DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2002/71

Neogene uplift, erosion and resedimentation in West Greenland. Field report summer 2002

Peter Japsen, Johan Bonow, Knud Erik Klint
and Frederik Kromann Jensen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

G E U S

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Contribution to the SNF 2002: "Neogen uplift, erosion and redeposition in West Greenland - identification of pre-glacial landforms and neotectonic activity" and to the GEUS 2002 project: "Fracture systems in West Greenland"

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We are grateful for having been able to work at Arktisk Station in Godhavn and for having had MS Porsild at our disposal for five days.

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1. Summary

New insight into the development of large-scale landforms and structural relations during the Phanerozoic in central West Greenland has resulted from observations made during the one-year SNF project “Neogene uplift, erosion and redeposition in West Greenland – identification of pre-glacial landforms and neotectonic activity”.

Reconnaissance field work was carried out in the area between Kangerlussuaq/Sisimiut and the Nuussuaq peninsula during three weeks of summer 2002. The field work was focussed on describing large-scale landforms and identifying effects of neotectonic activity, along with recording orientation and sense of movement of fractures in general as part of a GEUS assignment. Furthermore, 40 rock samples for possible future fission track analysis and (U-Th)/He-dating were collected.

The Precambrian basement on Bugt area is characterised by a hilly relief with a relative relief of 100-300 m. The hilly relief associated with deep weathering products (saprolites) on Disko strongly suggesting its origin as an etch surface. The hilly relief is overlain by Paleocene basalt, proving the landscape to be pre-60 Ma in age. The hilly relief is therefore an important feature for understanding the development of relief in the Precambrian basement. The hilly relief observed onshore south of Disko Bugt, in the Lersletten area, suggests that the present land surface here is an exposed etched surface, maybe of Cretaceous age. The preservation of the etch surface indicate that it was recently re-exposed, probably after a Neogene uplift event, which may have resulted in fluvial erosion of Cretaceous–Palaeogene cover rocks. The etch surface was finally re-shaped by glacial erosion. The timing and magnitude of this hypothetical pre-glacial erosional event may eventually be confirmed by thermochronological analysis.

An undulating summit plain with shallow valleys is clearly distinct from the deeply incised valleys between Sukkertoppen Iskappe to Nassuttooq, east of Lersletten and Disko Bugt and on Nuussuaq. This planated relief is above 500 m a.s.l. and in many areas above 1000 m a.s.l. (e.g. on Nuussuaq, Disko and south of Kangerlussuaq). This landform configuration is similar to the Palaeic relief and the deeply incised valleys in southern Norway (Lidmar-Bergström et al. 2002). The planated relief with its shallow valleys developed during a prolonged period with stable baselevel condition. This relief is cut by deeply incised valleys and is thus older than the valleys, which originally must have been formed by fluvial incision as a consequence of a lowered base level/uplift. During interglacial periods the fluvial development has been enhanced. The present high plain and the more or less glacially eroded incised valleys indicate an uplift during pre-Quaternary times in the investigated area. On the basis of this observation we believe that the surface uplift occurred during the Neogene and that its magnitude reaches 1 km in many parts of the study area.

The one kilometre of surface uplift is particularly evident from geomorphological observations on Nuussuaq, and is in agreement with the occurrence of marine deposits of both Late Cretaceous and Paleocene age c. 1 km above sea level (Birkelund 1956; Pedersen et al. 1993). The suggested timing of uplift is in agreement with studies of structural relations and basin modelling from Nuussuaq (Mathiesen 1998; Chalmers 2000). The planated relief on eastern Nuussuaq extends across landscape covered by Paleocene basalt into exposed

Precambrian basement. This suggests that the planated relief was formed during mid-Cenozoic erosion, a hypothesis that may be tested by thermochronological analysis. Subsequent to the mid-Cenozoic planation event, the planated relief appears to have been uplifted during pre-Quaternary times by as much as 1 km.

Results from Apatite Fission Track Analysis and (U-Th)/He-dating may provide new information about the Phanerozoic burial and erosional history of central West Greenland, in particular about the extent, thickness and removal of possible Palaeozoic cover rocks. Fission track analysis and He-dating of four basement samples collected at Nordre Isortoq and Ilulissat are currently being analysed at Geotrack International by P.F. Green.

Detailed structural analysis of a number of locations was carried out during the field work. The structural analysis was based on inspection of aerial photos prior to field work followed by field measurement of primary lineaments. Special emphasis was dedicated to analysis of bedrock fractures because they may provide evidence of tectonic events after stripping of cover rocks. Such widespread fractures can thus be used as indicators for the direction of regional palaeo-stress fields and modes of deformation when primary faults are buried below sediment in valleys.

Four post-Proterozoic deformation phases could be established from the event-stratigraphic analysis of a single locality at Inugsuk. The area is dominated by meta-sedimentary rocks that were folded during Proterozoic times (NW of Nassuttooq). The majority of the structures may be related to lateral compression, whereas only one deformation phase may be related to younger extensional tectonics. Pseudotachylits (minerals formed during faulting) were found on major fault planes and samples were collected for dating of the formation of these minerals.

Separation of regional and local tectonic impact was possible through fracture analysis at multiple locations in a larger area on southern Disko (around Godhavn and in Diskofjord). Two major extensional tectonic events were found to have affected southern Disko after the Palaeogene volcanism. These events are manifested by two fracture systems that truncate the Precambrian basement and the overlying Paleocene basalts: One system of primary N-S striking fractures and normal faults and a secondary system of fractures and normal faults striking NW-SE. The N-S striking fracture system correlates with the primary zone of normal faulting to the west that cut across central Disko from north to south. The field investigations showed that the characteristic narrow and straight valleys in the sub-aerial basalts outline primary fractures and faults that are related to both tectonic events. Local variations in the fracture distribution may be related to local contraction processes during the cooling of the basalt-flows.

Detailed mapping of faults and fractures at the Nussaq location, central Nuussuaq, showed the same primary N-S and NW-SE directions which were measured on southern Disko. Consequently, these directions seem to be the result of a regional tectonic event. A further study of these major structures may reveal a more detailed picture regarding timing and stress history of these events.

Neotectonic faults are expected to penetrate the contact between the bedrock and overlying Quaternary sediments. However, no such faults or fractures could be positively identified during a brief inspection of thick, *in situ* glacigene sediments within the primary riverbed in the Itilli Valley, NW Nuussuaq. Neotectonic structures are generally sparse and often restricted to areas directly above the active faults. The inspected part of the Itilli valley was not situated directly over the primary fault, and more attention should be paid to the small side valleys, that are oriented perpendicular to the Itilli fault. Other valleys that truncate the primary N-S trending fault systems, may also be good candidates for further investigation.

Subsequent to the field work, a likely location for neotectonic activity has been identified on the south coast of Nuussuaq, between Paatuut and Saqqaq. We have thus found that a flexure of a Paleocene marker horizon with a relative down-sagging to the east of about 400 m (Pedersen & Dueholm 1992) may be a Neogene feature. This interpretation is based on integrated analysis of geomorphology and structural relations of the Palaeogene basalts in the area.

The fracture measurements carried out on various sites in central West Greenland have revealed multiple tectonic events and a discrimination of local and regional events has been possible. This underlines that detailed fracture analysis may give important geological information that otherwise may be overlooked during traditional structural analysis.

1.1 Future work

The observations and samples from the field work have not yet been fully processed (in particular fission track analysis of rock samples), but localities for possible field work during a future project are:

- The hinterland of the Nuussuaq Basin: Investigations of the 2 km high half-dome defined by the sub-basalt surface. The timing of formation of the dome may be inferred by combining studies of structural relations (including multimodel photogrammetry), landforms and thermochronology (cf. Pulvertaft & Larsen 2002).
- Nuussuaq: The area has a key role for understanding the development of West Greenland as the youngest pre-Quaternary rocks are found here. Structural investigations of the 1.5 km high asymmetric anticline defining the large-scale landform of Nuussuaq should be carried out, e.g. of the 400 m relative down-sagging to the east of a Paleocene marker horizon.
- Disko: The re-exposed sub-Paleocene etch surface should be studied in detail and in relation to glacial impact. Locations close to the Paleocene cover and locations where no cover rocks are preserved should be analysed and compared. The etch surface on Disko is an important reference surface for comparison with supposed etched relief in the Lersletten area (see below).
- Lersletten area: The hypothesis of the Lersletten area as a re-exposed sub-Cretaceous etch surface should be tested by comparison with the re-exposed sub-Palaeocene etch surface on Disko. The hilly relief of the Lersletten area should also be compared to the area with planated relief south of Nordre Strømfjord Shear Zone. The coincidence of the Shear Zone and the transition between the hilly and the planated relief may indicate that Phanerozoic movements took place along the Shear

Zone. Furthermore, a continuation of the Cretaceous Boundary Fault System may be identified onshore south-east of Disko Bugt.

- Area between Nassuttoq and Sukkertoppen Iskappe: Analysis of the continuous planated surface with shallow valleys cut by incised valleys and its dissected western part in relation to uplift/fluvial incision and glacial erosion

Furthermore, Apatite Fission Track Analysis and U/(Th-He) analysis may lead to new constraints on the development of West Greenland. Timing and magnitude of cooling episodes may be used to estimate thickness and age of removed sedimentary covers. Based on analysis of some 40 samples gathered during 2002, it will be possible to set up a strategy for renewed sampling. The understanding of the regional development will benefit from integration of the results from the onshore field work with studies of the offshore geology based on fission tracks analysis and seismic data.

2. Introduction

2.1 Background for the field work

In the early 20th century geomorphologists got the idea that the Scandinavian mountains and the Scottish Highlands were formed late in geological history (see Japsen & Chalmers 2000). However, only within the last ten years has it been discussed in the geological literature to what extent a major tectonic event uplifted all continental margins around the North Atlantic in the period just prior to the start of the late Cenozoic ice ages (e.g. Jensen *et al.* 1992; Solheim *et al.* 1996; Chalmers & Cloetingh 2000). Such uplift movements have frequently been ignored because they are manifested by removal of material and led to exhumation of rocks that were formed long before onset of erosion. Deformation age may therefore be mistaken for uplift age, e.g. the Caledonian orogeny (*c.* 400 Ma) and Neogene uplift of southern Norway respectively.

There appear to have been at least two marked episodes of uplift around the North Atlantic since the end of the Cretaceous, and both episodes have affected West Greenland. The first episode occurred some 60–65 million years ago and was closely related to the impact of the Iceland plume (Dam *et al*. 1998) and the widespread volcanic activity during the onset of sea-floor spreading. The second episode occurred during the last 25 million years and comprised uplift and erosion of basin margins as well as accelerated subsidence in basins offshore the uplifted landmasses (Mathiesen 1998; Chalmers 2000). However, the timing and the exact magnitude of these movements are still uncertain.

The origin of these Neogene vertical movements throughout the North Atlantic region remains highly controversial. Hypotheses have commonly been based on local observations that are not valid regionally. A general model must therefore be constrained by observations from all affected areas, and must separate the effects of older uplift events along plate boundaries from effects of younger uplift that have had an impact far from plate boundaries. West Greenland constitutes an ideal area for testing several of the hypotheses for the origin of Neogene uplift as a counterpart to localities along the Atlantic margin (e.g. Norway). Understanding these processes of uplift is of great importance, not only to an understanding of the behaviour of the Earth's interior, but also an understanding of the development of the climate during the last few million years. The uplift of Scandinavia and other areas around the North Atlantic must have had a major impact on precipitation distribution and on the formation of ice caps and ice sheets. Vertical movements of the sea floor must have led to radical changes of sea currents and to oceanic heat exchange. Uplift, erosion and resedimentation also led to redistribution of huge amounts of material and thus to increased burial and heating of hydrocarbon-generating sediments. Furthermore, events of uplift throughout the Phanerozoic have led to varying degrees of erosion of the Precambrian basement. An understanding of this development is also of practical importance in exploration for diamonds in West Greenland where kimberlite pipes have been eroded to different degrees. West Greenland is well suited for practical reasons as an area for investigating the mechanisms of Neogene uplift. West Greenland is relatively easily accessible, and a great variety of data is already available (including offshore seismic and well data). Investigations related to the Cenozoic development of the area are currently under way, supported by both public and industry funds. GEUS is planning more further field work on the west coast during the coming years.

Studies of structural geology in Greenland have been focused on primary deformation such as folds and faults whereas the most widespread structures, i.e. fractures, have been largely neglected. Fractures are, however, of great importance for construction of e.g. roads and tunnels and in relation to land slides. Furthermore, fractures are important for establishing stratigraphic models, in particular at contacts between rocks of different ages where an event stratigraphic model may be established and the palaeo-stress regime may be estimated.

The field work described in this report had the following aims:
1. Identification and description of pre-glacial landforms.
2. Identification of neotectonic activity.
3. Collection of rock samples for fission track analysis and (U-Th)/He-dating.
4. Measurement of fractures.

Studies of 1–3 were funded by the Danish National Research Council (SNF) ("Neogene uplift, erosion and redeposition in West Greenland – Identification of pre-glacial landforms and neotectonic activity") while work on 4 was funded by GEUS ("Measurement of fracture systems in West Greenland").

The field work was carried out by two teams:

1. Knud Erik Klint, research geologist, Kvartærgeologisk Afdeling, GEUS: Fracture measurements.
   Frederik Kromann Jensen, stud.scient., Københavns Universitet: Assistent, also aiming at defining a project for a cand.scient. thesis.
2. Johan Bonow, PhD student, Stockholm University: Geomorphology.
   Peter Japsen, senior research scientist, Geofysisk Afdeling, GEUS: Sampling of rocks for fission track analysis and (U-Th)/He-dating.

The calendar for the field work and the locations visited are given in Table 2-1 (see locations in Fig. 2-1 and outline of topography in Fig. 2-2).

2.2 Geological outline of the study area

Greenland is dominated by crystalline rocks of the Precambrian shield, which formed during a succession of Archaean and early Proterozoic events and stabilised as a part of the Laurentian shield about 1600 Ma ago (see Henriksen *et al*. 2000, Fig. 2-3). The exposed basement in the study area is characterised by Archaean terrains reworked during the early Proterozoic, around 1850 Ma ago. Gneiss dominate the exposed basement in the study area, but granites occur locally and ridges of mica-schist and amphibolite strike WSW–ENE.

During continental break-up in the Mesozoic and Early Cenozoic, rift-controlled sedimentary basins were developed on the continental margin of West Greenland, mainly in offshore areas. The former presence of a Lower Palaeozoic cover in West Greenland is documented by two onshore outliers (Stouge & Peel 1979; Peel & Secher 1979; Fig. 2-3). The occurrence is further supported by the presence of redeposited Palaeozoic fossils in Cretaceous sediments on Disko (Pedersen & Peel 1985) as well as in cuttings from wells offshore West Greenland, e.g. in Neogene sediments in the Qulleq-1 well (S. Piasecki pers.comm.). Magmatic intrusions in the southern part of the study area are important for understanding the geology of the area, in particular the Safartoq carbonatite complex (NE of Sukkertoppen Iskappe, *c.* 600 Ma), the Qaqqaarsuk carbonatite complex (S of Sukkertoppen Iskappe, *c.* 170 Ma) and the Sukkertoppen dyke swarm (near Manitsoq, 55 Ma) (Larsen & Rex 1992; Larsen *et al*. 1999; Fig. 2-3).

The Nuussuaq Basin in central West Greenland is the only onshore representative of the Mesozoic–Cenozoic rift basins of West Greenland. It contains a 6–8 km thick Mesozoic succession in an early rift basin to the west, whereas the eastern part may be part of a Late Cretaceous thermal subsidence basin (see Chalmers *et al.* 1999; Chalmers & Pulvertaft 2001; Fig <disko<). Renewed faulting involving both reactivation of older faults and generation of new faults took place in latest Cretaceous–early Paleocene time, and was accompanied by uplift, extensive erosion and phases of incision and infilling of valley systems (Dam *et al*. 1998). Renewed subsidence occurred immediately prior to eruption of extensive middle Paleocene and Eocene continental flood basalts. The final phase of faulting took place in connection with sea-floor spreading in Baffin Bay and the Labrador Sea during the Eocene.

During most of the Quaternary Greenland was completely, or almost completely, covered by ice, and surficial glacial deposits are widespread in the present ice-free land areas and on the adjacent shelf (e.g. Funder 1989). Onset of glaciation may have occurred as early as the late Miocene (*c.* 7 Ma ago) (Larsen *et al*. 1994). Evidence from the shelf areas shows that an early glaciation of Greenland at the end of the Pliocene (*c*. 2.4 Ma ago) was more extensive than any succeeding glaciation (Funder 1989). The superficial deposits found on the ice-free land areas are mainly of late Quaternary age (< *c.* 130 000 years) (Henriksen *et al*. 2000). The retreat of the Inland Ice after the last glacial period began 14 000–10 000 years ago and continued with oscillations to a maximum stage of withdrawal approximately 6000 years ago when the ice margin was up to 10 km inside its present position. Due to isostatic bound, coastal West Greenland has been uplifted (Funder & Hansen 1996).

Table 2-1. Field work and travel, summer 2002

All 4	24 July	25 July	26 July	27 July	28 July	29 July
Day	9.30 Departure Copenhagen	Kangerlussuaq, Angmalortup:	10:35 Departure Kangerlussuaq	Nassuttoq (N.Str.), Iterlak:	Nassuttoq (N.Str.), Naujarssuit:	W of Agdo, Rifkol:
	10:55 Arrival Kangerlussuaq	P+J geomorph. obs. FT profile 715 m	11:05 Arrival Sisimiut	P+J geomorph. obs. FT profile 660 m	P+J geomorph. obs. FT profile 750 m	P+J geomorph. obs. FT profile 275 m
	Check in KISS	Kangerlussuaq:	Boarding MS Søkongen, Sisimiut	N of Nassuttoq, Inugsuk:	N of Nassuttoq, Inugsuk:	S of Aasiat, Alangorssup:
	Field trip to the Inland Ice with	KE+F fracture measurements	Sisimiut -> Nassuttooq (N.Str.)	KE+F fracture measurements	KE+F fracture measurements	P+J geomorph. obs. FT profile 230 m
	Karsten Secher, GEUS		Geomorphological observations		KE+F: Pick up	
Night			KE+F: Inugsuk, N of Nassuttoq	KE+F: Inugsuk, N of Nassuttoq		
	KISS, Kangerlussuaq	KISS, Kangerlussuaq	Søkongen -> Onto Nassuttoq (N.Str.)	Søkongen <- Out of Nassuttoq (N.Str.)	Søkongen towards N	Søkongen towards Aasiat

Yellow	Air transport
Green	Land-based field work
Cyan	Boat-based field work

	Knud Erik, Frederik				All 4	
	30 July	**31 July**	**1 August**	**2 August**	**3 August**	**4 August**
Day	Disembarking Søkongen, Aasiat	8:55 Departure Aasiat	Qeqertarsuaq, Arktisk Station: J+F Cret. Outcrops	Qeqertarsuaq - SW, Killiit (Fortunebay): KE+F fracture measurements	Qeqertarsuaq - SW, Killiit (Fortunebay): All 4, basement - basalt contact, fracture measurements	Qeqertarsuaq - SE, Kuussuaq (Røde Elv) KE+F fracture measurements
		12.30 Arrival Qeqertarsuaq				
		Qeqertarsuaq, Godhavn harbour KE+F fracture measurements				Qeqertarsuaq SE, Assoq: J+F Cret. Outcrops
Night	Sømandshjemmet, Aasiat	Fox Hostel, Qeqertarsuaq	Fox Hostel, Qeqertarsuaq	Fox Hostel, Qeqertarsuaq	Arktisk Station, Qeqertarsuaq	Arktisk Station, Qeqertarsuaq

	Johan, Peter					
	30 July	**31 July**	**1 August**	**2 August**		
Day	Disembarking Søkongen, Aasiat	Boat trip, Sisimiut -> N. Isortoq	Sisimiut, Kællingehætten: J+P geomorph. obs. FT profile 785 m	9:35 Departure Sisismiut		
	9:35 Departure Aasiat	N. Isortoq, Natarnivingup: J+P geom. obs. FT profile 570 m		10:05 Arr. Kangerl. 11.40 Dept. Kangerl.		
	10:20 Arr. Kangerl. 11.00 Dept. Kangerl.			12:25 Arrival Aasiat 13.00 Departure Aasiat		
	11:30 Arrival Sisimiut	Boat trip, N.Isortoq -> Sisimiut		13:25 Arrival Godhavn		
Night	Sømandshjemmet, Sisimiut	Sømandshjemmet, Sisimiut	Sømandshjemmet, Sisimiut	Arktisk Station, Qeqertarsuaq		

All 4	5 August	6 August	7 August	8 August	9 August	10 August
Day	Board, MS Porsild, Qeqertarsuaq	Kangerluk (Diskofj), Kannaa	Nuussuaq - N, Itilli Valley:	Nuussuaq - N, Nulup qaqa:	Saqqaq, Palungataaq:	Disembarking Porsild, Ilulissat
	Qeqertarsuaq -> Kagerluk (Diskofj)	All 4 fault zone observation	All 4: Cret. + Quat. exposures,	P+J geomorph. obs. to 780 m	P+J geomorph. obs. FT profile 830 m	
	Kangerluk (Diskofj), Kannaa	Diskofjord -> Nuussuaq, Maraat	topography	N. Nussuaq, Nuussaq	Saqqaq -> Ilulissat	
	All 4 basement - basalt contact, fault zone			KE+F fracture measurements		
	measuremtents, exhumed etch surface			N.Nuussuaq -> Saqqaq		
Night	Porsild, Diskofjord	Porsild, Nuussuaq, Maraat	Porsild, Nuussuaq, Maraat	Porsild, Saqqaq	Porsild, Ilulissat	Hvide Falk, Ilulissat

All 4	11 August	12 August	13 August
Day	Ilulissat, Qaqqarsuatsiaq	Shipment of cargo	5:55 Arrival København
	P+J+F geom. obs., FT profile 315 m	20:05 Departure Ilulissat	
		20:50 Arrival Kangerlussuaq	
		21:40 Departure Kangerlussuaq	
Night	Hvide Falk, Ilulissat	Airplane	

Figure 2-1. Location map.

