

A multi-disciplinary study of Phanerozoic landscape development in West Greenland

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The western margin of the Greenland craton has been much less stable in the Phanerozoic than previously thought. This new insight has come from close integration of independent data sets: geomorphological analysis of large-scale landscapes, apatite fission track analysis (AFTA), onshore and offshore stratigraphy and analysis of onshore fault and fracture systems. Each data set records specific and unique parts of the event chronology and is equally important to establish a consistent model. A key area for understanding the Mesozoic–Cenozoic landscape evolution and into the present is the uplifted part of the Nuussuaq Basin, where remnants of planation surfaces cut across the Cretaceous to Eocene sedimentary and volcanic rocks. Our integrated analysis concluded that the West Greenland mountains were formed by late Neogene tectonic uplift (Fig. 1) and also provided new insight into early Phanerozoic development. To understand our model, we present the different methods and the results that can be deduced from them.

Basic concepts

The mapping of volcanic and sedimentary successions within the Nuussuaq Basin is crucial for understanding the late Mesozoic–Palaeogene landscape development (e.g. Dam *et al.* 1998; Chalmers *et al.* 1999; Dalhoff *et al.* 2003). Especially important for the landscape analysis is the availability of maps showing vertical geological sections (Pedersen *et al.* 2006). Exploration for hydrocarbons has resulted in many seismic data, and several deep wells have been drilled both onshore and offshore (e.g. Chalmers *et al.* 1999; Piasecki 2003).

Landscape analysis aims at setting up a relative tectonic event chronology through identification and mapping of both extensive baselevel governed surfaces and re-exposed surfaces. These palaeosurfaces, formed by erosion in climates or tectonic settings different from the present, cut across bedrock of different ages and can be arranged in chronological order based on (1) stratigraphical relationships with cover rocks, (2) geometrical relationships between different palaeosurfaces, and (3) analysis of the detailed forms of the large-scale landscapes, reflecting climatic-driven formation processes. The baselevel is fundamental, as lowering of baselevel (an uplift event) causes valley incision and initiation of surface

formation while raising baselevel (subsidence) causes palaeosurfaces to be preserved below cover rocks (Bonow 2005; Bonow *et al.* 2006a, b).

AFTA is a method for defining the temperature history of rock samples, based on analysis of radiation damage features ('fission tracks') produced by spontaneous fission of ^{238}U atoms within apatite crystals. Tracks are produced continu-

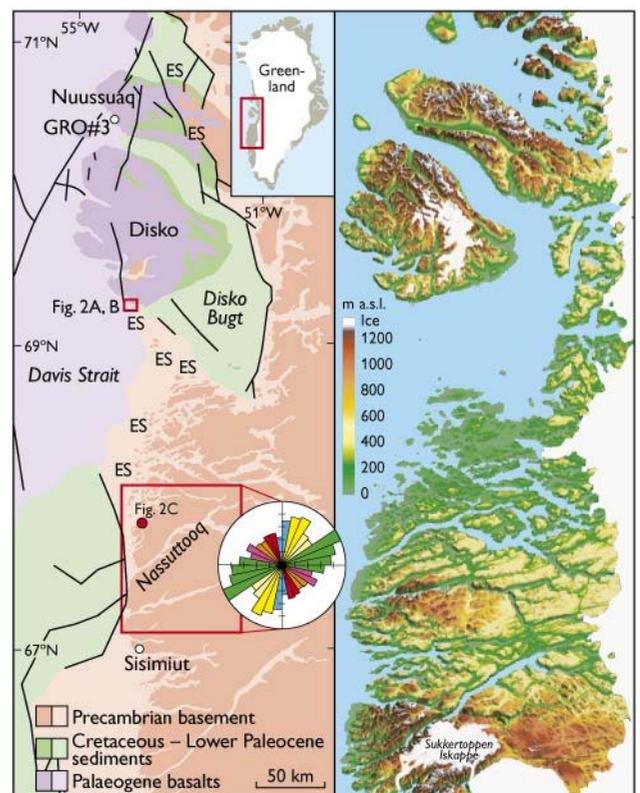


Fig. 1. **Left:** Study area with Precambrian basement and cover rocks that are crucial for determining the relative age of palaeosurfaces. The rose diagram summarises the regional lineament patterns, based on field mapping in the framed area (cf. Wilson *et al.* 2006). The relationship between lineaments onshore and offshore allows for a relative event chronology; colouring refers to timing (cf. Fig. 3). Position of GRO#3 well indicated. **ES**, etch surface of Late Mesozoic – Paleocene age. Note its position close to cover rocks. Modified from Bonow *et al.* (2006a). **Right:** Topography. A regionally developed Oligocene–Miocene planation surface was differentially uplifted on separate tectonic blocks in the Neogene. Today it is close to the summit level and has been tilted in different directions.

