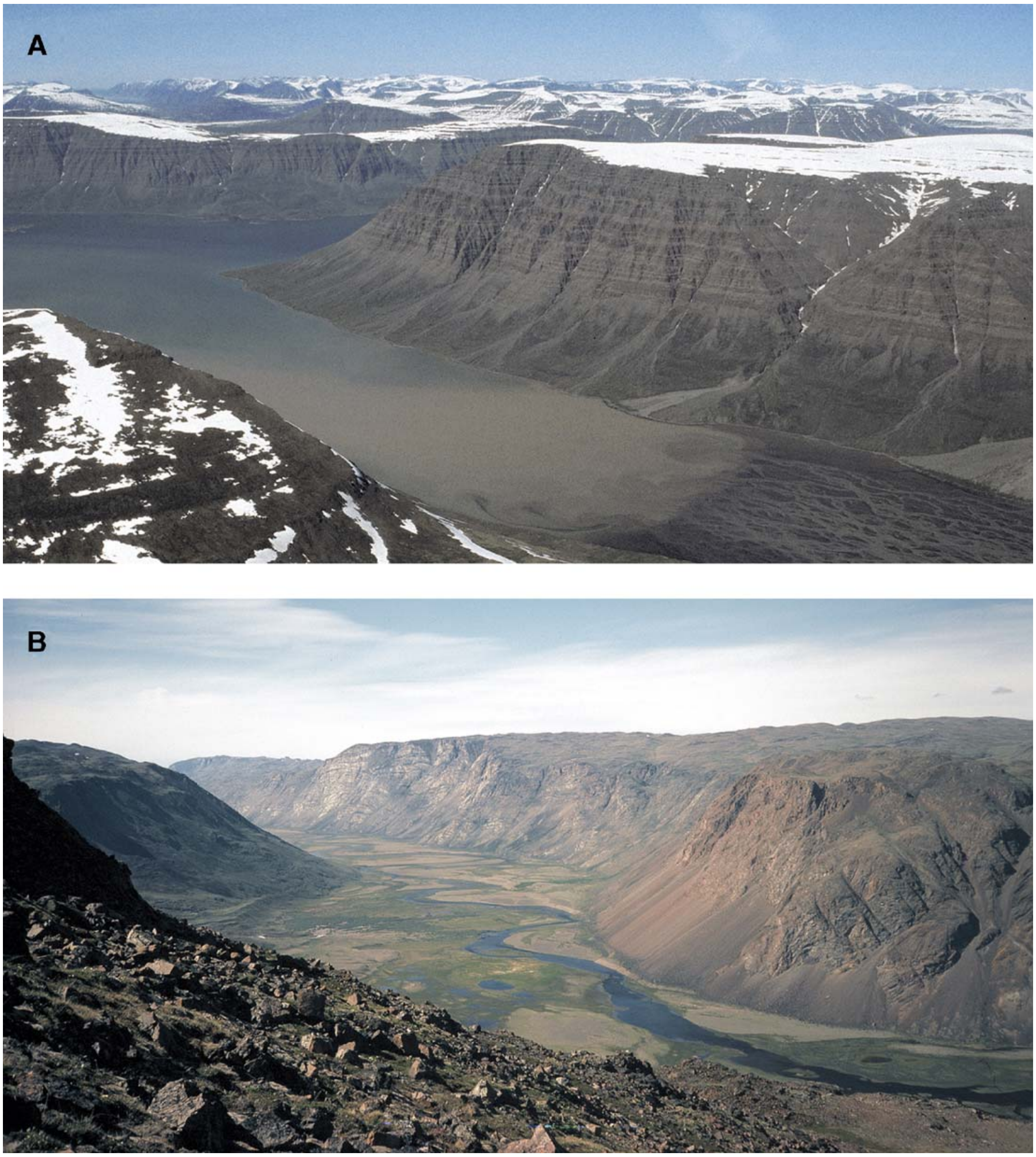


Fig. 4. Photos of the uplifted, upper planation surface (UPS) on southern Disko (A) and north–east of Sukkertoppen Iskappe (B), in both cases around 900 m a.s.l. The UPS cuts across Precambrian basement (B), but the erosion surface can be traced northwards, where it cuts across Paleocene basalt on Disko (A). The UPS is thus of Cenozoic age across central West Greenland. Photo locations on Fig. 1. Photo A (Kangerluk): Niels Nielsen, photo B (Sarfartoq): Karsten Secher.

may cause instabilities and thus induce post-rift uplift movements [32,39–41]. Alternatively, the occurrence of late Cenozoic epeirogenic movements in very different areas of the Earth [42–44] may indicate that a global, tectonic process is involved in triggering vertical movements along zones of lithospheric heterogeneity. The regional nature of the uplift movements along passive margins and their considerable distance from active plate boundaries suggest that the causal mechanisms must be located in the deep crust or the upper mantle where the thickness of the crust and lithosphere changes substantially over a short distance [37,39–41,45].

Acknowledgements

We thank the Bureau of Minerals and Petroleum (Government of Greenland) for co-operation and financial support, Chris Pulvertaft and Knud Erik Klint for fruitful discussions and reviewers John F. Dewey and Tim Stern for constructive comments. This study was supported by the Danish Natural Science Research Council, the Carlsberg Foundation, Arktisk Station, GEUS, the Swedish Research Council, Stiftelsen Margit Althins stipendiefond and John Söderbergs stiftelse. The digital elevation model was by courtesy of KMS (Copenhagen). The paper is published with permission from the Geological Survey of Denmark and Greenland.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2006.05.036.

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