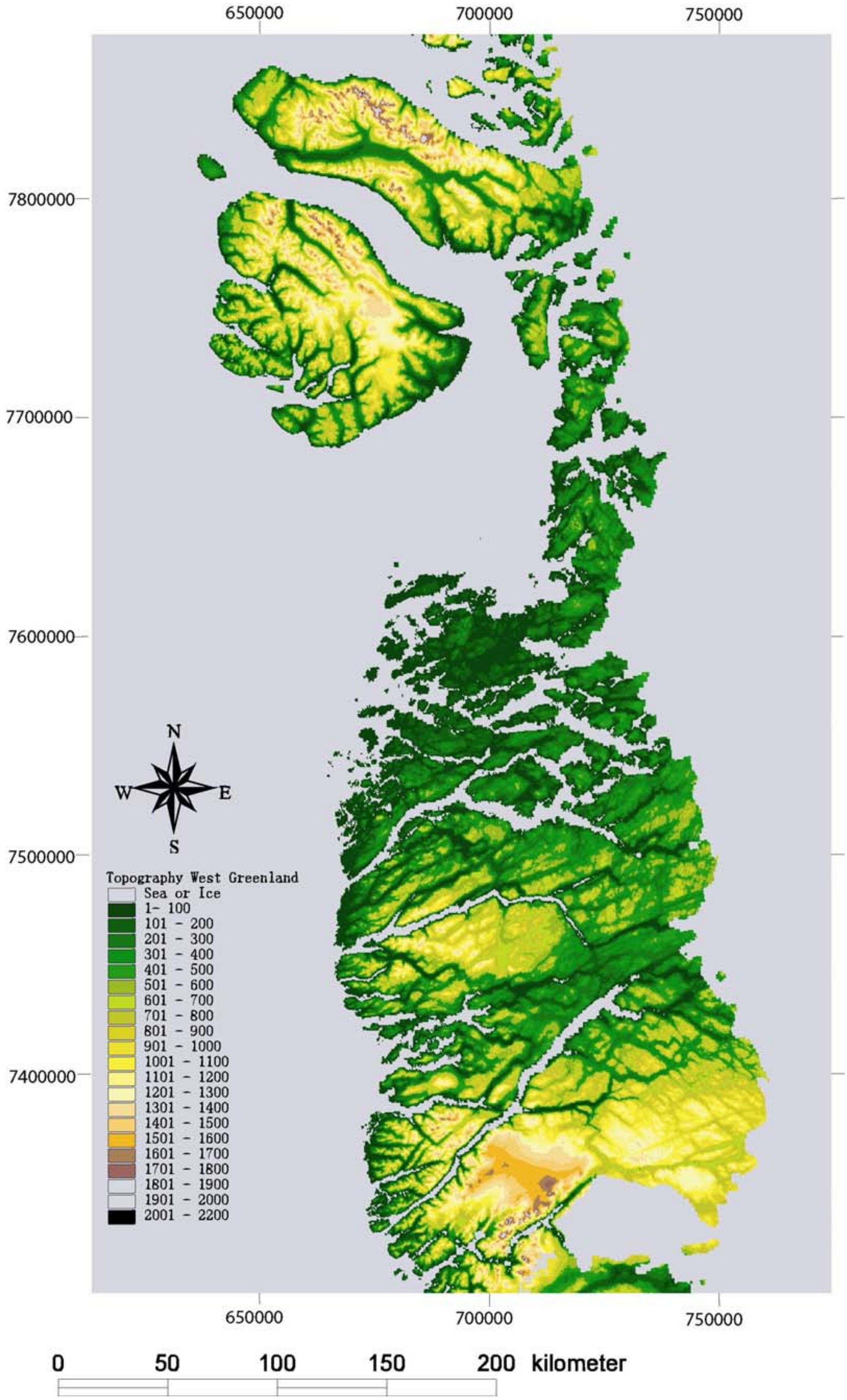


Figure 2-2. Topography of the study area.

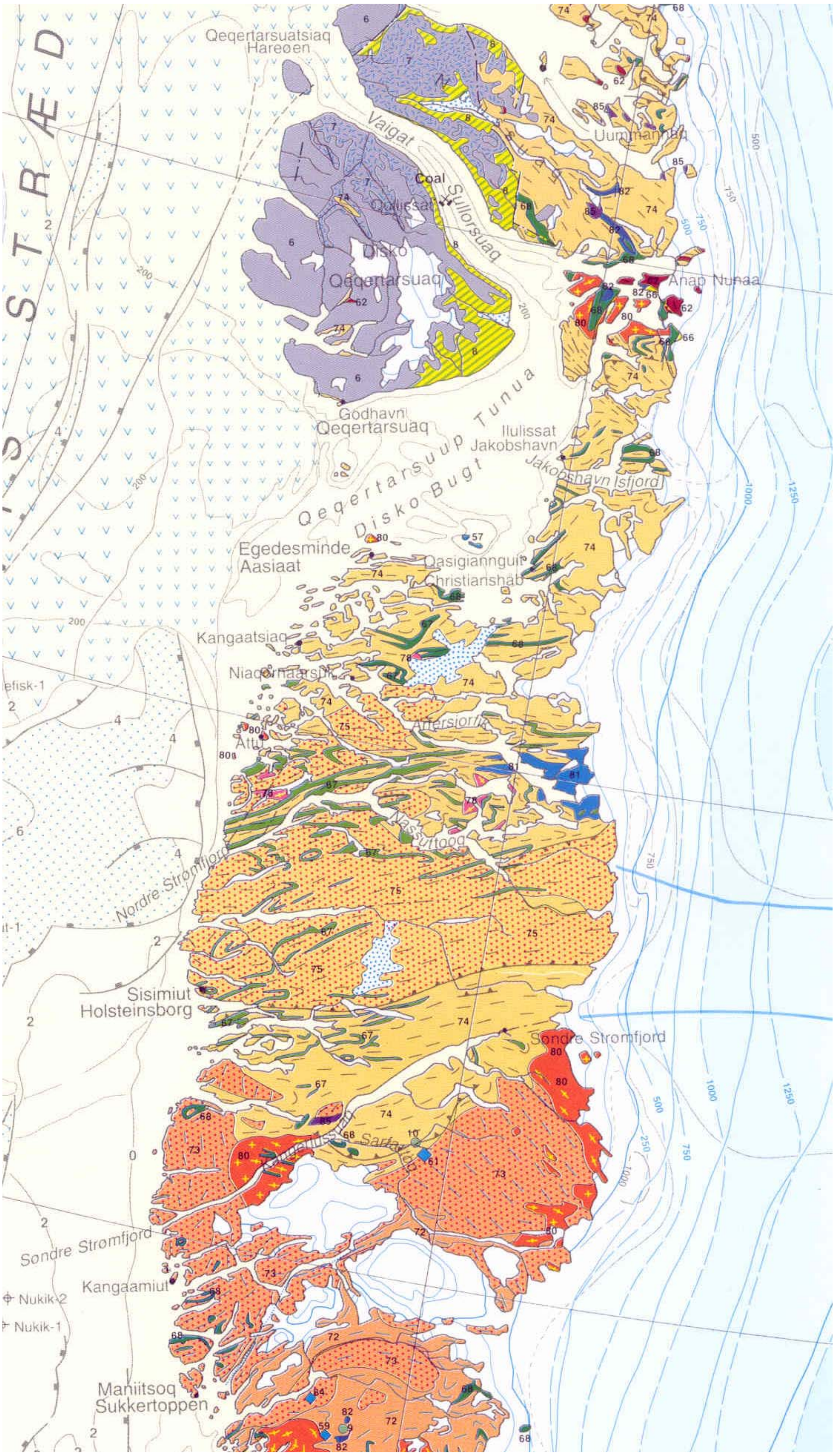


Figure 2-3a. Part of the Geological map of Greenland 1:2 500 000 (Henriksen *et al*. 2000).

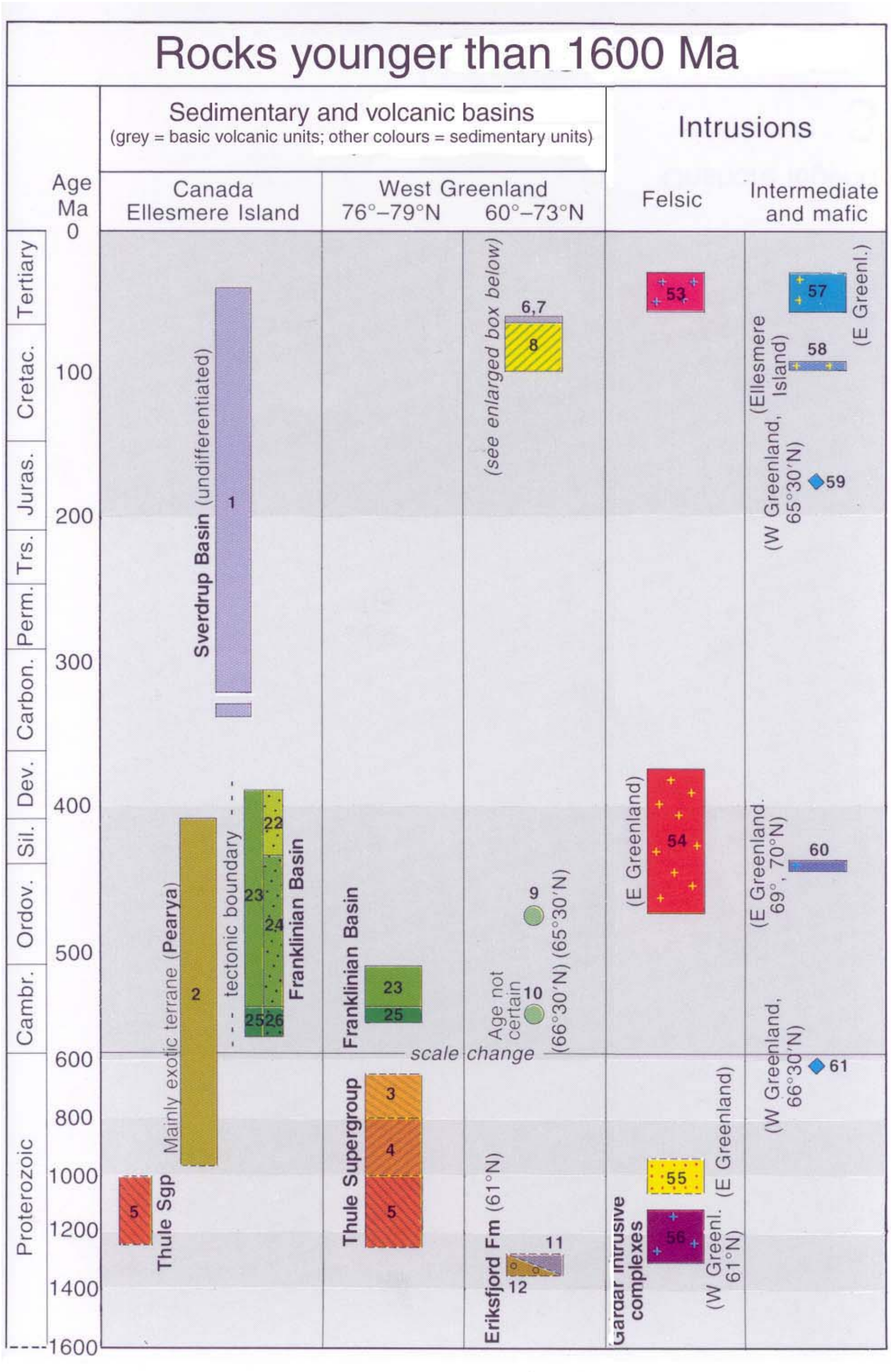


Figure 2-3b. Part of the legend to the Geological map of Greenland 1:2 500 000 (Henriksen *et al*. 2000).

3. Structural analysis

3.1 Introduction

Regional tectonic uplift of the crust may lead to erosion of both crystalline basement rocks and possible sedimentary cover rocks. The erosion of these rocks also removes important structures that may have reflected the nature, magnitude and timing of the uplift history. Some evidence of the geological events may however still be present, primarily in the form of faults and fractures in the remaining basement. Major fault zones are, however, often eroded into valley systems and the faults may accordingly be buried under younger sediments, while the fractures are widespread and exposed in a wide area.

Construction of event-stratigraphical models is a well known method to solve the geological history in an area. The method aims at identifying the correct order of geological events (sedimentary, deformational, intrusive and erosional history) and at establishing the stratigraphical correct order of these geological events from the simple theory, that younger geological deformation structures overprint or truncate older structures. Detailed analysis of faults and fractures may thus be an important tool for the reconstruction of the geological history of such areas.

A record of the Neogene uplift and erosion of West Greenland may be preserved in the pattern of fractures and faults in the exposed basement and cover rocks. The project thus aimed at testing different methods to identify and possibly date fault systems and their related fracture systems on a number of locations on West Greenland. Investigations were carried out in the exposed basement and remnants of the Cretaceous-Palaeogene cover as well as in Quaternary deposits in order to separate local and regional fracture/faults systems of different origin and age.

3.2 Objectives

The aim of the fieldwork was to test various methods to identify the relative order of tectonic movement in the basement, and possibly reconstruct the age and nature of these movements. The first investigation was a detailed photo-geological analysis of three selected areas (Nassuttooq, Disko and Nuussuaq). Based on the analysis fieldwork was carried out in order to:

1. Test the possibility for establishing a detailed event-stratigraphy based on primarily fracture and fault analysis for two small areas (~3 km^2) covered by Precambrian gneiss, Paleocene basalt and Quaternary deposits.
2. Test the possibility to identify and separate regional fracture systems from locally derived fractures in a larger area dominated by old gneiss and young basalts (~50 km^2).

3. Identify and evaluate possible neotectonic deformations by investigating exposed sections with Quaternary sediments, and especially contacts between Prequaternary rocks and Quaternary sediments.
4. Investigate and identify primary regional faults and fault systems.
5. Test methodologies for dating minerals formed during faulting (pseudo-tachyliths).

3.3 Methods

Characterisation of fractures includes a full-scale geological investigation, as the distributions of the fractures are closely related to both rock mechanical properties and to the tectonic history of the area. Fractures in non-stratabound rocks such as intrusive rocks are in general very different from fractures in stratabound rocks such as sandstone or limestone. Attempts to construct a regional conceptual fracture model thus depends on the number and quality of the field data.

A number of outcrops with large and well-exposed fractures were selected for detailed fracture analysis. Large-scale analyses of fracture distributions were carried out using analysis of aerial photos with visible fracture traces on exposed outcrops. The observations were later verified on the ground.

3.3.1 Fracture classification

Fractures include all brittle failures such as joints, fissures, cracks, veins, etc. which are not faults, beddings or cleavages, and which are larger than the grain size of the rock. In general, fractures are defined as dominantly opening mode fractures, and as such, they are associated with characteristic stress, strain and displacement fields. They are distinguished from small faults by distinctive surface textures and lack of shear displacements. Some fractures may however show a small displacement between the two fracture surfaces, with additional development of stria or "slickensides" on the surface, and are thus referred to as shear fractures or micro-faults.

Fractures form in relation to a certain stress field, either as systematic sets of parallel fractures with a distinct orientation, or in some cases as more irregular non systematic fractures with an overall random orientation. Systematic fractures thus form “families” of fractures with special characteristics that may be related to distinct tectonic processes. The classification of fractures is primarily based on the orientation of the fractures. Once classified as systematic or non-systematic, the fracture properties may be calculated, and a more detailed classification related to other characteristics such as fracture shape and size may be included in the classification, by comparing with the characteristics of the different fracture types.

3.3.2 Fracture parameters

Fracture Orientation is important for classifying the fractures into distinct fracture sets or systems. The orientation data may be illustrated in pole diagrams or pole density diagrams on a *Stereographic Projection,* (Kazi & Knill 1973) where all fractures are plotted as the pole to the fracture plane. Systematic fractures will plot in characteristic clusters and non-systematic fractures will be randomly distributed on the stereographic plot. The fracture data are normally contoured in order to visualise the fracture distribution and identify fracture systems. A Gaussian counting method (K=100) was used (Robin & Jowett 1986). This method is also useful for analysing distribution of fractures with special characteristics such as characteristic surface precipitation or slickensides at the fracture surfaces etc. The fracture strike may also be illustrated in a *Rose Diagram* (Nemec 1988; Davis 1984) showing the strike variation of the fractures. The latter method gives an excellent visual presentation of the fracture orientation, but it does not account for the dip and is only used on vertical/sub-vertical fractures.

Fracture Spacing (S) is the mean perpendicular distance between adjacent fractures in an almost parallel fracture set.
The best way to calculate the spacing is to measure all spacing between fractures in the same fracture-system directly in the field and calculate the mean spacing as the average distance of all the spacings as described by Bosscher & Connel (1988). This is however quite difficult to do if several different fracture systems coexist in the same place, and near wall-parallel fractures are normally biased.

Fracture Intensity (I): 1/S is the number of fractures per meter for a single set of parallel fractures.
The spacing may be illustrated as the Fracture Intensity (1/S), which is the inverse of the fracture spacing. The Fracture Intensity allows the spacing to be illustrated on a "*Rose diagram*" or a graph. The sum of all fracture intensities are then showing the total number of fractures in an average cubic-meter of rock termed the *Fracture Bulk Intensity* (T_{otal}).

3.3.3 Fracture measurement technique

Order/System: The fractures were classified as 1st, 2'nd or 3'rd order fractures, with the 1st order fractures as the dominating fractures cross cutting all other fractures (in general > 10 m long in crystalline rocks), 2'nd order fractures were less dominating fractures sometimes connecting 1st order fractures without crossing them (in general between 1 and 4 m), and 3'rd order fractures were minor irregular fractures (in general < 0,5 m). The scale is however relative, and in some cases where the 1st order fractures may be more than 100 m long, the 2'nd order fractures may be more than 10 m long. If a clear systematic set of fractures could be recognised in the field, it was given a number as system 1 fractures, and another set as system 2 etc.

Faults were classified according to type (normal/reverse dip-slip faults or transform dextral/sinestral strike slip faults (right hand or left hand movement of the hanging wall). Direction of slickensides were measured and the magnitude of the displacement if possible.

Dykes were described in terms of rock type and thickness and orientation.

Orientation: The orientation of the fracture/fault/dike-contact surface was measured with a compass with a clinometer and the strike and the dip of the plane were measured.

Surface shape: The overall fracture shape (m scale) was described as listric, planar, undulating or irregular.

Surface roughness character: The surface roughness character is described in mm scale as smooth, rough or slickenside (striae).

Remarks: Some fractures/faults had a filling of iron oxide precipitates or quartz crystals, or preferential growth of other crystals on the surface showing the slip direction. The direction of the slickensides were measured on most fault-surfaces. Special types of fractures such as Conjugating shear-fractures, En echelon fracture, plumose jointing etc. were noted if positively identified.

3.4 Structural analysis at Inugsuk

This location is an example of Proterozoic rocks (~1.7 billion years old) that has suffered multiple deformation phases since the time of the rock formation. The area is dominated by intensely folded meta-sedimentary and meta-volcanic quartzo-felspatic or calc-silicate rocks. The basement rocks are covered with Quaternary glacigene sediments in some areas and Holocene marine sediments in other areas. Approximately 3 km^2 were mapped along the coast and a primary fault 500-1000 meter inland.

The primary goals of the investigation on this location were therefore:

1. Identify the origin and nature of lineaments deduced from the aerial photos.
2. Classify the possible folds, faults and fractures.
3. Set up an event-stratigraphy for the area.
4. Collect samples for dating the faults (pseudo-tachyliths).
5. Investigate possible contacts between the young Quaternary sediments and the older rocks that may be truncated by faults and fractures (neotectonics).

At least four characteristic lineaments are truncating these rocks. The lineaments were identified by detailed analysis of aerial photos prior to the fieldwork (Fig. 3.4.1). They were regarded to be either related to the competence of the rocks (heterogeneous weathering and glacial erosion), to primary structures such as folds, faults or fractures, or more likely as a combination of these features.

3.4.1 Geomorphology

The area has a general low relief compared to the area south of Nassuttooq. A number of E-W striking elongated hills (70-80^0) and valleys dominate the topography. The hills rise to approximately 2-300 meter above sea level and the valleys are eroded relatively 50-150 meter down in the basement. A secondary system of characteristic valleys with a NE-SW trend (25-35^0) and an average distance of 1 km truncate the landscape and the primary E-W striking hills in an angle of approximately 40^0.

The valleys are generally covered with thick vegetation, and on several locations small elongated lakes and bogs appear in the valley-floor. The hills are generally covered with mosses, while nice outcrops are exposed on the valley sides. The rocks are well exposed along the coastline, and several small bays and rifts outline primary structures in the rocks, such as fault and fracture zones as well as areas dominated by less competent rocks. The valleys form bays and are generally covered with loose sediments such as stones and sandy deposits, while the hills are forming high cliff sections of solid very well exposed rocks. Characteristic old beach ridges consisting of well rounded stones are present at several levels up to 30 m above sea-level. The rocks in the area are generally well rounded and ice scoured in an E-W direction and bare witness of former glaciers advancing over the area.

3.4.2 Geological description

The area is dominated by Proterozoic generally highly deformed metamorphic quartzo-felspatic rocks (primarily orthopyroxene-gneiss, garnet-biotite-gneiss, garnet-biotite-schist) and meta-sedimentary calc-silicate rocks and biotite-graphite-schist. The rocks are intensively folded in the southernmost part where the folds are tight-isoclinal with almost parallel flanks striking 65-75^0 and a steep dip (70-80^0) towards NW and an average fold-axis orientation on 70/10^0 (Fig. 3-4-3). The central part of the area is dominated by a large open anticline fold with a fold-axis orientation 78/12 (Fig. 3-4-3). The core of the fold are dominated by intensive parasitic folding of a rusty Biotite-graphite-pyroxene schist. The rocks are more gently folded further north with flanks dipping less steep. The strike is gradually changing towards 45-15^0 dipping 30-15^0 SE. The primary fault directions and general orientation of fold axis and fold flanks, as well as the foliation in the gneiss, indicate that the area has been subjected to intensive simple shear in a NE-SW direction and subsequent compression with the maximum stress-direction oriented in a NW-SE direction (Folding).

Four different fault/fracture systems were identified within the research area (Fig. 3-4-1) System 1-3 truncate the folds and belong accordingly to younger tectonic events. The faulting is dominated by two transverse strike slip fault systems. These faults were truncated by the primary strike slip faulting. The primary deformation style in the area is accordingly dominated by structures related to compressive deformation rather than extension, and they are generally regarded to be very old. The presence of younger dykes may however indicate periods of extension and intrusion and the NW-SE striking fault-system 2 may therefore be related to extension during a younger tectonic event, but no striations indicating normal faulting were positively identified. The schedule allowed only detailed fracture analysis on one location (Fig. 3-4-2). Several fracture systems are accordingly missing, and a thorough investigation of the fractures on at least five more locations would have completed the picture. The fracture measurement technique however proved very useful. The outcrops were excellently exposed, and it is possible to measure fractures in all dimensions. The use of aerial photo analysis of lineaments was very well suited for preliminary investigations. It was easy to identify major lineaments on site using the constructed lineament maps, and the major fracture/fault systems were all verified in the field.