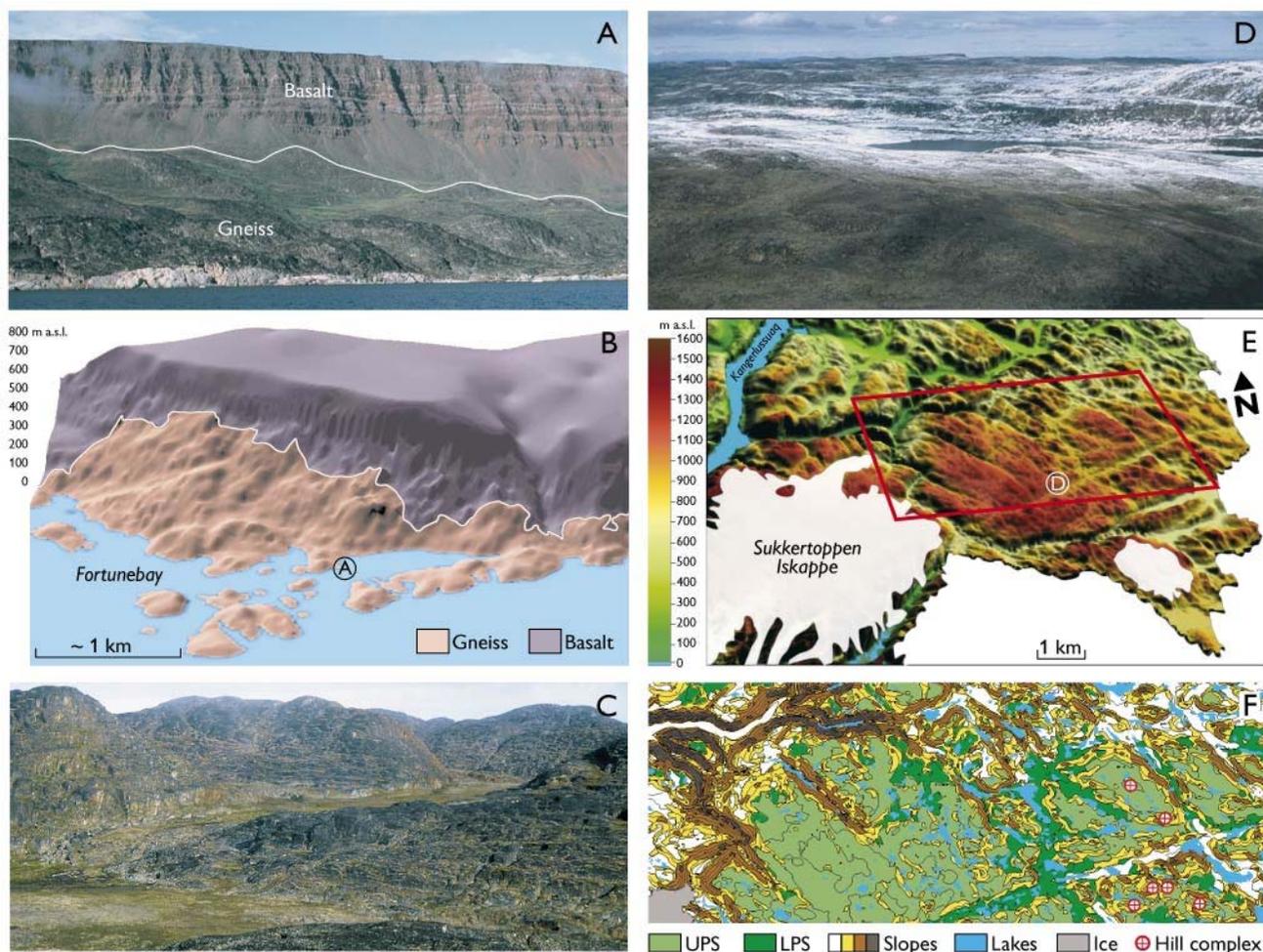


Fig. 2. Views of the etch surface (ES) and the upper and lower planation surfaces (UPS and LPS) formed in basement rocks. **A:** The re-exposed ES at Fortunebay, southern Disko. The white line shows the approximate border between Paleocene basalt and gneiss. Area location in Fig. 1. Photo location in B. **B:** 3D model of the Fortunebay area. Note the Oligocene–Miocene planation surface at high elevation across the basalt. Modified from Bonow (2005). **C:** The stripped ES at Nassuttooq. Location in Fig. 1. **D:** The Oligocene–Miocene UPS east of Sukkertoppen Iskappe cuts across Precambrian basement. Location in E. **E:** 3D model showing the well-preserved UPS east of Sukkertoppen Iskappe. Red frame indicates position of map in F. **F:** Map showing UPS and LPS. Hill complexes rising above the UPS may be part of a sub-Ordovician peneplain. Modified from Bonow *et al.* (2006a).