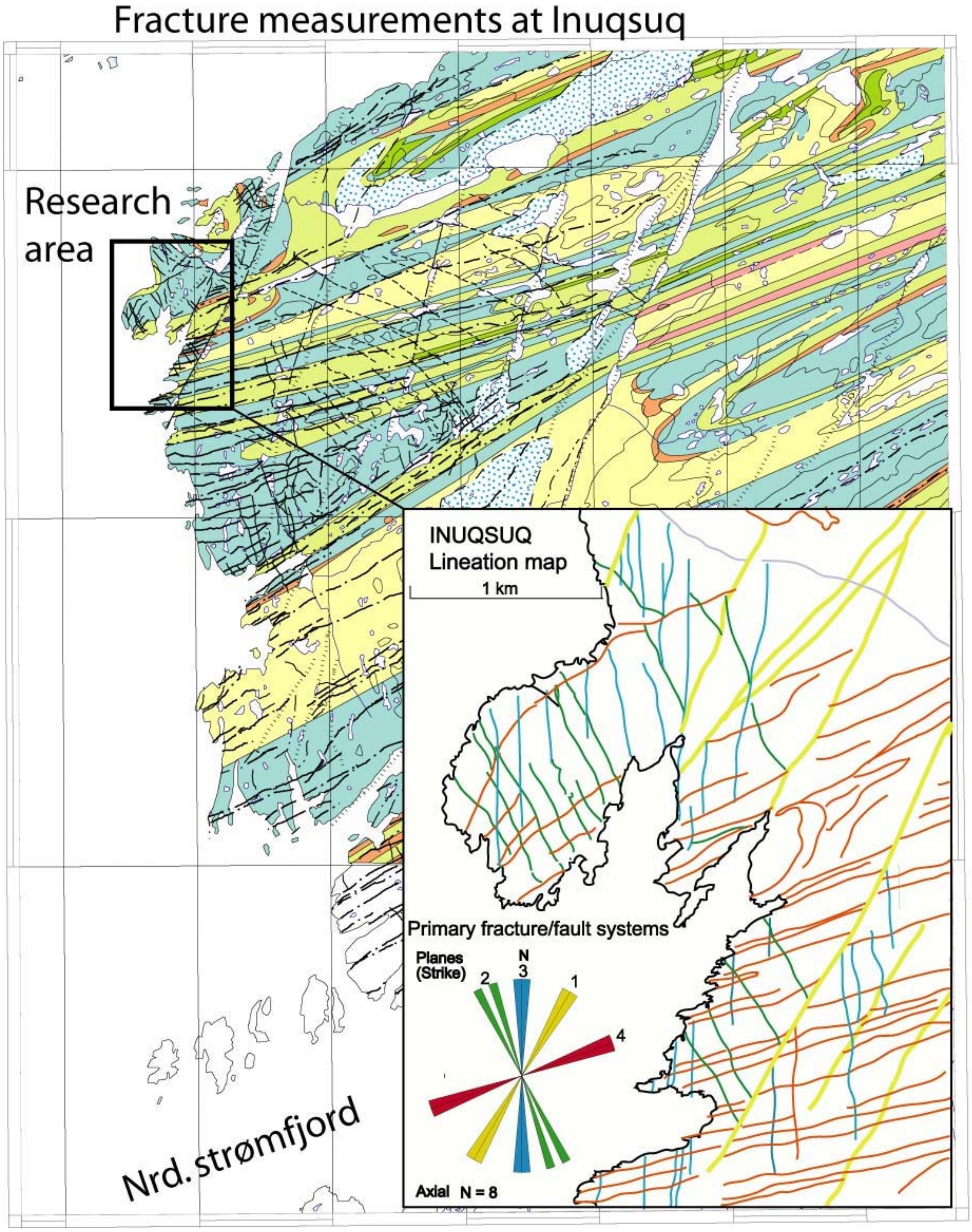


Figure 3-4-1. *Geological map from the Nassuttooq area with the research area and characteristic lineaments deduced from aerial photo analysis. Four characteristic directions may be recognised from this map: System 1 comprises major sinestral transform strike slip faults. These faults are the youngest faults in the area. System 2 are possible normal faults. System 3 are primarily a fracture system, but with small dextral displacements on some minor transform strike-slip faults. System 4 is old shear planes between contacts of different rock types. These planes were later folded and outlines today also the folds and lithology.*

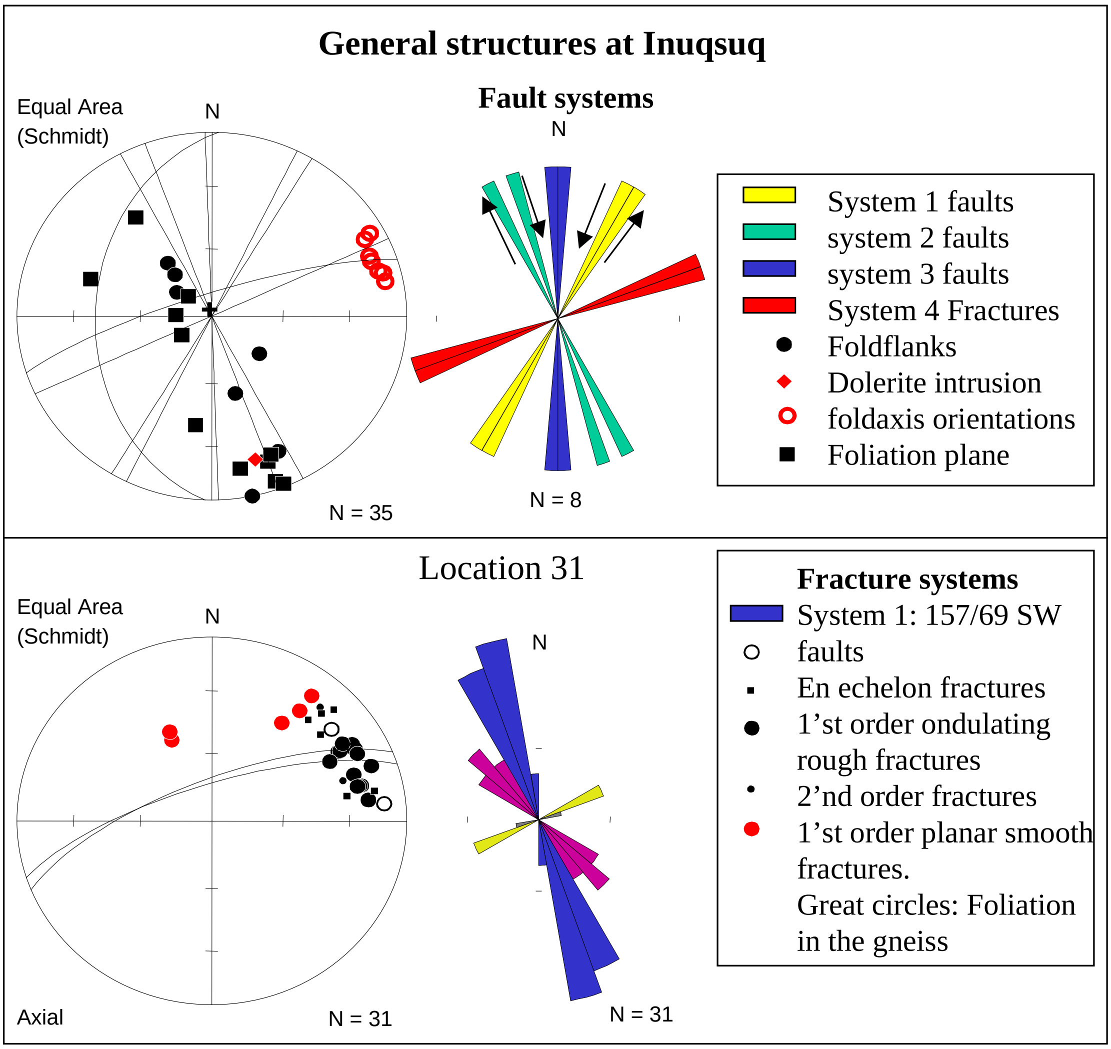


Figure 3-4-2. Structural analysis at Inugsuk.

Figure 3-4-3. *Anticline fold in the central part of the area*.

3.5 Regional fracture analysis in basalt and gneiss on Disko

Regional fracture/fault analysis in an area dominated by three different rock types: Proterozoic crystalline rocks (gneiss). Paleocene volcanic rocks (basalt-flows) and Quaternary sediments.

The primary goals of these investigations were:
1. Identify the lineaments deduced from the aerial photo analysis.
2. Analyse and classify the fracture/fault-systems on a significant number of locations in the old gneiss and in the younger basalt.
3. Identify regional fracture/fault systems and investigate them.
4. Establish an event-stratigraphy for the area.
5. Investigate possible contacts between the young Quaternary sediments and the older rocks, that may be truncated by faults and fractures (neotectonics).

All descriptions are related to the geological map Fig. 3-5-11.

3.5.1 Geomorphology

The southern part of Disko is characterised by highly deformed gneiss complexes overlain by basalt. The gneiss is exposed along the coast and has well-rounded hills with ice-scoured surface and an undulating relief . The contact between the gneiss and the basalt is marking the Palaeocene relief. The basalt rises abruptly from the gneiss to a with a relative flat plateau at approximately 1400 m a.s.l. (partly covered with ice-caps). Large fans of loose material are deposited along the basalt walls and hide the gneiss basalt contact, except on a few locations. This basalt plateau is dissected by a number of relatively straight, predominantly N-S striking valleys and the largest of them are occupied by rivers, that are deeply eroded into the basalt, especially along the river Kuussuaq (Røde Elv). A number of characteristic N-S striking valleys are truncating the basalt plateaus on the southern coast of Disko, and show a classical U-shape with a V-shape in the bottom indicating glacial eroded valleys that have been further eroded by rivers after the retreat of the glaciers. At Fortunebay another low basalt plateau appears. In contrast to the plateau near Godhavn, this plateau seems to be less eroded. Only two N-S striking valleys were identified from aerial photos. This fact may be related to different types of basalt. Apparently the brecciated sub-aqueous basalt around Godhavn is less resistant to erosion than the more massive sub-aerial basalt flows near Fortunebay.

3.5.2 Geology

The area is dominated by Proterozoic generally highly deformed metamorphic quartzo-felspatic rocks along the coastline, from Godhavn in the east to Fortunebay in the west. The rocks consist primarily of nicely foliated gneiss with local intrusions of amphibolite and ultra mafic lenses. These rocks are overlain by basalt from the Lower Maligat Fm, and consist primarily of feldspar phyric, and aphyric sub-aqueous brecciated lava flows in the area east of Godhavn, and feldspar phyric, and aphyric sub-aerial lava flows at Fortunebay. The contact between the basalt and the underlying gneiss is only exposed on three small outcrops (location 2, 6 and 7), while large fans of talus cover the lowest part of the basalt. Glacigene diamict deposits are covering large areas in front of the talus fans, and marine deposits are abundant especially at Fortunebay and just south of the Arktisk Station.

3.5.3 Fracture distribution on southern Disko

During the fieldwork a number of locations along the southern coast of Disko were investigated. At least two sections more or less perpendicular to each other were measured on each location in order to catch all the fracture systems. At least 50 fractures should be measured on each location in order to get good statistical values, but simple lack of fractures on some locations prevented collection of sufficient data, still smaller numbers give important information. A total of 364 fractures/faults were measured on the seven locations, and an additional 242 lineaments were measured on the aerial photographs.

Location 1 is situated in strongly deformed gneiss just west of Godhavn (Fig. 3-5-11). A small bay is outlining some primary fracture orientations and 50 fractures were measured along two transects. Another 50 fractures were measured along a freshly exposed outcrop along the harbour (Fig. 3-5-1). The general fracture density is medium (1-2 fractures/m).

The fractures in this area are dominated by two systems of major planar straight fractures, and a secondary system of low angle minor fractures often parallel to the foliation within the gneiss:

- System 1 consists of *primary more* than 20 meter long sub-vertical fractures striking N-S (1/89W). One normal fault was displacing a dyke in the gneiss a few cm. And this system is generally regarded to be related to extensional tectonics. It was not possible to identify displacement of the system 2 fractures, and the relative age is accordingly not clear.
- System 2 consists of primary sub-vertical fractures striking NE-SW (46/83NW). Three minor faults were oriented parallel to this system and are regarded to belong to the same tectonic event.
- System 3 consists of primarily 2'nd order fractures striking NW-SE (131/17NE).

Location 2 is situated in an area where gneiss crop out just north of Arktisk Station (Fig. 3-5-11). This area is densely fractured with an average fracture density of more than 6 fractures/m (Fig. 3-5-2). The fractures are more irregular than on location 1, with undulating rough surfaces and few very long fractures (>20 m). The foliation in the gneiss showed that the gneiss in this area has been gently folded into large weak folds with a fold axis orientation of 37/14. Four fracture systems may be recognised though they are generally rather weakly developed.

- System 1 is the most conspicuous of the fracture systems. It consists of relatively straight sub-vertical fractures with an undulating rough surface and an average orientation of 44/89SE. This fracture system is sub-parallel to the fold axis of the folded gneiss, but it seems to predate the folding since the orientation remains quite constant. It may be correlated to the system 2 fractures on location 1.
- System 2 fractures are irregular NW-SE striking vertical fractures with an average orientation 135/88SW. One of these fractures had a large aperture of ~10 cm, which was infilled with quartz.
- System 3 fractures consist of a few, but rather large, vertical, straight fractures striking NNW-SSE (170/79E). This system may be correlated to the system 1 fractures on location 1.
- System 4 fractures are highly irregular sub horizontal fractures with an average orientation of 87/25N that follows natural weakness zones in the gneiss, and they may be regarded as exfoliation fractures formed as a result of stress release during uplift.

The fracture style and the very high fracture density differ from all other locations that were measured.

Location 3 is situated on the basalt plateau just east of the Arktisk Station (Fig. 3-5-11). The plateau is dissected by a large number of crevasses, which are cut 3-5 meters into the surface. They form a system of long elongated micro valleys. Some of them have small streams in the bottom while others seem to be dry most of the year. A large number of relatively straight fractures are typically oriented parallel to the valleys while smaller secondary fractures seem oriented more or less perpendicular to the valleys. A total of 46 fractures were measured in six of these valleys. The fracture distribution is illustrated on Fig. 3-5-3. Three systems were recognised:

- System 1 is oriented 149/90 and consists of large straight fractures with a generally rough surface. The fracture density is low with less than 1 fracture/m, and the fractures were all sub-parallel to the valley in which they was measured.

- System 2 fractures followed a second valley system that were striking N-S. These fractures were likewise the system 2 fractures with an average orientation of 176/90.
- System 3 fractures were primarily 2'nd order irregular smaller fractures with an average orientation of 70/78S.

System 1 and 2 fractures are regarded to penetrate the basalt and continue into the underlying gneiss. These fractures are accordingly regarded to be among the youngest fracture systems in the area, since they truncate all other rocks and structures, except the Quaternary deposits.

Location 4 is situated on the basalt plateau near Fortunebay (Fig. 3-5-11). The basalt is intensively fractured, but the fractures are generally very irregular with curving surfaces and a typical polygonal pattern that is clearly related to contraction processes rather than a regional tectonic stress fields. There is a large difference between the fractures in the basalt at location 2 and these fractures. The reason is clearly related to the nature of the basalt. The fractures in the sub-aerial basalt flows at this location, has formed as a result of contraction during the cooling process, while the fractures in the brecciated sub-aqueous basalt on location 2 are large, straight planar fractures with a regional uniform distribution. The fractures on this location also show a general random orientation (Fig. 3-5-4), except for three sub-parallel, vertical, irregular, but overall straight fractures striking N-S. These fractures may therefore be related to a general tectonic event, but the overall picture is random.

Location 5 is situated in well exposed gneiss outcrops at the coast close to location 4 (Fig. 3-5-11). The gneiss here is very systematically fractured. Two major systems of very long planar fractures, with a generally smooth surface, are very dominating while a secondary system of minor fractures also seems to have a systematic distribution in the area..

- System 1 consists of sub-vertical fractures striking E-W (91/72S). The intensity of the fractures are close to 1 fracture/m.
- System 2 fractures are likewise the system 1 fractures very long (>100 m), with a generally smooth planar surface (Fig. 3-5-5). The mean orientation of the fractures is 158/78SW, with a fracture intensity of 1-1.5 fractures /m.
- System 3 fractures are secondary fractures striking NE-SW (47/78SE). The fractures are generally small (1-5 meter long).

Location 6 is situated in the westernmost part of the area of Fortunebay (Fig. 3-5-11). The contact between the basalt and the gneiss is preserved in a small outcrop here. The gneiss is deeply weathered (> 5 m) and thus represent the Palaeo surface as it must have looked prior to the volcanism in the area.

The gneiss is intensively deformed in this area, and a large thrust fault dominated the structures. The hanging-wall block was thrusted along a low-angle thrust plane oriented 67/31SE. Striation on the thrust plane indicated a relative movement from SE towards NW (133/21). The gneiss was generally foliated with the foliation striking N-S and dipping steeply toward W. A number of fractures were measured in the area and two fracture systems similar to location 5 were recognised (Fig. 3-5-6).

- System 1 consists of subvertical straight planar 1st order fractures oriented 172/77W.
- System 2 fractures were sub-vertical planar fractures oriented 96/84S. One strike slip fault was oriented parallel to these fractures.

Location 7 was located in the central part of the Fortunebay area (Fig. 3-5-11). Poorly exposed outcrops revealed three fracture systems in this area (Fig. 3-5-7):

- System 1 is a pronounced system of large planar sub-vertical fractures striking NNW-SSE (156/87SW).
- System 2 fractures are likewise large planar sub-vertical fractures striking N-S (6/87E). It is a question whether system 1 and 2 are the same system as the fractures have the same characteristics.
- System 3 is a third system of dominating 1st order large planar sub-vertical fractures striking NE-SW (47/86SE). This fracture system is also very pronounced on the aerial photographs of this area, and may be correlated to the system 2 fractures on location 1.

Location 8 was situated along the river Kuussuaq (Røde Elv). The primary task with the investigations on this location was measurement of primary fractures in the riverbed and inspection of possible fractures/faults that truncated the between basalt in the riverbed and the glacigene Quaternary deposits that covered the area. Approximately 3 km of the river were covered, but the rather steep gradient on the relief on both sides of the river facilitated solifluction in the Quaternary deposits. Soil-creep and sediment flows into the riverbed had therefore effectively covered or destroyed all potential neotectonic structures. Instead a number of fractures within the riverbed were measured.

The river is predominantly running N-S until it reaches the Waterfall (approximately 1 km upriver from the coast. Here it bends and runs NE for 200 meter before it reassumes the N-S trend again. It is very clear that the river is oriented parallel to the fractures in the river. At this spot close to the waterfalls, a secondary fracture direction facilitate the characteristic bend of the river. The fractures were generally sparse, but especially close to the coast a higher fracture intensity occurred. Some very large sub-vertical fractures with a clear opening mode and thick fillings of quarts were situated close to where the bridge cross the river.
In general one system of dominant sub vertical NNE-SSW striking fractures existed, but three minor local systems of 2’nd order fractures were recognised (Fig. 3-5-8).

3.5.4 Fracture analysis

Along with the analysis of the lineaments on Southern Disko (Fig. 3-5-9) more than 500 fractures were measured and described. It is clear that the gneiss contains a large number of fracture systems. According to Fig. 3-5-10, at least four major systems may be recognised along with a number of faults. Some of the systems are restricted to a part of the area. The E-W trending fractures (yellow system) are thus primarily restricted to the Fortunebay area, while the NE-SW trending system (red system) is dominating the central part of the area. Two systems seem to be represented on a regional scale. That is the green system striking NW-SE and the blue system Striking N-S. Both systems are penetrating the eastern basalt plateau while only the N-S striking blue system are seen in the western basalt plateau. Several minor primarily 2'nd order fractures in the basalt are probably related to local conditions and may not be regarded a regional system. The fact that the green and blue system (Fig. 3-5-10) penetrates both gneiss and basalt, implies a relatively young age, at least younger than the basalt. It also implies a connection to a major regional stress regime that most likely is related to the formation of the primary N-S trending fault system, that down-thrust all Western Disko 2-300 m, just west of Fortunebay. This fault may be followed all the way to Nuussuaq. The fractures are accordingly associated with post basaltic tectonism and may thus prove to be important evidence of the youngest tectonic history of this area.

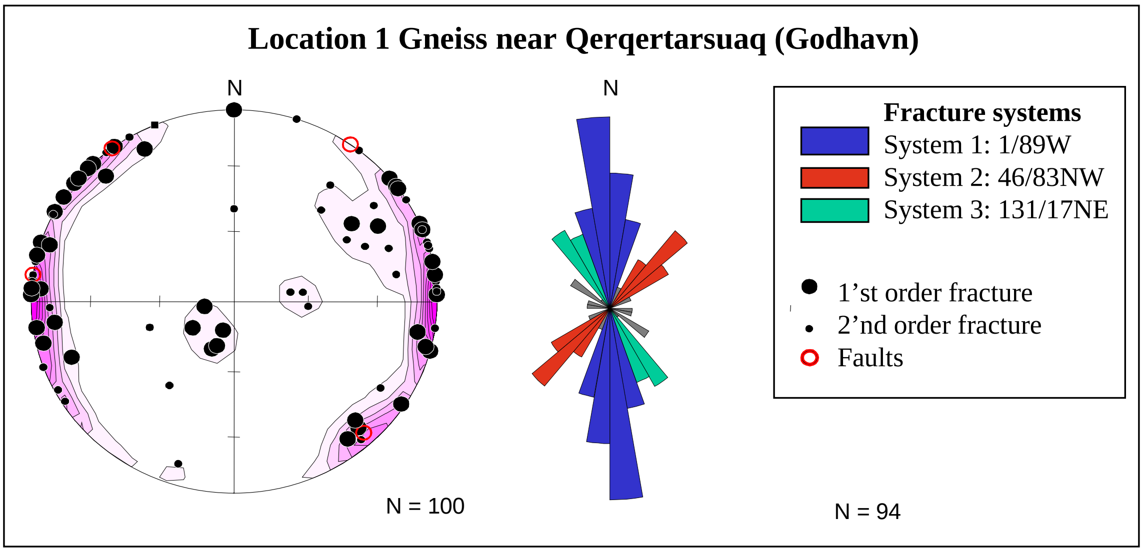


Figure 3-5-1. *Fracture analysis on location 1. Photo shows fractures on profile no. 3 close to the harbour.*

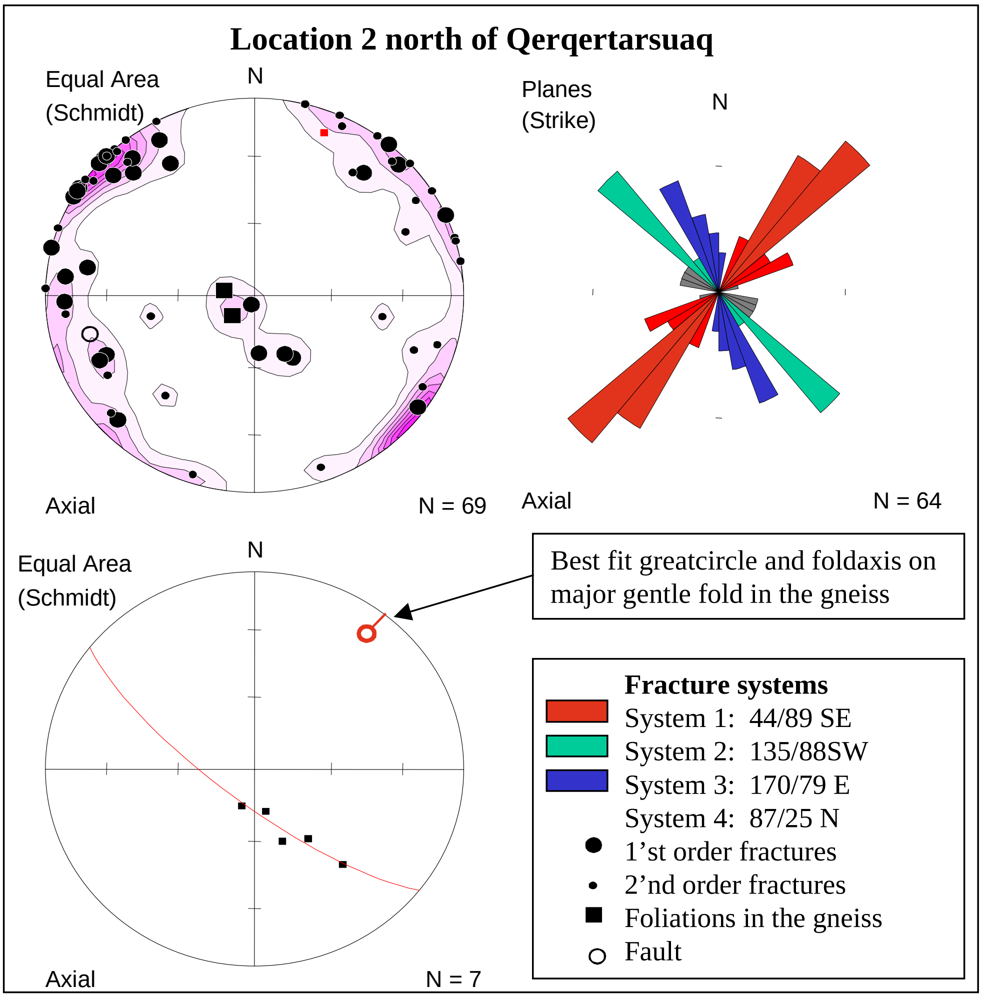


Figure 3-5-2. *Fracture analysis on location 2. Photo shows fractured gneiss just north of Arktisk Station.*

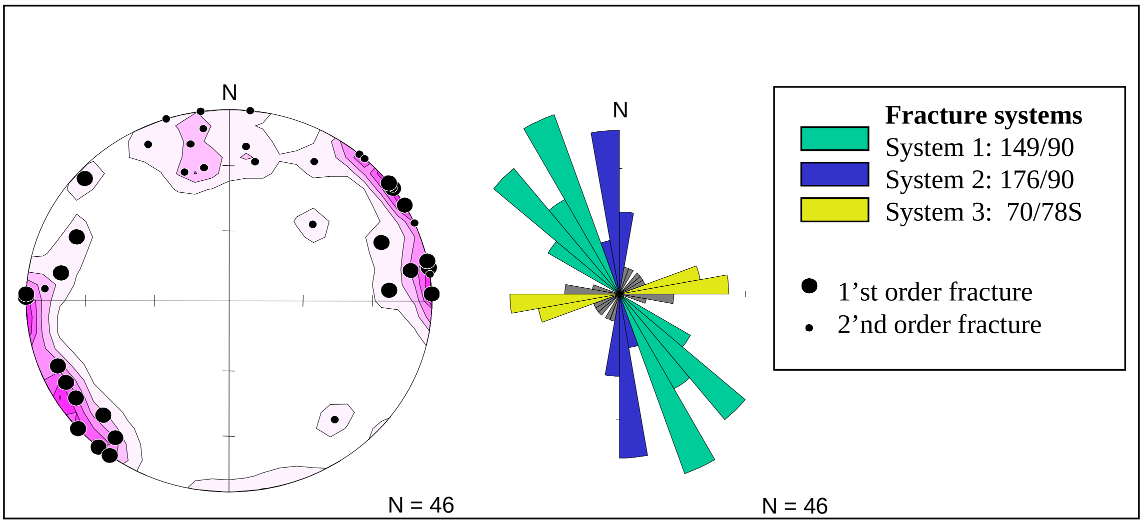


Figure 3-5-3. *Fracture analysis on location 3. Photo shows fractures in a small valley that is eroded into the basalt plateau, just east of Arktisk Station.*

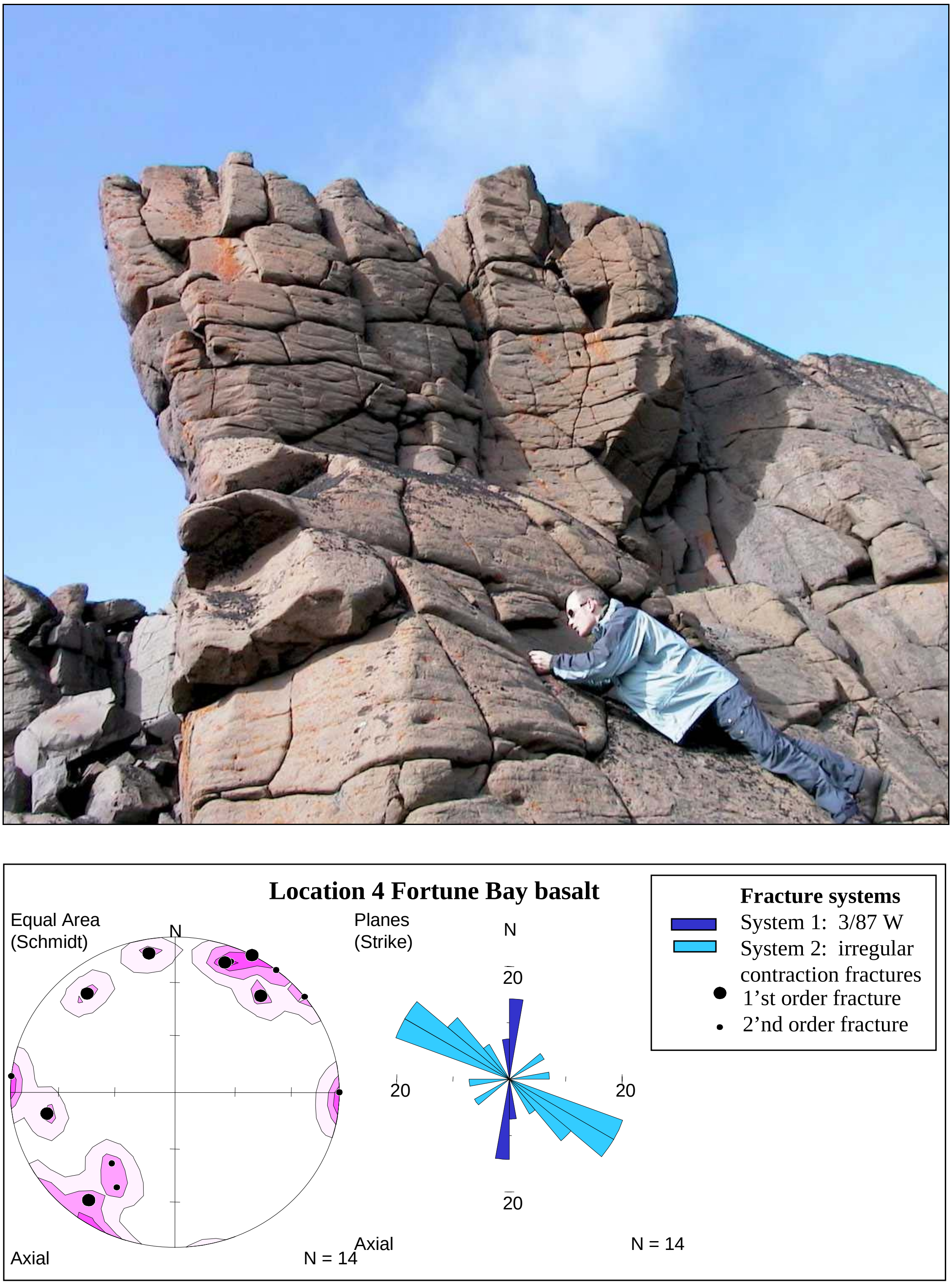


Figure 3-5-4. *Fracture analysis on location 4. Photo shows fractures in basalt near Fortunebay.*

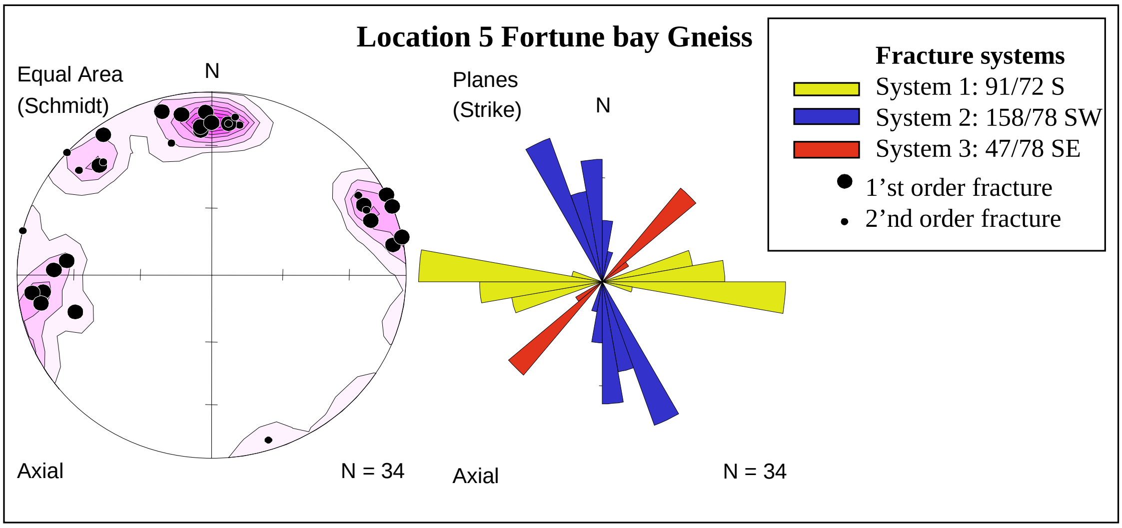


Figure 3-5-5. *Fracture analysis on location 5. Photo shows fractures in gneiss near Fortunebay*

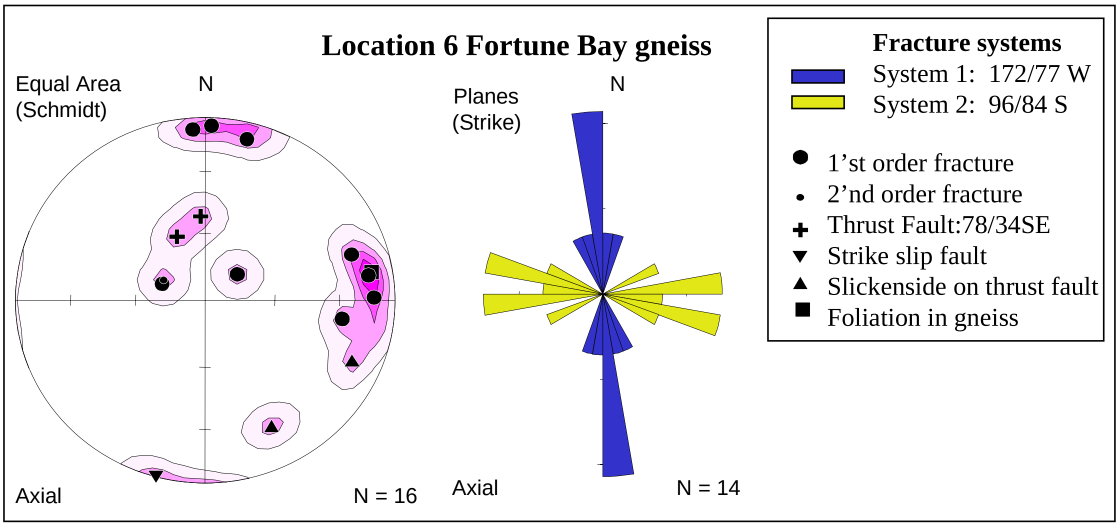


Figure 3-5-6. *Fracture analysis on location 6. Photo shows major thrust fault in gneiss near Fortunebay.*

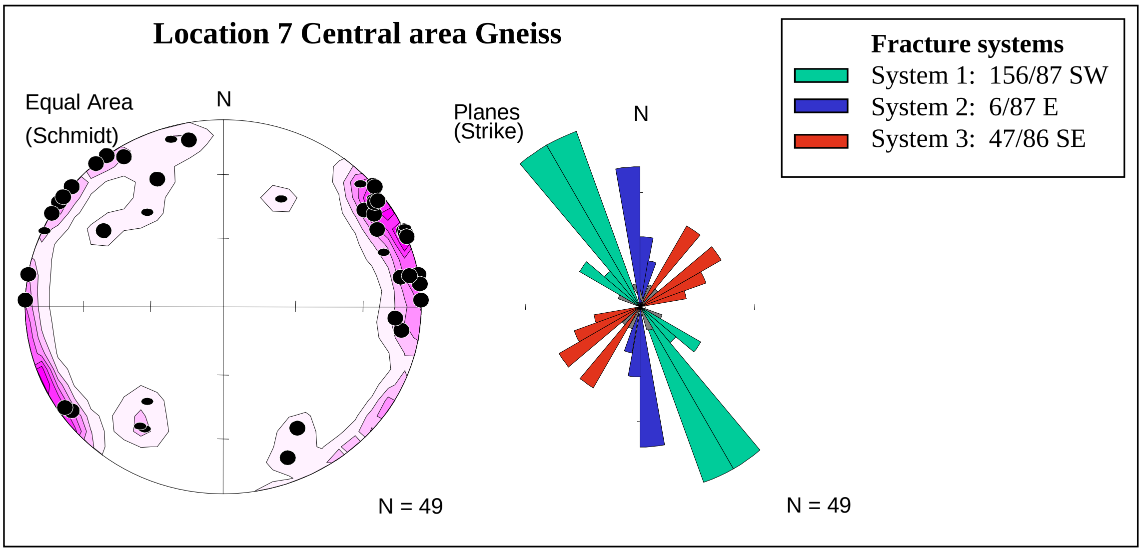
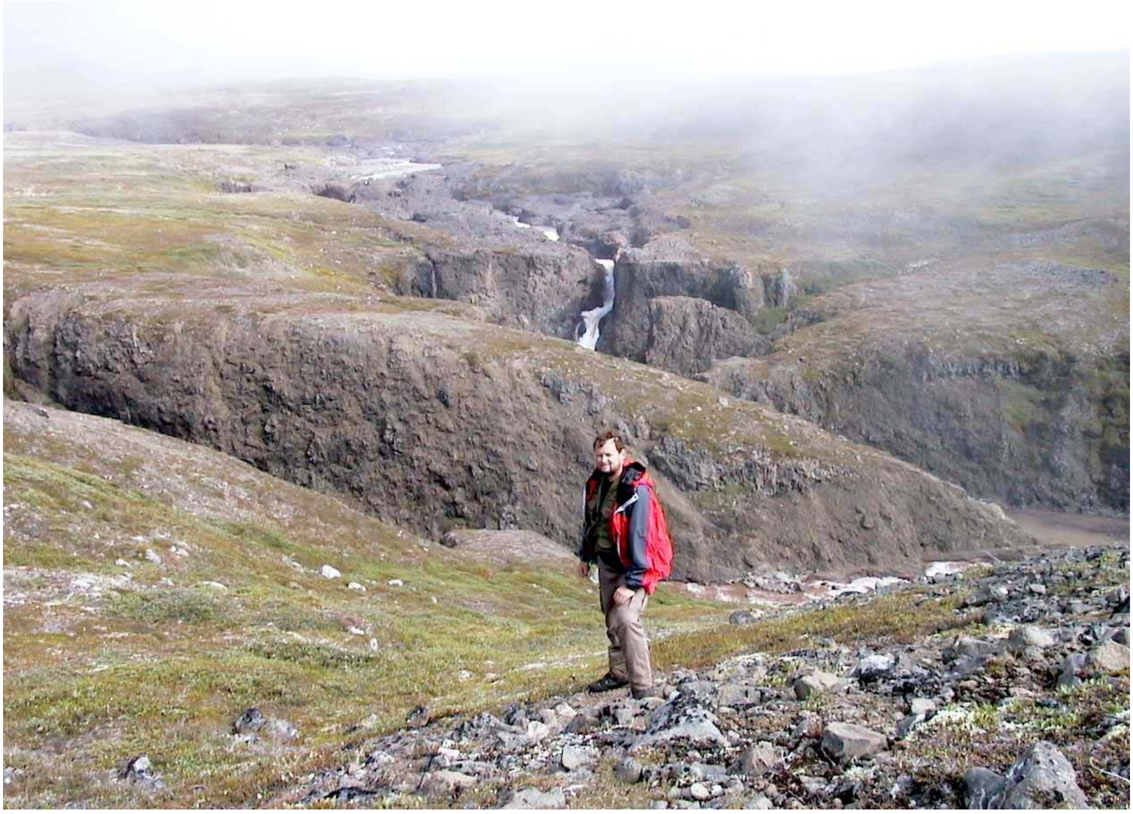


Figure 3-5-7. *Fracture analysis on location 7 (central part of Fortunebay).*



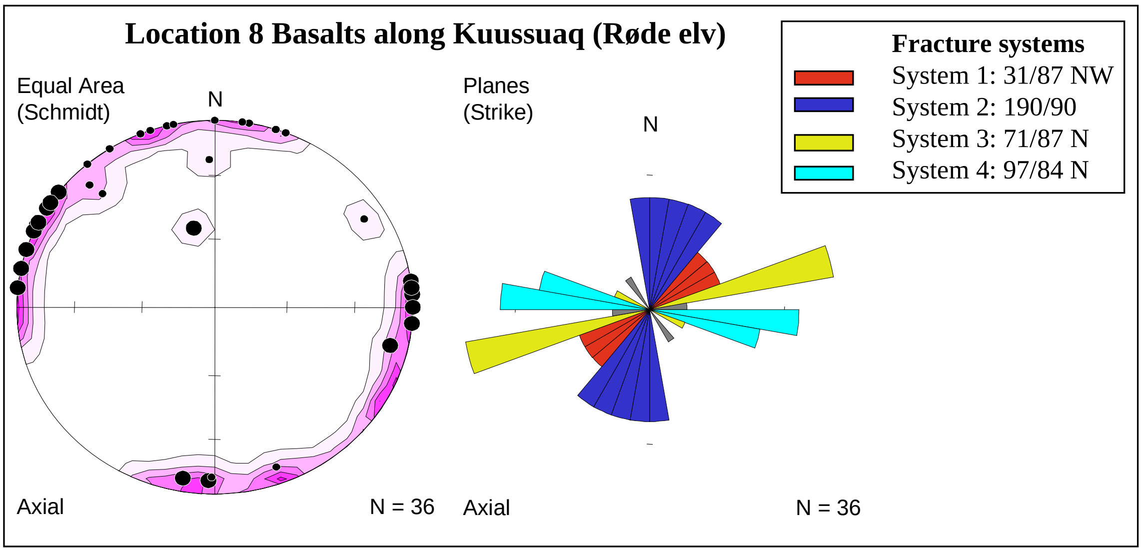


Figure 3-5-8. *Fracture analysis on location 8. Photo shows valley deeply eroded into basalt by the river Kuussuaq (Røde Elv).*

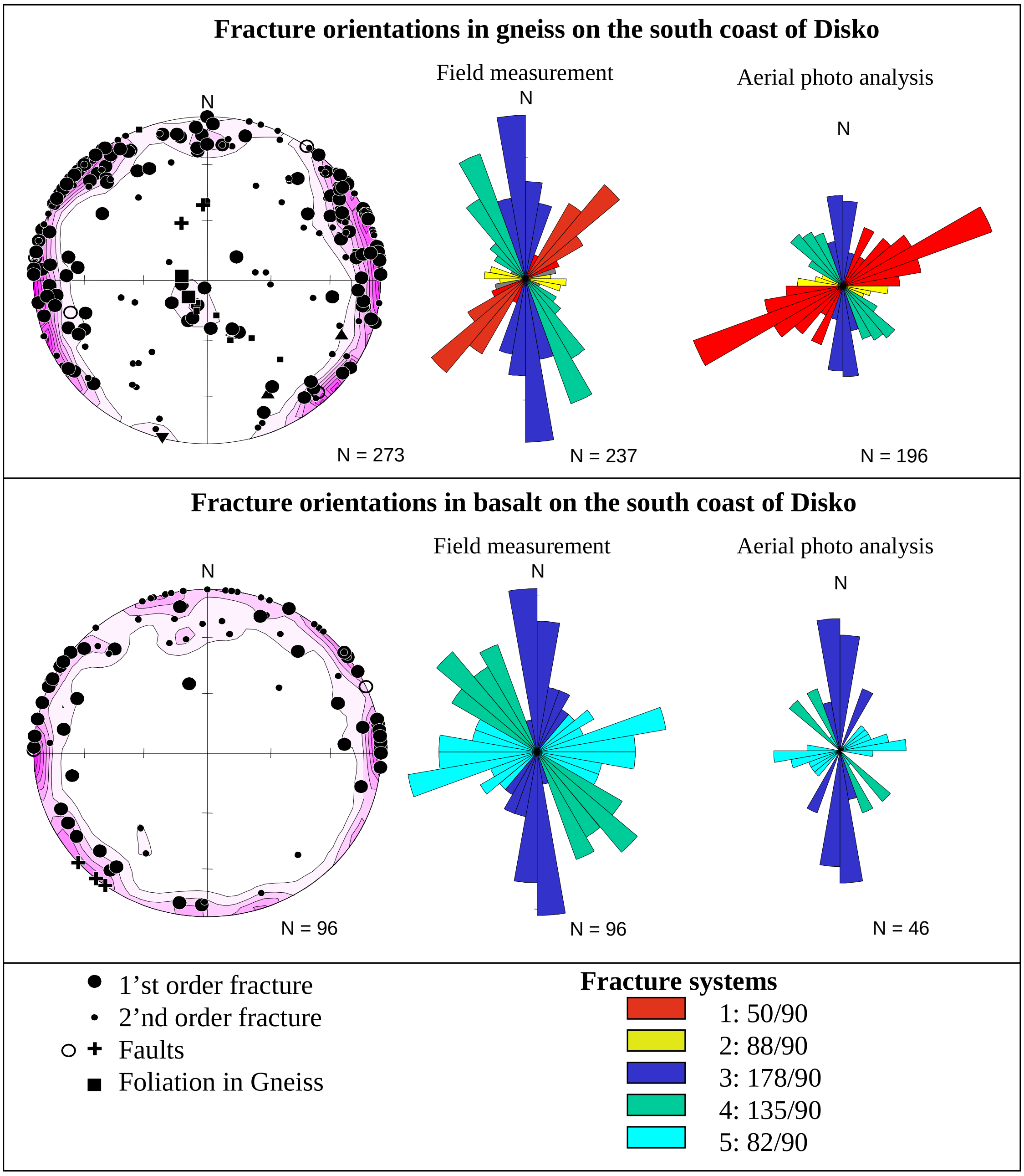


Figure 3-5-9. *Orientation on lineaments deduced from aerial photo analysis (south coast of Disko).*