ously over geological time, but are shortened at a rate that depends on the prevailing temperature, until at temperatures higher than *c.* 120°C tracks are totally erased ('annealing'). Fission track age and track length data provide the basis for estimating the time at which a sample began to cool from a palaeo-thermal maximum as well as the magnitude of the maximum palaeotemperature. Cooling can be interpreted as either change of heat-flow within the crust or erosion of overlying rocks (e.g. Green *et al.* 2002).

Structural analysis of faults and fracture systems aims to establish a relative chronology of tectonic movements that have changed the stress field, as a change will lead to the formation of a new set of faults and possibly the reactivation of older ones. Structural analysis of the area between Nuussuaq and Sisimiut forms the basis for a regional model, explaining different tectonic movements through time (Wilson *et al.* 2006).

Key results

Geology. The Cretaceous–Palaeogene sedimentary and volcanic successions within the Nuussuaq Basin record deep incision of valleys in the Maastrichtian and early Paleocene (e.g. Dam *et al.* 1998), subsidence during volcanism, and deposition of marine sediments within the volcanic succession now at high elevation (Piasecki *et al.* 1992), which are evidence that both uplift and subsidence of kilometre scale took place during and after rifting (Chalmers *et al.* 1999). During the Palaeogene the basalts offshore (and probably onshore, Japsen *et al.* 2006a) became buried below sediments. Seismic sections west of Nuussuaq show that Palaeogene and younger sequences have been tilted seawards and truncated at a late date (Chalmers 2000).

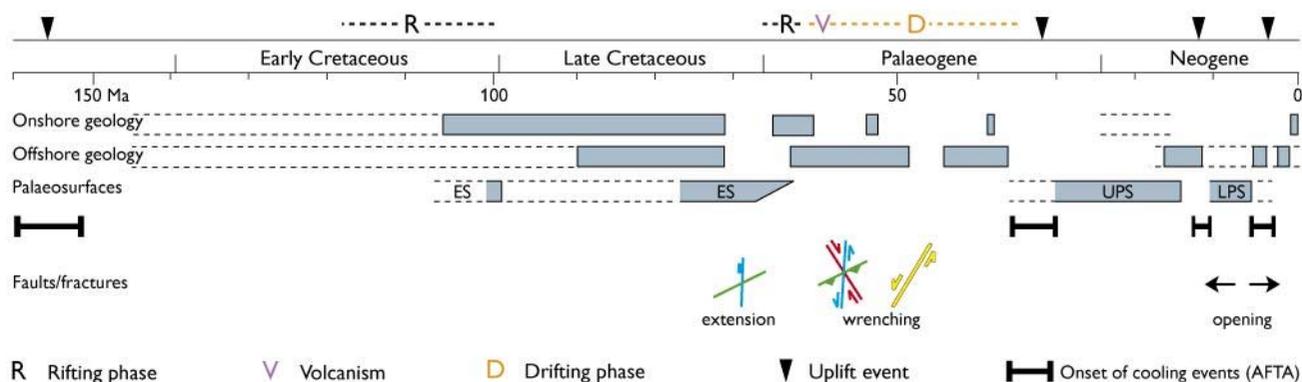


Fig. 3. Event chronology for central West Greenland based on data from the separate disciplines. Integration of these data sets shows that the western margin of the Greenland craton has been less stable than previously thought. Shaded intervals indicate the proven age of geological units, onshore and offshore, and the estimated time required for formation of palaeosurfaces. Horizontal arrows indicate extensional reactivation and opening of vertical fault and fracture systems. The associated intervals indicated by stippled lines illustrate the probable geological age range and uncertainties in dating palaeo-surfaces. **ES**, etch surfaces; **UPS**, upper planation surface; **LPS**, lower planation surface. Data from Piasecki *et al.* (1992); Dam *et al.* (1998); Chalmers *et al.* (1999); Chalmers (2000); Dalhoff *et al.* (2003); Piasecki (2003); Bonow (2005); Japsen *et al.* (2005, 2006a); Bonow *et al.* (2006a, b, c); Pedersen *et al.* (2006) and Wilson *et al.* (2006).