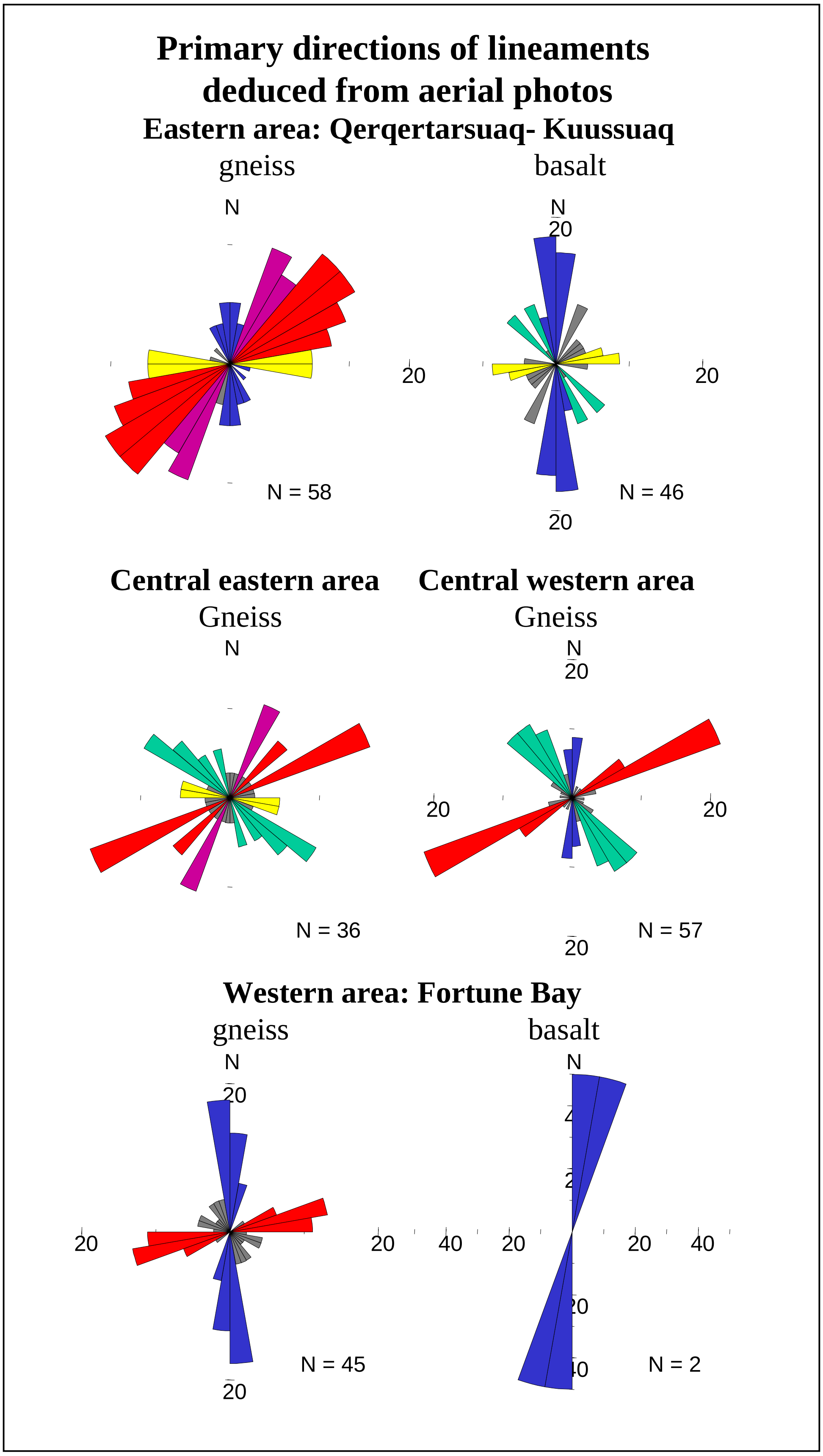


Figure 3-5-10. *Total distribution of fractures and fracture systems on southern Disko.*

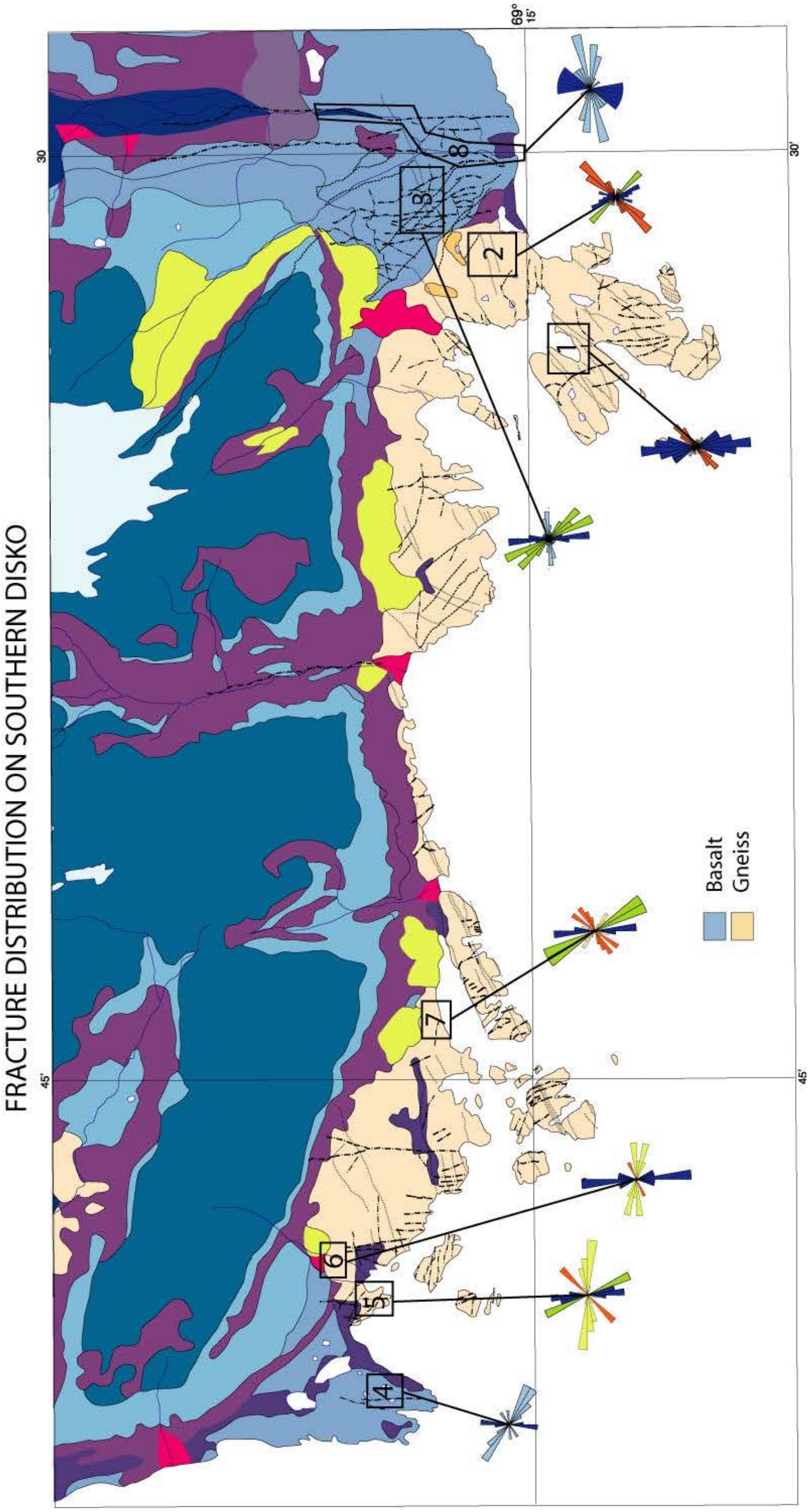


Figure 3-5-11. *Composite map showing the position of the field work locations and the fracture distribution on southern Disko.*

3.6 Inspection of a major fault system in Kannaa (Diskofjord)

During two days a number of large faults were inspected at Kannaa in Diskofjord, across from the village of Kangerluk. One of the largest faults on Disko truncate this area. The major fault is trending N-S with a relative down-throw of the western side in the order of 2-300 m. The gneiss-basalt contact that is exposed along the southern coast of the fjord at Quinnquaq and Naanngisat was similar to the locality investigated at southern Disko.

Location 1: Primary fault on the north side of the peninsula Qatigassu.
The coast was investigated along some well exposed outcrops. Several areas were highly fractured, and a major fault zone was exposed in the central part of the outcrop (Fig. 3-6-1). A 40 m wide zone of crushed basalt marked a fault zone. The eastern side of the fault was down-thrusted and the western part of the area is accordingly forming a small horst relative to the primary fault further west. 50 fractures and faults were measured along a profile. The primary fracture system is oriented 20/86NW and the primary fault is probably following the same trend. A series of secondary faults and fractures penetrate the area. Five of the secondary faults are oriented almost perpendicular to the primary fault, while one fault is striking NE-SE parallel to the second major fault in the area.

Location 2: Primary Fault on the south side of the peninsula Qatigassu.
Another fault is truncating the area here. It is striking NW-SE (148^0) and down-throws the western part of the peninsula Qatigassu approximately 100 m. We followed the fault across the talus fan and into a narrow valley. Nice slickensides and sections of totally crushed basalt were observed on several fault planes in this valley.

The stratigraphy and especially the relation between the three major fault systems in the area are accordingly very complex, and further analysis should be carried out in order to understand the relationship between the individual faults. It is clear that the same primary fracture directions on Southern Disko correlates perfectly with the trend of the two primary faults in this area. A more detailed investigation of this location may answer the question of the relative age of these two fracture systems.

Figure 3-6-1. *Normal fault. The left side is down thrusted and the right side is the crushed fault zone (location 9, Kannaa).*

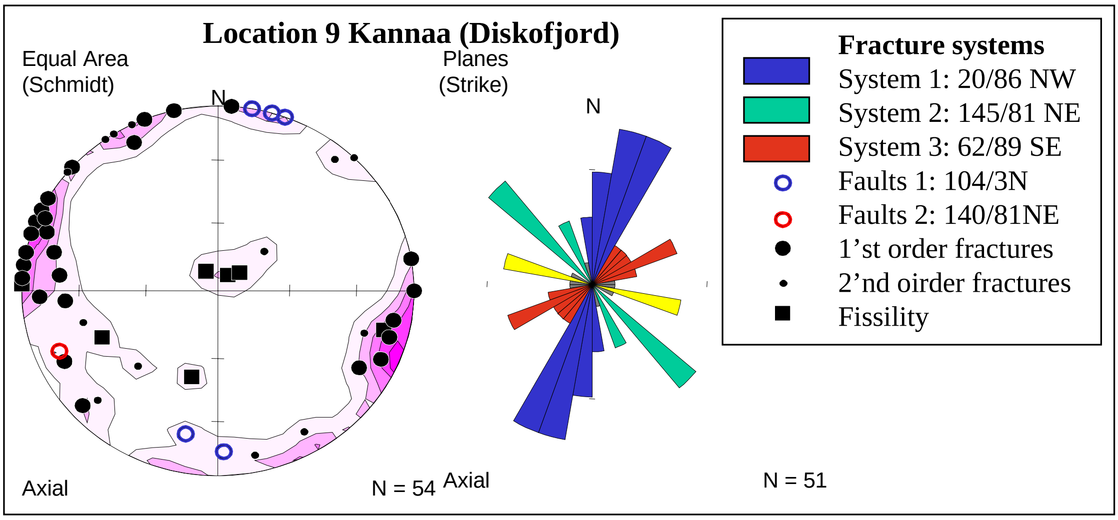


Figure 3-6-2. *Fracture and fault orientations (location 9, Kannaa).*

3.7 Inspection of Quaternary deposits in the Itilli Valley

Nuussuaq is characterised by intensively fractured Cretaceous sediments and dominated Paleogene basalt, Quaternary glacigene sediments and some very large fault systems (the Itilli fault, the Cretaceous Boundary Fault near Saqqaq etc.). Two areas were selected for more detailed investigations. The Itilli valley that are situated above a large fault, and an intensively fractured area near Nussag. The Itilli fault is one of the youngest structures on Nuussuaq (see Chalmers *et al.1999)*. It is marked by an escarpment to the NW and a large river valley striking NE-SW just east of the escarpment. A 6 km long section was visually inspected for well exposed outcrops of Quaternary sediments that may have been influenced by neotectonic deformation. In general the Itilli valley consist of a broad undulating till plain that rises rather steeply towards the escarpment on the western side of the valley and less steep on the eastern side of the valley. Several large side moraines mark earlier extensions of former glaciers. The river has cut 30-50 meters into the till plain and forms a 100-300 meter wide river valley with a braided river system dominated by coarse fluvial sediments (gravel and stones). A large delta with barrier islands marks the outflow into Vaigat.

The river has eroded into both sides of the valley and exposed outcrops of glacigene sediments, but solifluction is very active in the uppermost part of till plain, especially where the gradient becomes steeper close to the escarpment. Seepage of water makes the riverbanks highly unstable. The result is that several large sediment flows cover most parts of the riverbanks.

Only two large outcrops with glacigene sediments were found along the first 5 km of the river. Further up the river several sections with shale and sandstone were well exposed, and all of them seemed well-suited for closer investigations, though the section with fluvial sediment seemed rather unstable. The tight schedule allowed only rough evaluations and photographs to be taken.

Location 1. Glacio-fluvial melt water sediments along the Itilli valley (Fig. 3-7-1). The section consists of glacio-fluvial sand and gravel interceded with layers of stones and boulders. A number of fractures were visible in these sediments, they seemed to have a systematic orientation, but no visible faults were positively identified.

Location 2. Glacigene diamict deposits in a side valley perpendicular to the Itilli valley (Fig. 3-7-2). A number of the layers are clearly deformed, and low angle faults truncate some of the layers. The origin of these faults are however uncertain. The deformations may thus have been formed as a result of glaciotectonic deformation. The section is rather steep and in order to perform a more detailed investigation it would be necessary to clean the surface of parts of the outcrop.

Location 3. This location was situated on the western riverbank 5-6 km upstream. Nicely exposed outcrops consisting of Cretaceous black shale and sandstone were highly deformed. Faults, fractures and folds indicate that the area has suffered multiple deformation phases, and some well-developed slickensides were indicating strike-slip transverse faulting perpendicular to the valley at this point (Fig. 3-7-3). The transition towards the overlying glacigene Quaternary sediments was poorly exposed on this location, and it was not possible to identify structures truncating the contact. There may however be better outcrops further upstream.

Figure 3-7-1. *Glacio-fluvial melt water sediments along the Itilli valley. The section consist of glacio fluvial sand and gravel interbedded with layers of stones and boulders. A number fractures are visible in these sediments, but the origin is uncertain.*

Figure 3-7-2. *Glacigene diamict deposits in a side valley perpendicular to the Itilli valley. A number of the layers are deformed, and low-angle normal faults truncate some of the layers. These deformations are all regarded to have been formed as a result of local glacio-tectonic deformations, since a lower transition seems intact.*

Figure 3-7-3. *The Cretaceous sediments were exposed on both sides of the Valley approximately 5-6 km upstream from the coast. The photo show Slickensides on the surface of a dextral strike slip fault in the sandstone.*

3.8 Fracture and fault analysis in pillow basalt near Nussaq

From the aerial photographs it appears that the area around Nussaq (south coast of Nussuaq) is extremely fractured (Fig. 3-8-5). Elongated valley systems truncate each other at several different directions. This area has earlier caught attention because oil seeps were discovered primarily along dykes that truncated the area.

3.8.1 Geomorphology

The area covers an area of approximately 25 km^2. It consists predominantly of hyolaclastites and pillow basalt that rises to a height of 300 meter a.s.l. The area is bounded by a large valley towards north which ends in a mighty river delta at Siorarssiut towards the west. The basalt is strongly modulated by glacial erosion and the hilly morphology is accordingly well rounded with erratic boulders scattered around (Fig. 3-8-1). A number of very characteristic valleys are deeply truncated into the basalt, and they must be related to fault or fracture zones. These valleys are further eroded by the glaciers as documented by the glacial scouring on dykes in the valleys (Fig. 3-8-2). The valleys have varying sizes, but one system of NW-SE striking valleys seems to be particularly deep. The valley floors are generally covered with vegetation and different kinds of sediments, and in some of the valleys small lakes have formed.

3.8.2 Geology

The area is dominated by basalt, primarily brecciated pillow basalt from the lower part of the basalt (Fig. 3-8-3). The basalt layers are generally dipping 20-25 degrees towards east, but vary to some degree. The basalt is generally truncated by dykes that have intruded the primary basalt breccias during later intrusive periods. It is difficult to see whether the intrusions follow faults or fracture zones, as potential marker horizons are missing. The aerial photo analysis of the area (Fig. 3-8-4) indicates that the valley more or less truncate each other without displacing them. This indicates that the valleys in the area are dominated by fracture zones rather than fault zones, or that the fracture zones are younger than the fault zones. Special attention was directed towards the N-S striking valley systems, as they form a direct line towards some major N-S striking fault systems on Disko directly south of Nussag.

3.8.3 Fracture analysis

Seven locations were investigated, on a 5 km^2 large area Fig. 3-8-6. Most of the locations were selected where two valleys truncated each other, in order to measure fractures along two sections perpendicular to each other. All primary fractures were measured in this way. Some locations were dominated by one or two fracture systems, but by measuring seven locations all primary fracture systems were measured. On Fig. 3-8-6 the results of the fracture measurement are illustrated. A total of four fracture systems seem to penetrate the area.

- System 1 fractures strike E-W (80/90). This system seems to be one of the strongest fracture systems. A number of the dykes were oriented parallel to this direction and the question is whether the dykes and the fractures are somehow related to the same tectonic event.
- System 2 fractures are the N-S striking fracture system (170/90). This fracture system was originally regarded to be a fault system, since it runs parallel to the N-S striking fault systems on Disko. It may still be a fault system, but the homogeneity of the rocks on both sides makes it impossible to identify markers that have been displaced relatively to each other. There is no apparent displacement of the valleys that truncate the N-S striking valleys on the Aerial photos, but that could be explained either because, the system 2 is an older system than the other fracture systems, or because the faulting is pure dip-slip normal faulting. Some dykes have also intruded this fracture system as documented on Fig. 3-8-2. The relative relation between these dykes and other truncating fracture/faults systems or dykes will be able to answer these questions. They should accordingly be studied carefully, in order to establish an event stratigraphy for the area (Fig. 3-8-4).
- System 3 fractures are a secondary system of fractures striking NNE-SSW (17/90) that appeared in some areas.
- System 4 fractures are striking NW-SE (130/90). These fractures were poorly represented on the different locations, although this is the most prominent valley system deduced from the aerial photo analysis. It proves that additional measurements are necessary in order to establish a thorough event stratigraphic model for the area.

The key to the understanding of the history of fracturing and faulting in this area is closely related to the dykes. Previous investigations have shown that some of the dykes are displaced by faults in some areas (A. Boesen pers. com.). The possibility for establishing a detailed tectonic model on this location, could form an important contribution to the understanding of the regional tectonic history of Nuussuaq.

Figure 3-8-1. *The hilly landscape is a classic sub glacial relief with well rounded hills and large erratic blocks scattered throughout the area (Nussaq).*

Figure 3-8-2. *Ice scoured dyke in a characteristic N-S trending valley (Nussaq).*

Figure 3-8-3. *Brecciated pillow basalt at location 1 (Nussaq).*

Figure 3-8-4. *Conjugating dykes in a system 4 valley (NW-SE) (Nussaq).*

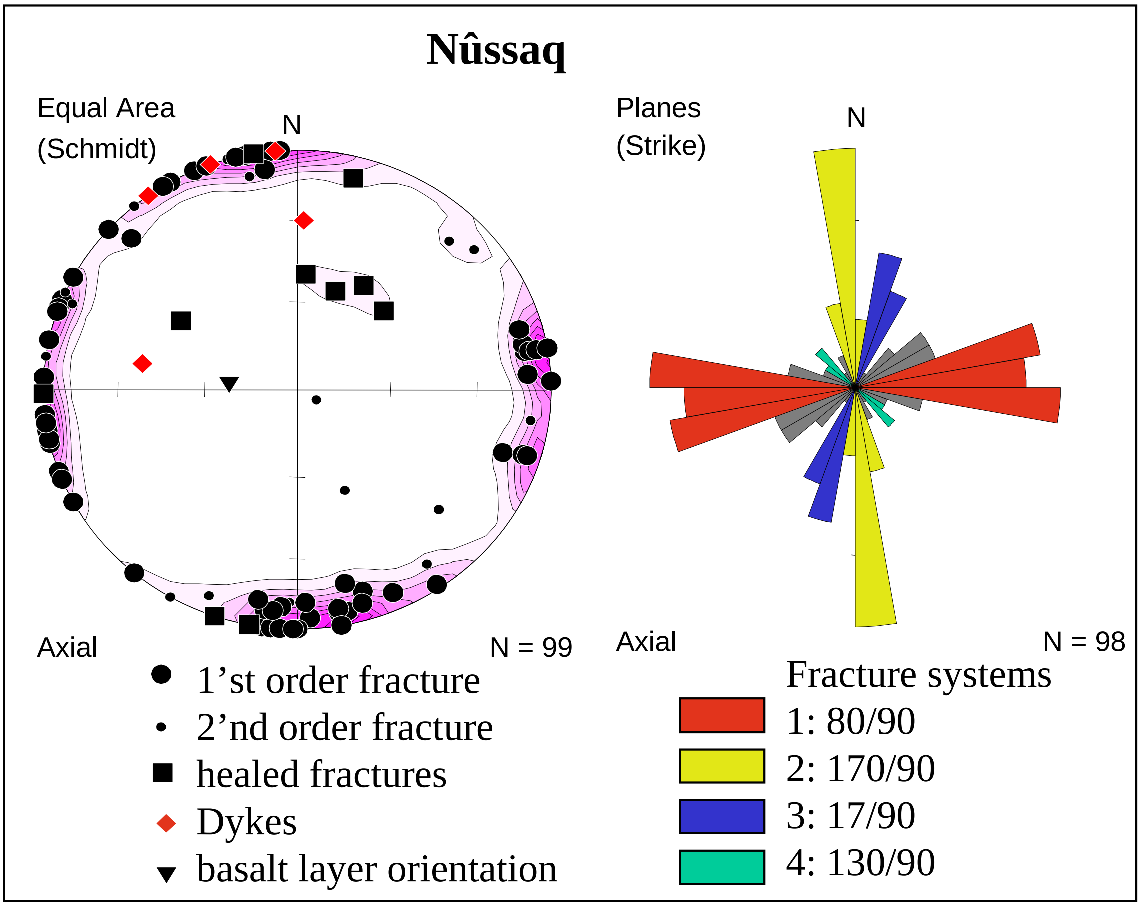


Figure 3-8-5. Fracture analysis at Nussaq.

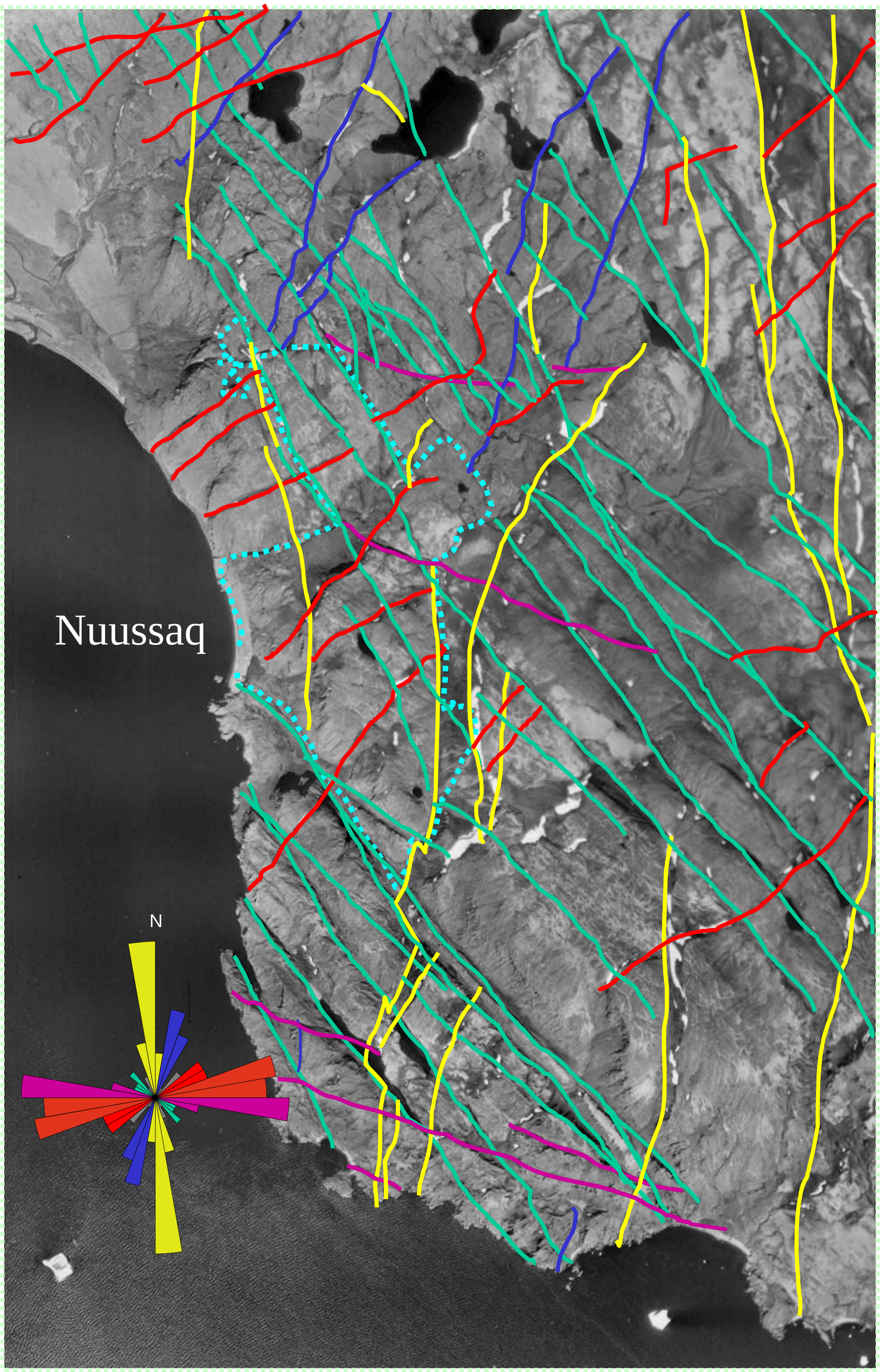


Figure 3-8-6. *Aerial photo of Nussaq, with characteristic lineaments and the area that was investigated during the fieldwork (dotted line).*

3.9 Conclusions

During this pilot project a number of methodologies have been tested in the field, and the majority of the methods proved useful for the analysis of fractures.

Aerial photo analysis
The use of detailed aerial photo analysis of lineaments in the land surface combined with advanced field investigations of fractures and faults were successfully applied on a small area in Inugsuk north of Nassuttooq.

Local fracture analysis at Inugsuk
An event-stratigraphic model shows that at least four deformation phases affected the area since the folding of the meta-sedimentary rocks within the area. Samples of pseudo-tachyliths were successfully collected from primary faults in the area, and dating of the minerals is in progress. Based on these data and a general geological mapping of the rocks in the area, an event-stratigraphic model has been constructed. The majority of the structures in the area may be related to regional tectonic events, primarily lateral compression, indicating collisions between continents. Very little deformation may be related to extensional tectonics, and only a detailed fracture analysis of at least five different areas may reveal structures that could be associated with Neogene extensional deformation related to uplift. Some of the fault systems are well exposed in the area, and they may have been reactivated at a later stage, and a detailed study of all outcrops with well exposed faults should therefore be carried out in order to identify secondary striations or displacements directly on the fault surfaces.

Regional fracture analysis in the Disko area
It was possible to identify and separate regional and local tectonic impact using fracture analysis of multiple locations in a larger region. At least two major tectonic events seem to have affected the Disko area after the Paleogene volcanism. These events have resulted in the formation of one system of primary N-S striking fractures and faults and a second system of fractures/faults striking NW-SE. These two fracture systems truncate both basalt and the underlying gneiss. Local variations in the fracture distribution are probably related to local contraction processes during the cooling phase of the basalt-flows, while characteristic narrow straight valleys are outlining primary fracture/fault zones in the basement. The two fracture systems and especially the north-south trending fault/fracture systems truncating both Precambrian basement and the basalt is probably the youngest structures (post-basaltic), and they appear to correlate with the primary normal fault-zone that truncate Disko from north to south. Fracture systems only identified in the gneiss are considered older than the Paleogene basalt.

Primary fault analysis
Investigations of primary fault systems are essential for the interpretation of possible young movements in the basement. Most primary fault systems are situated within river valleys and are accordingly covered with fluvial sediments and are thus difficult to inspect visually. Some of these major faults were, however, exposed in coastal sections within Diskofjord and in some narrow valleys, fault planes with slickensides were exposed and inspected on the sidewalls of the valley.

Neotectonic structures
In Denmark straight valleys of neotectonic origin are well known, but in arctic areas these morphologies are generally obliterated by the permafrost processes. The effect of permafrost and cryogenic processes in the Quaternary sediments (solifluction) makes therefore aerial photo analysis of lineaments questionable. Investigations of contacts between Quaternary sediments and the basement should therefore be concentrated on deep exposures, in the river valleys and along the coast. Elevated beach-ridges occur and are well-suited for young vertical movements during the last 5000 years and thus possible shifts across major faults evaluating such movements must, however, be differentiated from large-scale gravity movements of sliding blocks of basalt and underlying sandstone (km-size) in some regions.

The best exposures of *in situ* glacigene sediments were within the primary riverbeds. Exposures of this kind should be identified on aerial photos, and investigated during fieldwork. Special attention should be given to exposures that are perpendicular to fault zones. Attention should furthermore be directed towards relative elevation of old terraces on both sides of the river in the major valleys. Differences in elevations may reflect heterogeneous uplift and thus neotectonic activity of the fault zone below the river valley.

Dating methods
Sampling of minerals formed during faulting (pseudo-tachyliths) was successfully completed. The analysis is still in process.

4. Geomorphological analysis

4.1 Objectives

Few papers describe and analyse the geomorphology in western Greenland. Work has been made on glacial landforms and the Quaternary landscape development (e.g. Sugden 1974) and the landscape has been described and analysed from a detailed point of view. However, the large-scale landforms also reflect tectonic events and climate from pre-glacial time, and not only the overprinting of Quaternary glaciations. The pre-glacial development of landforms has been studied in many parts of former glaciated areas in the North Atlantic region (e.g. Lidmar-Bergström 1982; Hall & Sugden 1987; Peulvast *et al.* 1996; Lidmar-Bergström *et al.* 1999; Bouchard & Jolicoeur 2000; Bonow *et al.* in press). Regional studies and analyse of large-scale landforms contribute to the understanding of landscape development history and can lead to definition of constraints on the geological history, which can be applied by thermochronological absolute dating techniques. The aim is therefore to describe and to analyse the large-scale landforms and then interpret the long-term pre-glacial landscape development.

4.2 Methods

A digital elevation model (DEM), with a 250 by 250 metre grid, was obtained from Kort og Matrikelstyrelsen (KMS) in Copenhagen. The DEM was analysed in a GIS (Arc view) to describe the large-scale landforms in the study area, and to construct different types of maps. Profiles were extracted from the DEM, analysed and were compared with geological maps (location of profiles on Fig. 4-1). The large-scale landforms were analysed from aerial photographs (1:150 000) in a stereoscope and localities for field visits were selected. The study areas were visited (Fig. 2-1) and large-scale landforms were documented by photographs. A sample of weathered rock, saprolite, was collected from the gneiss basement/basalt contacts, but are yet to be analysed.

4.3 Selected areas and preliminary results

The study area has been divided into three main areas (Fig. 2-1):

1) Sukkertoppen Iskappe to Nassuttooq (Fig. 4-2),
2) Nassuttooq to Aasiat – the Lersletten area (Fig. 4-3)
3) Disko and Nuussuaq (Fig. 4-4)

The division is based on the large-scale appearance of the landscape (Fig. 4-5). The first of the main areas is furthermore subdivided into four groups.

4.3.1 Sukkertoppen Iskappe to Nassuttooq

Sugden (1974), who mainly investigated the glacial details in the area between Sukkertoppen Iskappe and Nassuttooq (Nordre Strømfjord) (Fig. 4-2), described the glacial scoured surfaces with roche moutonnée like forms, deep fjord valleys and alpine relief with cirqes in the highest areas close to the coast (Fig. A-4). However, the pre-glacial landscape development is less known.

A smooth summit landscape is a major component in the area between Sukkertoppen Iskappe and Nassuttooq. There is a general lowering in altitude of the summit level towards NE. Four areas with different appearance of the large-scale landscape were identified (Fig. 2-1), viz.:

1. **The area around Sukkertoppen Iskappe and towards the coast in the west.**
   This area has its height axis close to the coast. Areas not covered by glaciers, are characterised by flat summits at a continuous summit level (summit level mainly above 1400 m a.s.l.) and deeply incised valleys (Fig. A-13). The topography seems to continue beneath the Sukkertoppen Iskappe, which cover most of the area. The highest areas in the west have an alpine relief, and in the south part of the area summit reaches to more than 2100-m a.s.l. The area is bounded to the west by a great escarpment, parallel to the coast (Fig. A-14). The summit level decreases towards the east. Both fjords Kangerlussuaq (Figs A-3, A-13) and Kangerdlussuuatsiaq cut through the area (Fig. 4-6).

2. **The high plain with low relief east of Sukkertoppen Iskappe.**
   This undulating plain continues east of Sukkertoppen Iskappe in the area of Angujartorfiup Nuna (Fig. A-2). Its flat summit level extends from beneath the icecap at 1400 to 1300-m a.s.l., and descends gently towards the east until it reaches the inland ice at an altitude of 900 to 1000-m. The plain is characterised by small relative relief, less than the plain west of Sukkertoppen. The plain is inclined towards ENE, (Figs 4-2, 4-5, 4-6; for location see Fig. 4-1). Wide and shallow valleys in the plain are oriented in two directions: almost ENE-WSW and NW-SE. The valleys clearly follow main lineations in the bedrock. (Fig. 4-2). The shallow valleys have a common bottom level at 1100-m in the west and 900-m in the east (Fig. 4-6). Deeply incised narrow valleys are present between the shallow valleys and the fjords in the Angujartorfiup Nuna area (Fig. 4-2). In summary: The Angujartorfiup Nuna seems as an area where the main upper surface is mainly unaffected by glacial erosion (c.f. Sugden 1974).

3. **The area between the towns of Kangerlussuaq and Sisimiut.**
   This large-scale landscape is in general between 800 to 500 m a.s.l., and the summit level is characterised by flat tops. A great escarpment (about 800 m high) runs parallel to the coast. In front of the great escarpment is a coastal platform cut in gneiss, up to 5 km wide, of strandflaten type (Fig. A-6). This area is the most dissected in the area between Sukkertoppen Iskappe and Nassuttooq. The landscape contains small lakes, wet bogs and trough valleys (Figs A-4, A-5). In the east, around Kangerlussuaq town,

the valleys are filled with till and fluvial sediments. Despite these landforms indicating glacial overprinting, the bedrock surface seems mainly to be more or less unaffected.

4. **The high plain around the fjord Nordre Isortoq to the fjord Nassuttooq.**
   North of a line between the towns of Kangerlussuaq and Sisimiut the landscape is characterised by a high plain with low relief inclined towards NE, in the direction of Nassuttooq. The summits are at about 1200 m a.s.l. in the south part and at approximately 800 m a.s.l. around central Nassuttooq. Similar to the area around Sukkertoppen Iskappe, the area has a height axis close to the coast in the west and the fjord Nordre Isortoq cut through the highest area.

4.3.2 Nassuttooq to Aasiat – the Lersletten area

The Nassuttooq fjord runs zigzag NW-SE and ENE-WSW in its central and inner parts and then bends towards SW in its outer part (Figs 2-1, 4-3). Thereby it follows the main direction of bedrock structures. The central part of the fjord is wide, and in the outer part the fjord forms a deep trough between the flat mountains summits at 600 to 800 m a.s.l. The landscape around the inner/central parts of Nassuttooq is characterised by flat summits with lakes, and the summit level can continuously be identified towards the south, east and north (Figs A-9, A-12). North of Nassuttooq an escarpment stretches SW-NE along the Atarnup Nuna mountain complex at a level of 600 to 700-m. The summit level at the escarpment drop about 300-m in the west (Fig. A-11). Towards the east the change in summit level gradually becomes less and less accentuated (Figs 4-5, 4-7). North of Atarnup Nuna, a major shift occurs in the landscape as it shifts from a continuous flat top relief to a hilly relief (Figs A-8, A-10). The hills are usually well rounded with a size of up to a few hundred meters in diameter. Only a few hills reaches more than 200 m a.s.l., e.g. Rifkol and Alangorssup. A summit level can still be identified to the north, but is only seen as the level of the highest hills (Fig. A-7). A gentle decline in summit level is recorded towards the north and is close to sea level in the Aasiat area.

4.3.3 Disko

Disko is mainly covered by Palaeogene basalt. Several localities with contact between basement and basalt are known on Disko (Figs 4-4, A-15, A-26, 2-3). On Disko the strata are nearly horizontal with only a slight dip towards the west (Geological map of Greenland, Søndre Strømfjord – Nûgssuaq). A gneiss ridge beneath the basalt, sometimes exposed, runs north-south in central Disko (Chalmers *et al.* 1999). The gneiss/basalt contact is well exposed at Fortunebay on southern Disko and along the fjord Kangerdluarssuk in Kangerluk (Diskofjord). At both these locations contacts were identified and examined. The contacts are not easily detected as they are often covered by large talus or debris flows.

4.3.3.1 Fortunebay

Tectonic lineaments are mainly trending N-S in the basalt. In the gneiss three fracture directions are present, i.e. E-W, NNW-SSE and NE-SW (for details, see the chapter on fractures). Clefts have formed in the gneiss with a NNW-SSE direction. The clefts are five to ten metres deep and a few metres wide. Vertical as well as horizontal joints are affected by weathering, responsible for their well rounded appearance (Figs A-16, A-17), Tafoni-like forms and minor weathering pits (1 to 5 cm) on the vertical wall were also identified (Fig. A-18). In one of the weathering pits sand was encountered. At about 85 m a.s.l. the basalt/gneiss contact was exposed along a minor stream (Figs A-19, A-22). The basalt had overflown the basement in a non-marine environment (Geologisk kort over Grønland, Uiffaq 69V.1 Syd), and covered the pre-basalt land surface. The basement is deeply weathered with a more than 2.5 metre thick saprolite (Figs A-20, A-21). The transition zone is 0.5 to 1-m thick of sandy and clayey material. A sample was collected of the saprolite (Fig. A-24). Along the coast the gneiss basement is exposed. The large-scale landform of the exhumed basement is characterised by rounded hills, 50 to 100-m high and a few hundred metres in diameter (Fig. A-23).

4.3.3.2 Kangerdluarssuk-Kannaa

A contact between basalt and gneiss was identified. The transition zone was only 15 cm wide and no typical weathering mantle (saprolite) was identified. However, the basalt lies directly on basement and closer to the coastline the basement is exhumed along both sides of Kangerdluarssuk (Figs A-26, A-27). The large-scale landforms developed in basement are of hilly relief type, with individual hills 50 to 100-m high and 100 to 300 metres in diameter. Their appearance in Kangerdluarssuk is similar to the hilly relief at Fortunebay (c.f. Fig. A-23; Pulvertaft & Larsen 2002). The hilly relief can also be identified where the basalt is in close contact to the gneiss. The hills close to the fjord have been overridden by glaciers, indicated by complete absence of basalt. The sheet slabs structurally control the development of *roche moutonnées* (Fig. A-25). The main forms of the hilly relief are despite glacial reshaping dominant and the hilly relief has not been obliterated. The successive exhumation of the sub-Palaeocene landscape in the basement by glacial erosion, surface weathering and slope processes is well demonstrated in this area.

4.3.4 Nuussuaq

The western part of the Nuussuaq peninsula is mostly covered by Palaeogene basalt, with the youngest rocks west of Itilli valley/fault line. Remnants of Cretaceous sandstone is present along the Itilli fault line and is exposed *in situ* west of the Cretaceous Boundary Fault System (CBFS) near Saqqaq (Fig. 2-1; Chalmers *et al.* 1999). East of the CBFS gneiss basement is dominant, with only minor remnants of basalt.

4.3.4.1 Western Nuussuaq and the Itilli fault.

The Itilli valley cut the western part of Nuussuaq peninsula from SW to NE (Fig. 6-1). The present river in Itilli valley is incised in a low plain, at 300 to 400 m a.s.l. bordered by two escarpments. The landscape west of the Itilli valley is characterised of a high undulating plain, about 900 m a.s.l., which is slightly inclined towards NW (Figs A-33, 4-8, 4-4). The plain is mainly cut across the structure of the steeply dipping basalt (Fig. A-29; Chalmers *et al.* 1999). Most rivers on the plateaux drain towards the northwest following the internal structure of the basalt. The valleys running towards the NW are wide with minor canyons incised in their bottom. The plateaux end in the east by an escarpment, 800-m high, parallel to the Itilli valley. The escarpment is a dominant feature and work as a water divide for the westernmost part of Nuussuaq (Fig. A-28). Only some minor rivers cut across the escarpment and drain into the Itilli valley. The landscape east of the Itilli valley is also characterised by a plain, situated between 900 to 1100 m a.s.l. (Fig. A-30). The plain is bordered in the east by an escarpment with summits between 1400 to 1600 metres (Figs 4-8, 4-4).

The Itilli valley is thereby situated between the two escarpments on either side of the valley. A water divide passes across the valley floor at about 200 m a.s.l. The valley, which drains towards SW is characterised by an upper wide and U-shaped valley. A large V-shaped valley, mainly cut in sediments, is present at its bottom (Fig. A-30). The rivers east of Itilli valley have mainly developed their courses toward the NW, but a rearrangement of rivers towards the southeast and development of agnor valleys, e.g. Anariartorfik and Ilugigsorssuaq, are indicative of movement of the water divide to the north. The coast on southern Nuussuaq, west of Itilli valley, is low (Fig. A-31), but the coast east of the Itilli valley is steep with cliffs (10-20 m) (Fig. A-32).

4.3.4.2 Central Nuussuaq between Itilli valley and Saqqaq valley

Central Nuussuaq is inclined towards the west with its height-axis west of Saqqaq valley (Figs 4-8, 4-1). A major fault, the Cretaceous boundary fault system, NW-SE across Nuussuaq (e.g. Chalmers *et al*. 1999, Fig. 2-3). West of Saqqaq valley an 800-m high escarpment rises from an 800-m summit level. Central Nuussuaq is characterised by flat mountain summits. Local glaciers have reshaped the highest peaks, creating horns and arêtes. Not only the summit surface is inclined towards the west, so is also the common bottom level of valleys. The bottom level coincides with the summit level in westernmost part of Nuussuaq. The largest valleys are cut beneath this common valley bottom level.

4.3.4.3 Eastern Nuussuaq

The Cretaceous boundary fault west of Saqqaq is a clear marker in the geology (Fig. 2-3), but not in the landscape (Fig. 4-8). The relief is characterised by flat summits and a distinct summit level of about 1100 to 1300-m (Figs A-34, A-35), which cut across the Saqqaq fault line (Figs A-34, A-36, A-37). The summit level is generally rising towards the north (Fig. 2-2). The minor valleys in the gneiss region of Nuussuaq are not as deeply incised as they are in the basalt region (Fig. 4-4). The minor valleys are in general shallow in the plateau surface and only a few are deeply incised.