Geomorphology. Three different palaeosurfaces in the Precambrian basement have been identified in West Greenland, viz. a surface formed by deep weathering and stripping of the weathering mantle (etch surface, ES), and an upper and lower planation surface (UPS and LPS; Bonow 2005; Bonow *et al.* 2006a, b). The ES is characterised by distinct hills (Fig. 2A) and received its final shape in part prior to the deposition of Upper Cretaceous deltaic sediments and in part prior to the extrusion of Palaeogene basalts (Fig. 2B). The ES can mainly be identified at low elevations and close to cover rocks (Figs 1, 2C). The UPS has low relative relief compared to the ES (Fig. 2D) and must be younger as it cuts across both mid-Eocene basalts and the etch surface. The UPS forms the summits of differentially tilted, fault-bounded tectonic blocks. A planation surface cannot be formed as an inclined plain because any tilt would cause valleys to incise and the relief to rejuvenate towards the baselevel (Bonow *et al.* 2006b, fig. 6). The LPS was formed in response to lowered baselevel (uplift) and became incised into the UPS (Fig. 2E). Furthermore, summits of distinct hill complexes above the UPS (Fig. 2F)

Table 1. Onset of cooling episodes determined from AFTA data

Stratigraphic age	Onset of cooling, Ma
Cambrian / Early Ordovician	560–500
Late Devonian / Carboniferous	370–355
Triassic	230–220
Late Jurassic	160–150
Eocene–Oligocene	36–30
Late Miocene	11–10
Miocene–Pliocene	7–2

From Japsen *et al.* (2006a) and supplementary data herein.

may relate to a sub-Ordovician palaeosurface because remnants of Lower Palaeozoic rocks suggest that West Greenland may have had a long-lasting Palaeozoic cover (Bonow *et al.* 2006a). Consequently, erosion of Precambrian basement rocks has been limited since the early Palaeozoic, but this does not exclude deposition and subsequent removal of thick sequences of Phanerozoic cover rock as indicated by AFTA data.

Thermochronology. AFTA data from Cretaceous sedimentary rocks define three major Cenozoic cooling episodes, while basement samples define major Triassic and Jurassic cooling episodes (related to rifting?), and also earlier (Palaeozoic) episodes (Table 1). The deepest samples in the 3 km deep GRO#3 well on Nuussuaq are totally annealed (Fig. 1; Japsen *et al.* 2005). The progressive development of fission tracks can therefore be followed through the sedimentary section, giving a rare opportunity to resolve the details of the late Cenozoic cooling history. Oligocene cooling involved both exhumation and a decrease in basal heat flow, while Miocene and Pliocene cooling episodes were dominantly related to exhumation. The two latest cooling events constrain the cooling events into the present.

Faults and fractures. Analysis of regional lineament trends shows five main systems that fit a two-stage model (Wilson *et al.* 2006). A system of N–S- and NNW–SSE-trending normal faults reflects the fault patterns in the Davis Strait during the Late Cretaceous to Paleocene. This system was overprinted and reactivated by strike-slip faults associated with a later NNE–SSW-trending sinistral wrench system that reflects the development of the Ungava transform system during the Eocene.

The model and future implementation

Our model shows where in time independent constrained data exist and time-frames for uncertainties and lack of data (Fig. 3). The model shows that each discipline has long periods of no data, but when combined only few periods have no data representation at all. In particular, landscape analysis and AFTA data complement each other, because palaeosurfaces show that rock was exposed at the landsurface, whereas AFTA data indicate when and by how much a palaeosurface has been buried. This approach shows that the present summits were buried below up to 1 km of rocks prior to Eocene–Oligocene uplift, and that the UPS formed during the Oligocene–Miocene due to stable baselevel conditions. Similarly, uplift in the late Miocene resulted in valley incision (the LPS) and tilting of the UPS. Final uplift in the Pliocene resulted in the present-day mountains. Late uplift reactivated and opened the fault and fracture systems, thus facilitating both weathering and the development of a coastal escarpment (Bonow *et al.* 2006c). Our model is also used in ongoing uplift studies in South-West Greenland (Japsen *et al.* 2006b).

The integration of data from geomorphology, thermochronology, geology and fault/fracture patterns to show that the present landscape of West Greenland is the result of tectonic movements throughout the Phanerozoic with significant movements also in the Neogene and even into the present (Fig. 3). The approach presented here may be applied to understand landscape development along other passive continental margins.

Acknowledgements

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