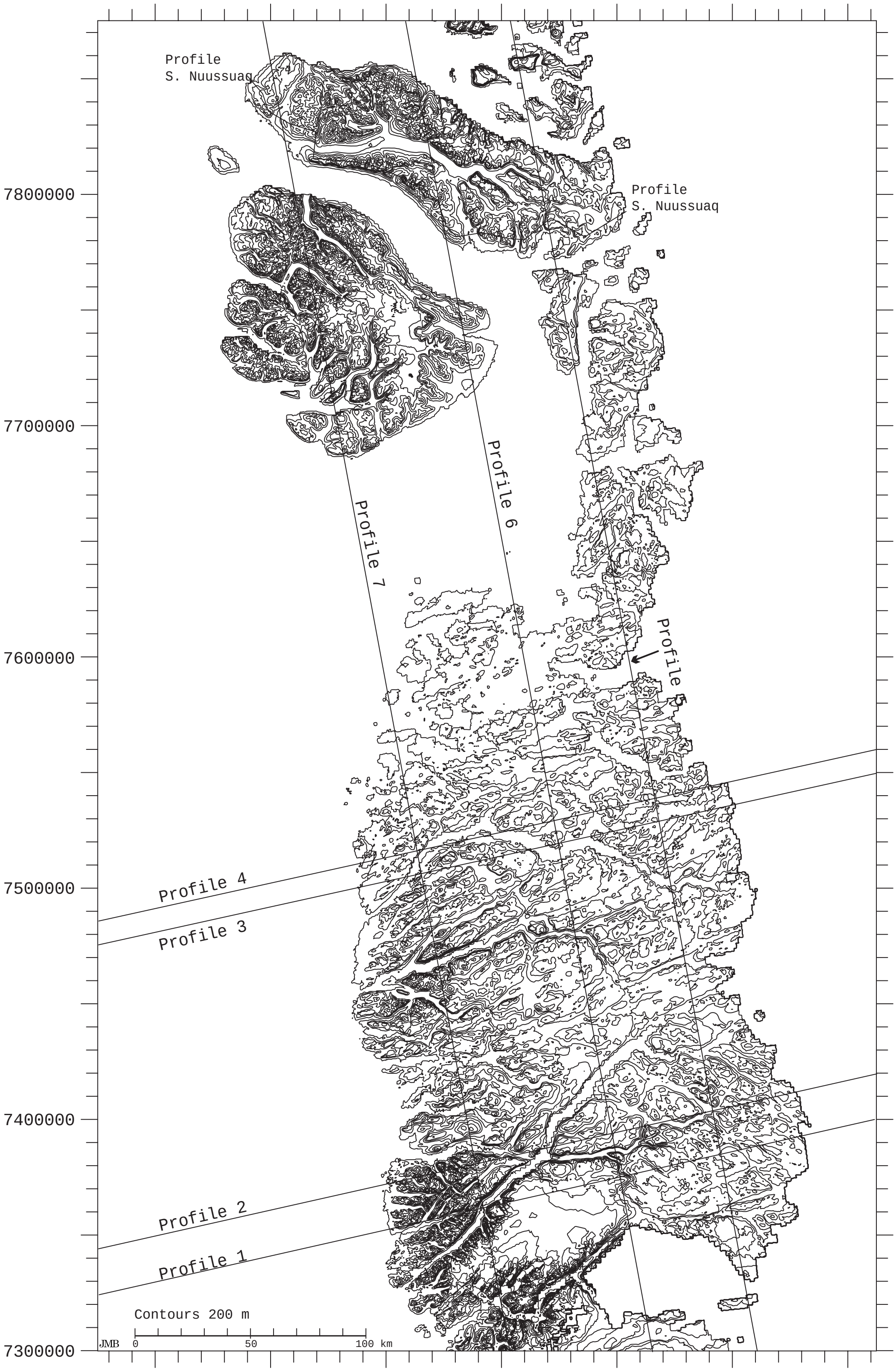


Figure 4-1. *Contour map based on 250 by 250 m digital elevation data.*

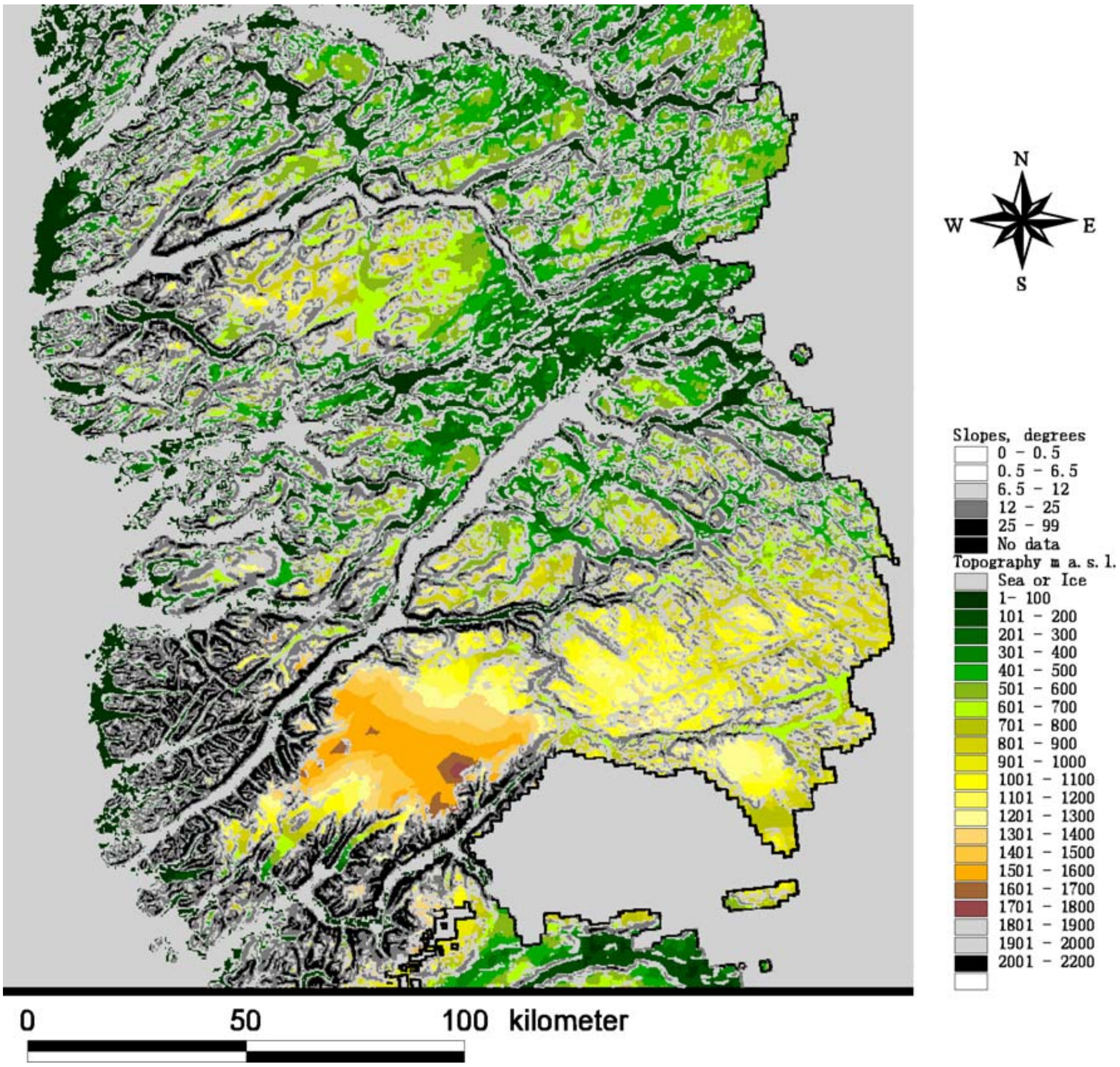


Figure 4-2. *Elevation and slope map of Sukkertoppen-Nassuttooq area.*

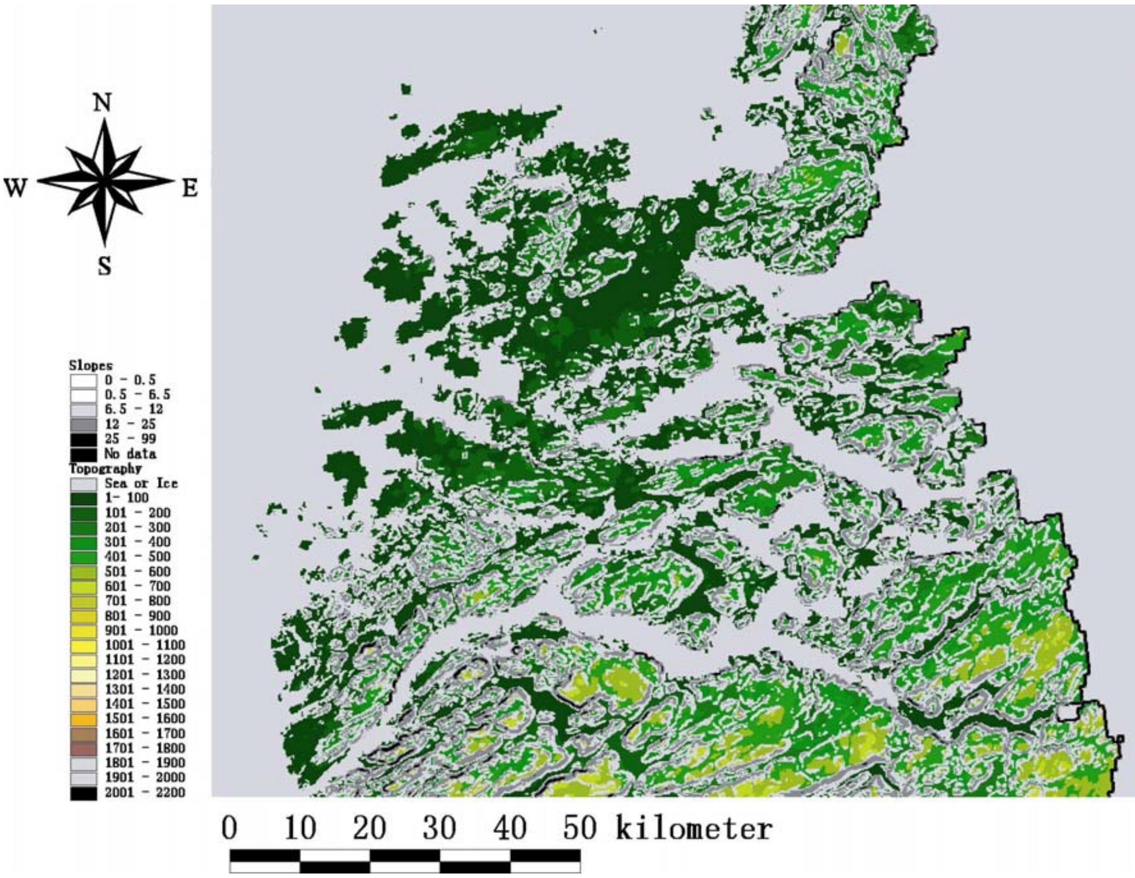


Figure 4-3. *Elevation- and slope map of Nassuttooq-Aasiat / Lersletten area.*

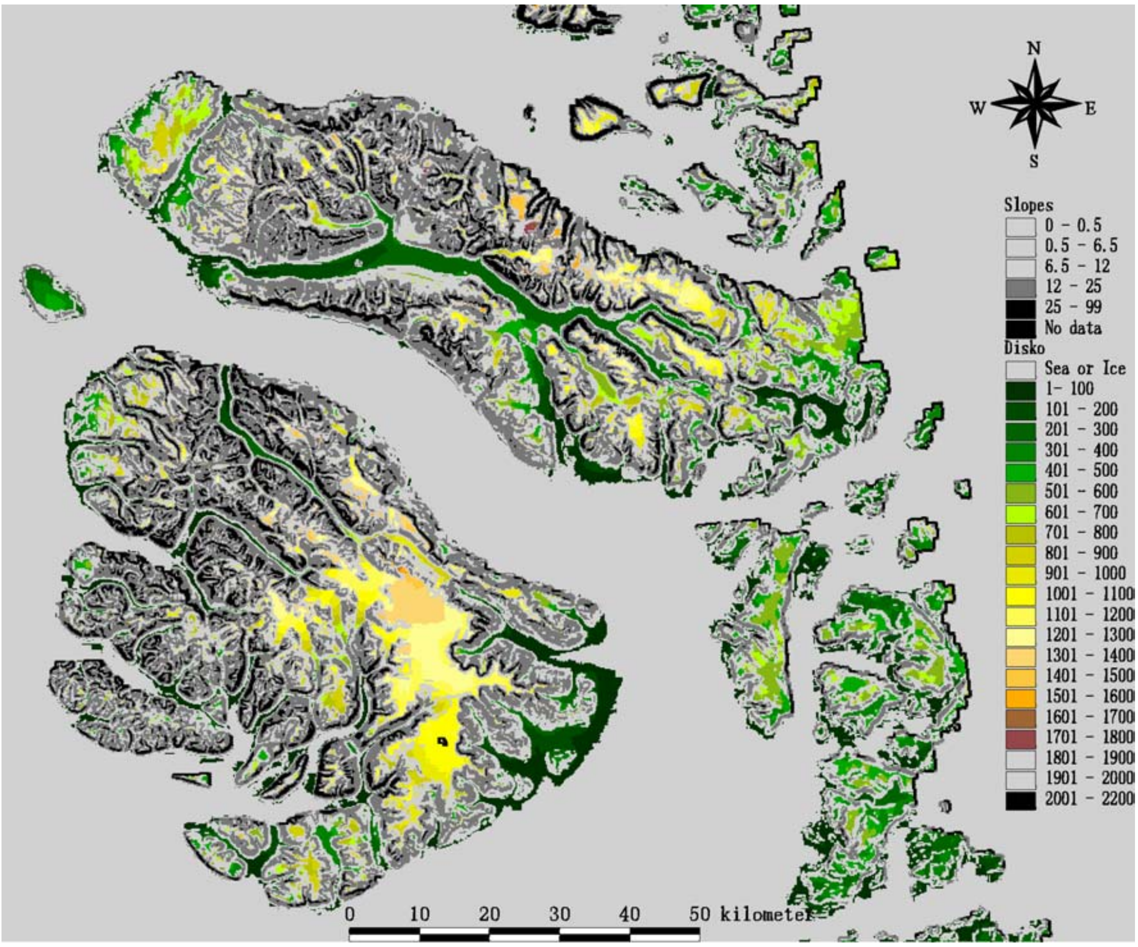


Figure 4-4. *Elevation- and slope map of Disko and Nuussuaq.*

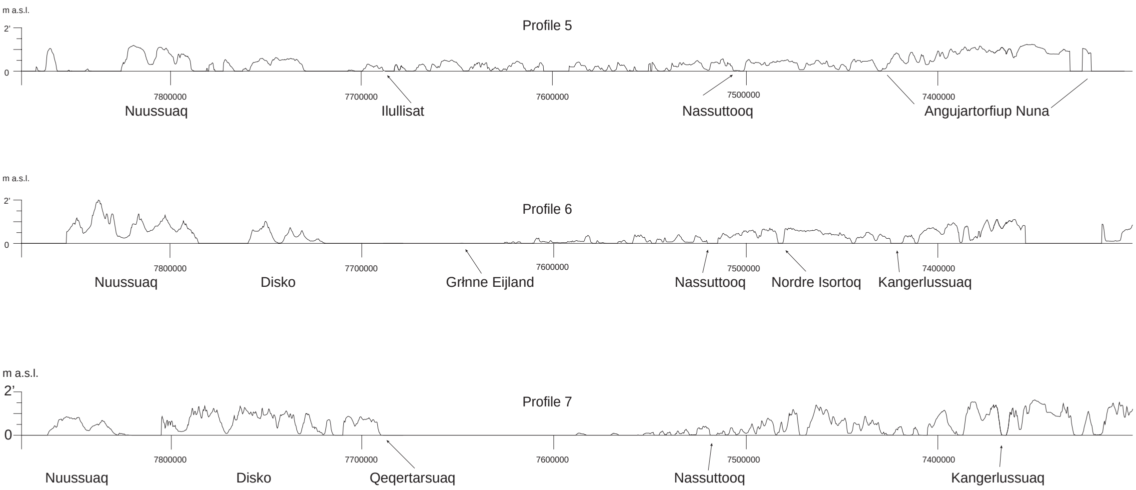


Figure 4-5. *N-S parallel running profiles over the study area, spaced west-east. For location see Fig. 4-1.*

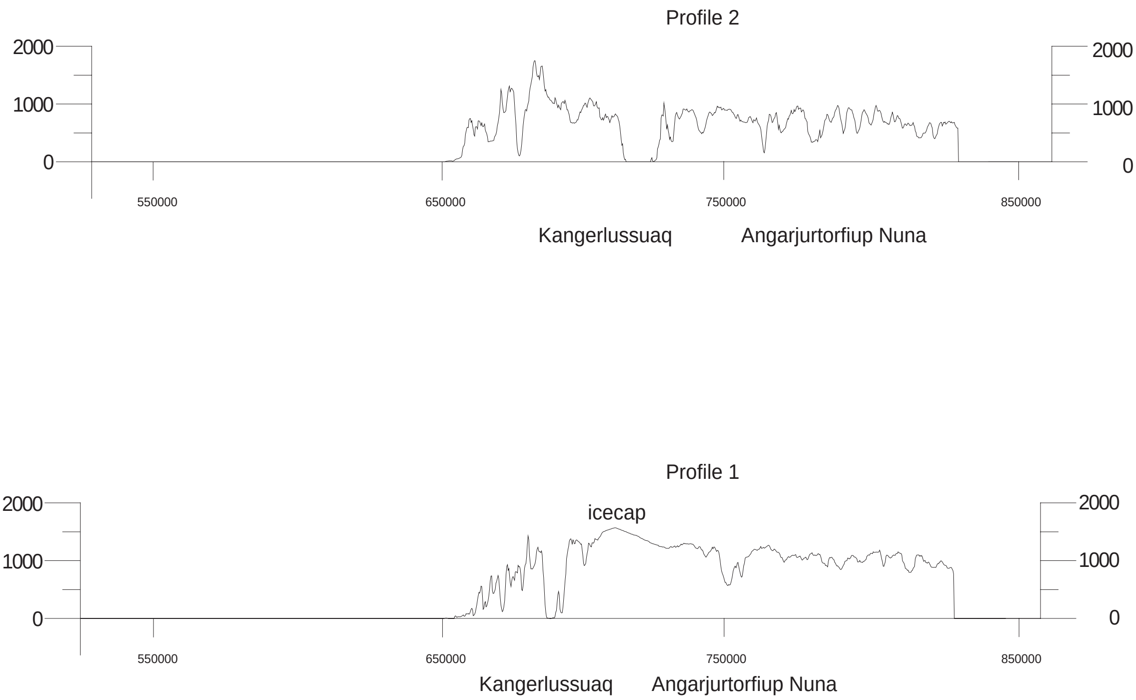


Figure 4-6. *West-East profiles over Sukkertoppen-Angujartorfiup Nuna. For location see Fig. 4-1.*

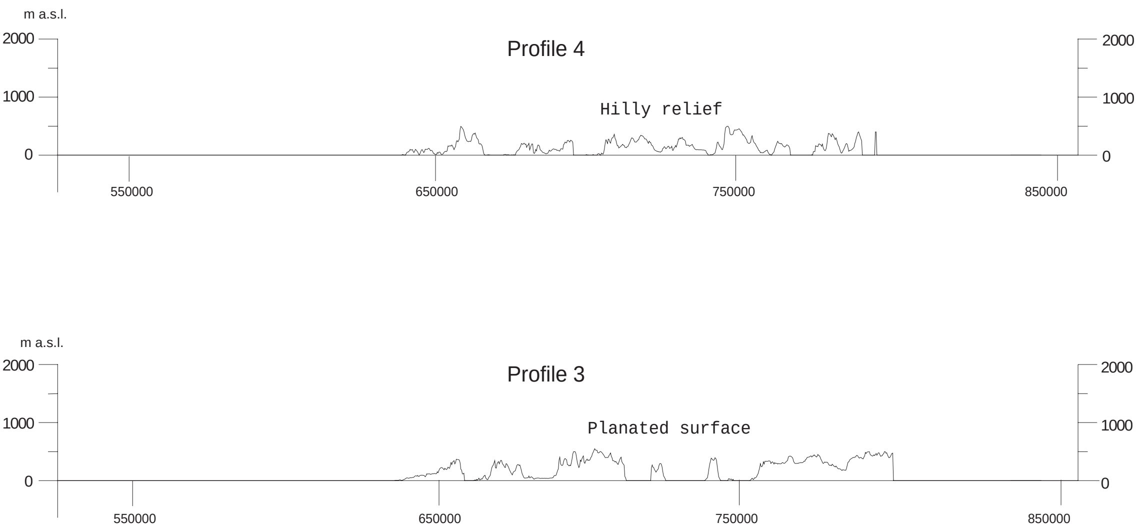


Figure 4-7. *West-East profiles. Profile 3 runs south of Nassuttooq and profile 4 runs north of Nassuttooq. For location see Fig. 4-1.*

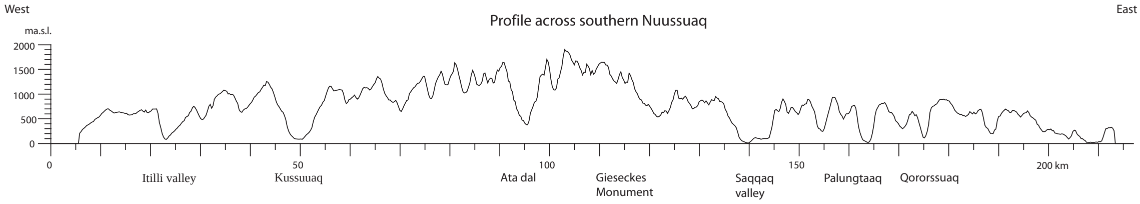


Figure 4-8. *Profile along the south coast of Nuussuaq. For location see Fig. 4-1.*

5. Collection of samples for thermochronological analysis

Collection of samples for fission track analysis Thermal history reconstruction using apatite fission track analysis allows determination of the timing of dominant episodes of heating and cooling, quantification of palaeo-temperatures, and characterisation of mechanisms of heating and cooling. Recently, the development of (U-Th)/He dating of apatite has allowed stronger constraints to be established on the timing of events at relatively low temperatures (<70°C). Thermochronological results from samples at different altitude in near-vertical transects may be combined to estimate palaeo-geothermal gradients. Integration of these methods thus enables identification of major events of burial and erosion during the Phanerozoic. Relative chronologies and surface exposure ages from geomorphological evidences may be used as constraints on thermal history reconstruction.

During fieldwork 39 rock samples were collected for possible future fission track and (U-Th)/He- thermochronological analysis. Samples of 1-2 kg were taken of unweathered in situ rocks expected to contain apatites. The samples were collected either as individual samples at sea level or–in transects over high relief differences (<830 m). Furthermore, two samples of weathered rocks were collected for possible cosmogenic dating, one sample were collected for analysis of clay mineralogy and one to document erosional forms in basement rocks. UTM coordinates were estimated using Garmin 12 GPS, whereas altitude above sea level was estimated from altimeter-readings corrected for diurnal variations. Pertinent data for the samples are given in Table 5-1 and sample locations for all but two samples are indicated on the key maps in Figures 5-1 - 5-7.

Four basement samples collected at Nordre Isortoq and Ilulissat were sent to Geotrack International in Australia, and are currently being analysed by P.F. Green. The purpose is to get a first picture of fission track ages and length distributions from this old basement area where similar investigations have not previously been carried out.

Table 5-1. Collected samples
a. Abbreviations etc.

CD	cosmogenic dating
Cret.	Cretaceous
EF	erosional forms
FT	fission track analysis
Prot.	Proterozoic
wt	wethering products

Map sheet	Sheet name	Scale
67 V.1 NORD	Agto	1:100 000
67 V.2 NORD	Ugssuit	1:100 000
69 V.1 SYD	Uiffaq	1:100 000
69 V.3 NORD	Ataa	1:100 000
70 V.1 NORD	Agatdal	1:100 000
-	Qarajaq *)	1:250 000
-	S.Str.-Nugs. *)	1:500 000
	*) See reference list	

Danish place name	Grenlandic place name
Sdr. Strømfjord	Kangerlussuaq
Ndr. Strømfjord	Nassuttooq
Godhavn	Qeqertarsuaq
Disko	Qeqertarsuaq
Diskofjord	Kangerluk
Fortunebay	Killiit
Røde Elv	Kuussuaq
Jakobshavn	Ilulissat
Egedesminde	Aasiat
Hosteinsborg	Sisimiut
Ndr. Isortoq	Sisimiut Isortuat
Arveprinsens Ejland	Alluttooq
Kællingehætten	Nasaasaaq

Comment	
In situ?	Possibility that rock was not in situ
weth.	wethered rock
Altitude?	Altitude based on GPS
x	within 30 cm from basalt, altered minerals??
xx	25 m from basalt laterally, vertically?

b. Sample coordinates etc.

Sample no.	UTM zone	utmx	utmy	Altitude, m a.s.l.	Locality	Region	Map sheet
4791-01	22	512677	7423166	715	Angmalortup	Kangerlussuaq	S.Str.-Nugs.
4791-02	22	513039	7426139	535	Angmalortup	Kangerlussuaq	S.Str.-Nugs.
4791-03	22	512849	7427118	370	Angmalortup	Kangerlussuaq	S.Str.-Nugs.
4791-04	22	512914	7428070	175	Angmalortup	Kangerlussuaq	S.Str.-Nugs.
4791-05	22	513305	7429528	45	Angmalortup	Kangerlussuaq	S.Str.-Nugs.
4791-06	22	457458	7502468	660	Iterlak	Nagssugtoq	Ugssuit
4791-07	22	459688	7503388	430	Iterlak	Nagssugtoq	Ugssuit
4791-08	22	461026	7503702	230	Iterlak	Nagssugtoq	Ugssuit
4791-09	22	462930	7503481	3	Iterlak	Nagssugtoq	Ugssuit
4791-10	22	406485	7494189	750	Naujarssuit	Nagssugtoq	Agto
4791-11	22	406485	7494189	750	Naujarssuit	Nagssugtoq	Agto
4791-12	22	406643	7494766	500	Naujarssuit	Nagssugtoq	Agto
4791-13	22	406600	7495267	250	Naujarssuit	Nagssugtoq	Agto
4791-14	22	406600	7495267	250	Naujarssuit	Nagssugtoq	Agto
4791-15	22	406191	7496134	5	Naujarssuit	Nagssugtoq	Agto
4791-16	22	382827	7417731	0	Inugsuk	Nagss., - N	Agto
4791-17	22	383435	7540754	10	Rifkol	Agto - W	Agto
4791-18	22	383668	7541895	275	Rifkol	Agto - W	Agto
4791-19	22	383668	7541895	275	Rifkol	Agto - W	Agto
4791-20	22	400013	7563086	230	Alangorssup	Aasiat - S	S.Str.-Nugs.
4791-21	22	398387	7562481	0	Alangorssup	Aasiat - S	S.Str.-Nugs.
4791-22	22	380132	7452549	570	Natarnivingup	N. Isortoq	S.Str.-Nugs.
4791-23	22	379391	7451986	290	Natarnivingup	N. Isortoq	S.Str.-Nugs.
4791-24	22	378364	7451917	0	Natarnivingup	N. Isortoq	S.Str.-Nugs.
4791-25	22	387893	745575	785	Kællinghætten	Sisimiut	S.Str.-Nugs.
4791-26	22	387158	7425686	525	Kællinghætten	Sisimiut	S.Str.-Nugs.
4791-27	22	387194	7426275	280	Kællinghætten	Sisimiut	S.Str.-Nugs.
4791-28	22	386491	7426959	40	Kællinghætten	Sisimiut	S.Str.-Nugs.
4791-29	22	389306	7686925	85	Fortunebay	Qeqertarsuaq	Uiffaq
4791-30	22	400496	7684643	5	Arktisk Station	Qeqertarsuaq	Uiffaq
4791-31	22	388477	7710167	10	Kannaa	Kangerluk	Uiffaq
4791-32	22	388453	7710179	10	Kannaa	Kangerluk	Uiffaq
4791-33	21	602744	7835912	115	Itilli Valley	Nuuss. - N	Agatdal
4791-34	22	476069	7769586	830	Palungataaq	Saqqaq	Qarajaq
4791-35	22	475631	7769104	630	Palungataaq	Saqqaq	Qarajaq
4791-36	22	475360	7768900	440	Palungataaq	Saqqaq	Qarajaq
4791-37	22	475306	7768146	200	Palungataaq	Saqqaq	Qarajaq
4791-38	22	475582	7767243	10	Palungataaq	Saqqaq	Qarajaq
4791-39	22	486676	7736654	0	Laksebugten	Arvepr. Ejl.	Ataa
4791-40	22	500300	7676994	315	Qaqqarsuatsiaq	Ilulissat	Qarajaq
4791-41	22	499696	7676631	150	Qaqqarsuatsiaq	Ilulissat	Qarajaq
4791-42	22	497591	7676604	0	Qaqqarsuatsiaq	Ilulissat	Qarajaq
4792-09	22	422869	7590348	0	Harbour	Aasiat	S.Str.-Nugs.

c. Sample lithology etc.

Sample nr.	Fig. no.	Lithology	Strat. Age	Kr. Age, Ma	Date	Pur-pose	Ini-tials	Com-ments
4791-01	5-1	Gneiss	Prot.	1750	25.7.02	ft	pj	weath.
4791-02	5-1	Gneiss	Prot.	1750	25.7.02	ft	pj	weath.
4791-03	5-1	Gneiss	Prot.	1750	25.7.02	ft	pj	weath.
4791-04	5-1	Gneiss	Prot.	1750	25.7.02	ft	pj	
4791-05	5-1	Gneiss	Prot.	1750	25.7.02	ft	pj	
4791-06	5-2	Gneiss	Prot.	1750	27.7.02	ft	pj	
4791-07	5-2	Gneiss	Prot.	1750	27.7.02	ft	pj	
4791-08	5-2	Gneiss	Prot.	1750	27.7.02	ft	pj	In situ?
4791-09	5-2	Gneiss	Prot.	1750	27.7.02	ft	pj	
4791-10	5-3	Gneiss	Prot.	1750	28.7.02	ft	pj	
4791-11	5-3	Gneiss	Prot.	1750	28.7.02	cd	pj/jb	
4791-12	5-3	Gneiss	Prot.	1750	28.7.02	ft	pj	
4791-13	5-3	Gneiss	Prot.	1750	28.7.02	ft	pj	Altitude?
4791-14	5-3	Gneiss	Prot.	1750	28.7.02	ef	pj/jb	
4791-15	5-3	Gneiss	Prot.	1750	28.7.02	ft	pj	
4791-16	5-3	Gneiss	Prot.	1750	28.7.02	ft	pj	
4791-17	5-4	Granitic	Prot.	1750	29.7.02	ft	pj	
4791-18	5-4	Granitic	Prot.	1750	29.7.02	ft	pj	
4791-19	5-4	Granitic	Prot.	1750	29.7.02	cd	pj/jb	
4791-20	5-4	Gneiss	Prot.	1750	29.7.02	ft	pj	
4791-21	5-4	Gneiss	Prot.	1750	29.7.02	ft	pj	
4791-22	5-5	Gneiss	Prot.	1750	31.7.02	ft	pj	
4791-23	5-5	Gneiss	Prot.	1750	31.7.02	ft	pj	
4791-24	5-5	Gneiss	Prot.	1750	31.7.02	ft	pj	
4791-25	5-5	Gneiss	Prot.	1750	1.8.02	ft	pj	
4791-26	5-5	Gneiss	Prot.	1750	1.8.02	ft	pj	
4791-27	5-5	Gneiss	Prot.	1750	1.8.02	ft	pj	
4791-28	5-5	Gneiss	Prot.	1750	1.8.02	ft	pj	
4791-29	5-6	Surface sed.	-		3.8.02	wt	pj/jb	
4791-30	5-6	Gneiss	Prot.	1750	4.8.02	ft	pj	
4791-31	5-6	Gneiss	Prot.	1750	5.8.02	ft	pj	x
4791-32	5-6	Gneiss	Prot.	1750	5.8.02	ft	pj	xx
4791-33	-	Sandstone	Cret.	70	7.8.02	ft	pj	
4791-34	5-7	Gneiss	Prot.	1750	9.8.02	ft	pj	
4791-35	5-7	Gneiss	Prot.	1750	9.8.02	ft	pj	
4791-36	5-7	Gneiss	Prot.	1750	9.8.02	ft	pj	
4791-37	5-7	Gneiss	Prot.	1750	9.8.02	ft	pj	
4791-38	5-7	Gneiss	Prot.	1750	9.8.02	ft	pj	
4791-39	5-7	Gneiss	Prot.	1750	9.8.02	ft	pj	
4791-40	5-7	Granodiorite	Prot.	1750	11.8.02	ft	pj	
4791-41	5-7	Granodiorite	Prot.	1750	11.8.02	ft	pj	
4791-42	5-7	Granodiorite	Prot.	1750	11.8.02	ft	pj	
4792-09	-	Gneiss	Prot.	1750	30.7.02	ft	kesk	

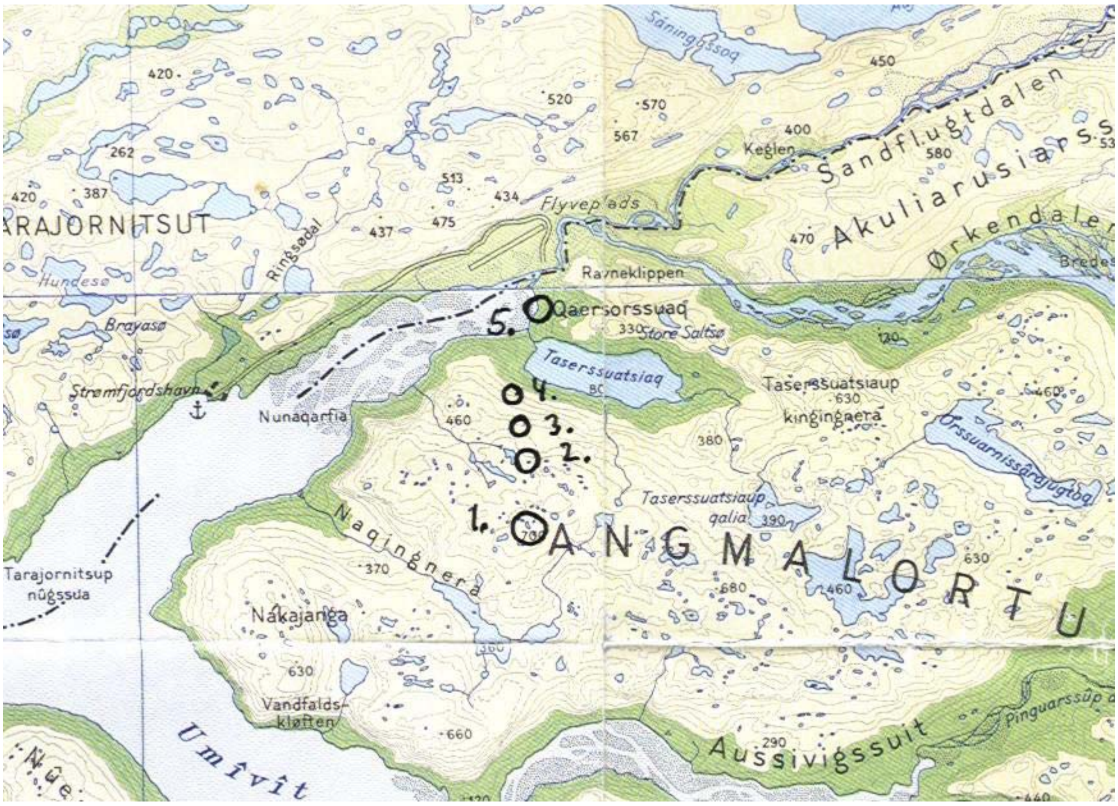


Figure 5-1. *Key map with sample locations in the area of Angmalortup (SW of Kangerlussuaq / Sdr. Strømfjord, FT profile 715 m). 1:250 000.*

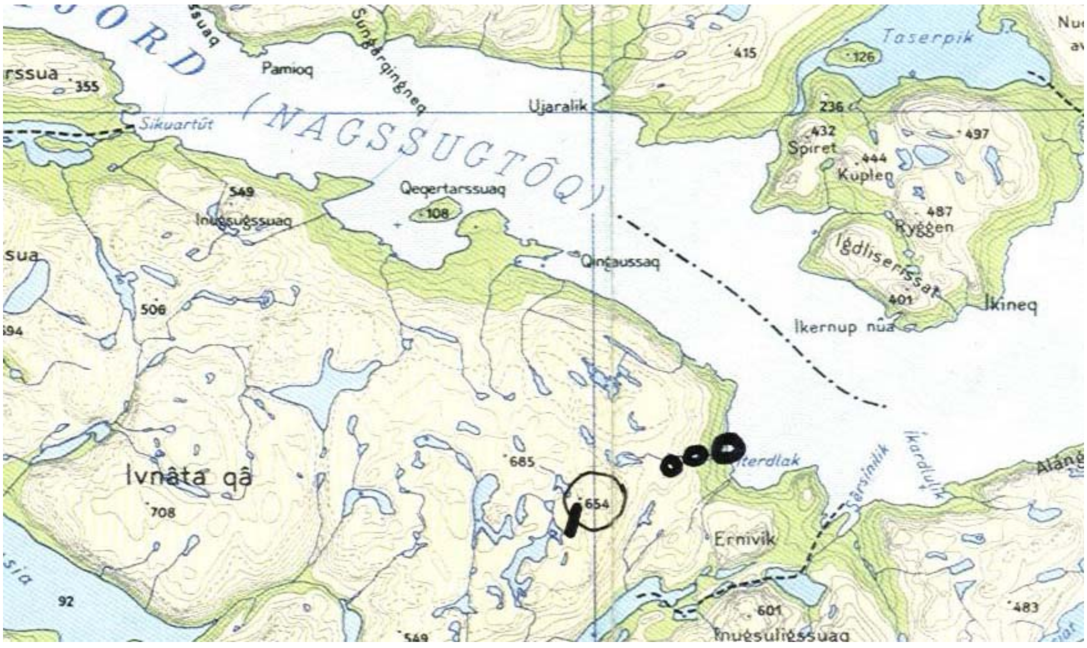


Figure 5-2. *Key map with sample locations in the area of Iterlak (Nassuttooq - Ndr. Strømfjord, FT profile 660 m). 1:250 000.*

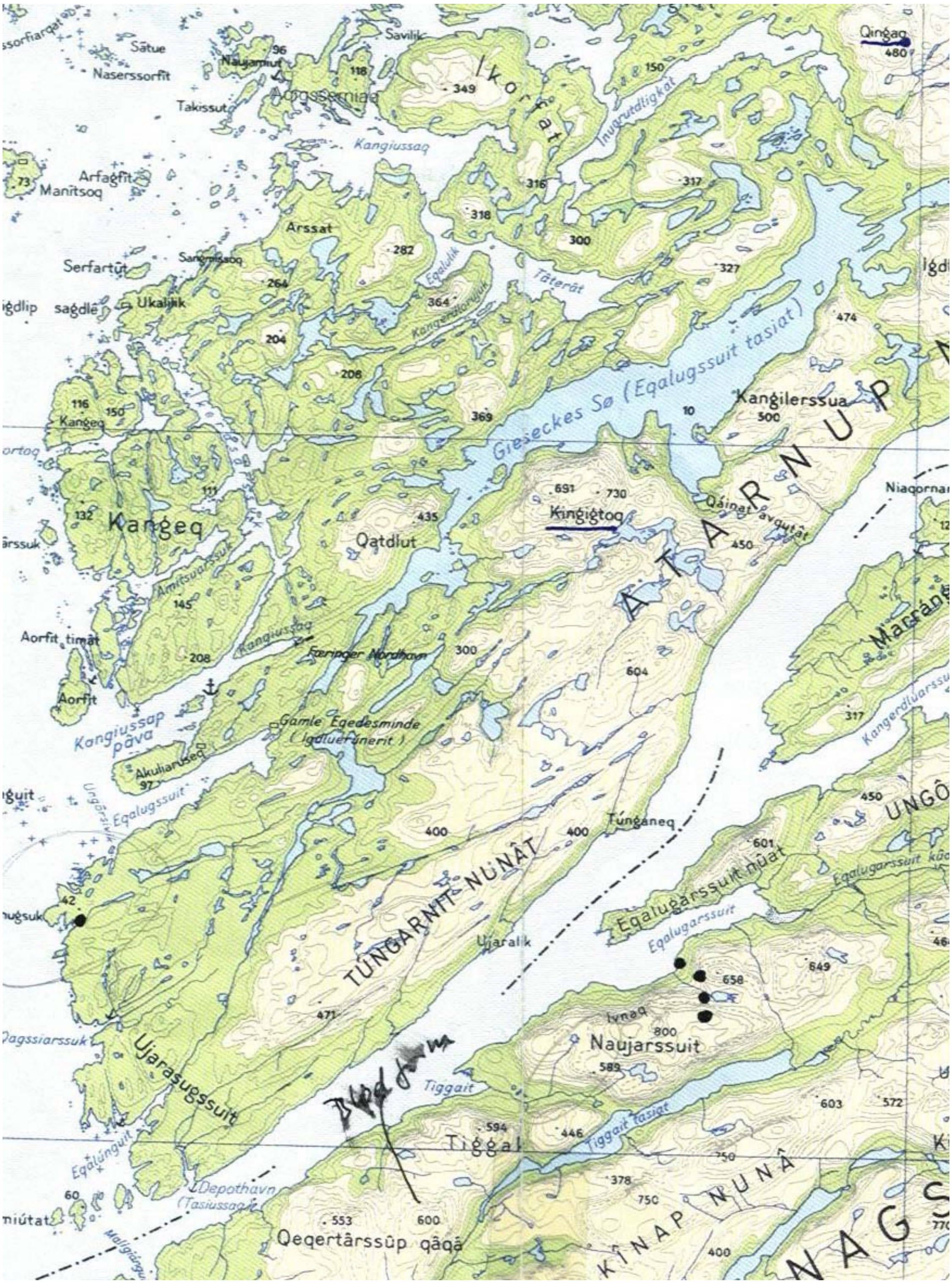


Figure 5-3. *Key map with sample locations in the areas of Naujarssuit (Nassuttooq / Ndr. Strømfjord, FT profile 750 m) and Inugsuk (north of Nassuttooq / Ndr. Strømfjord, 1 sample). 1:250 000.*

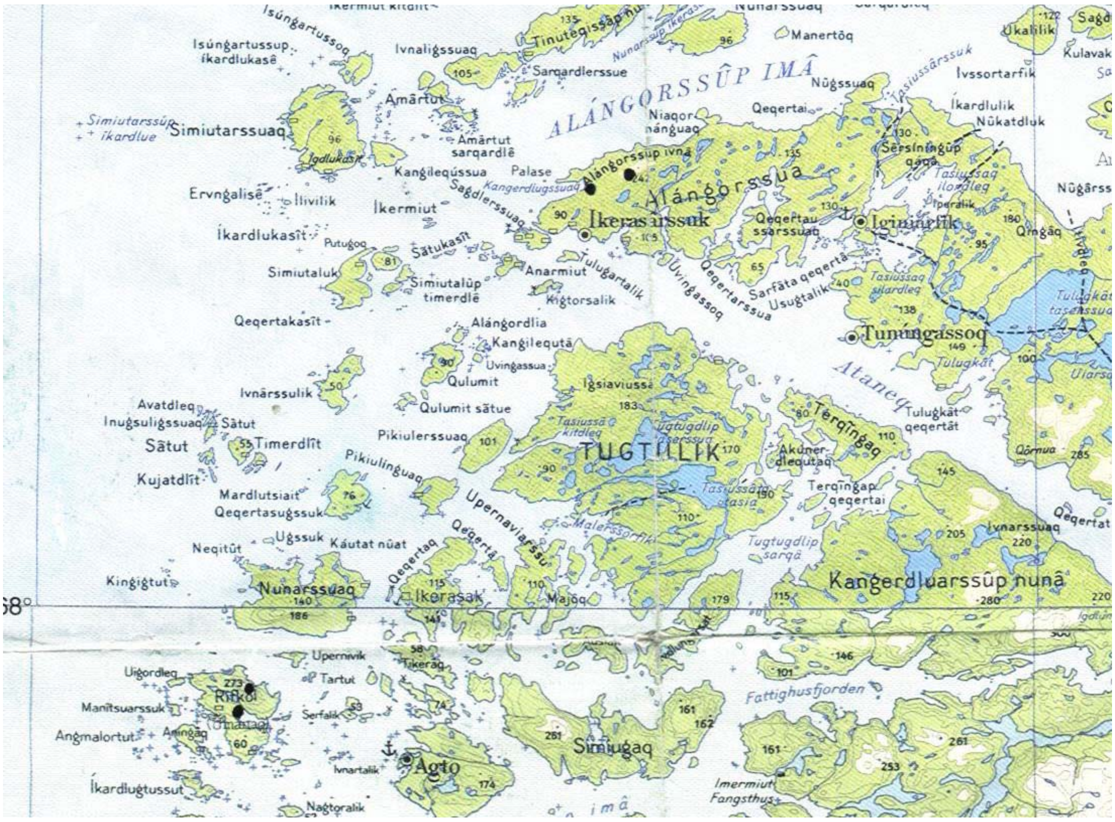


Figure 5-4. *Key map with sample locations in the areas of Rifkol (west of Agto, 275 m FT profile) and Alangorssup (S of Aasiat, FT profile 230 m). 1:250 000.*

Figure 5-5. *Key map with sample locations in the areas of Natarnivingup (Ndr. Isortoq, FT profile 570 m) and Kællingehætten (Sisimiut, 1.8: FT profile 785 m). 1:250 000.*

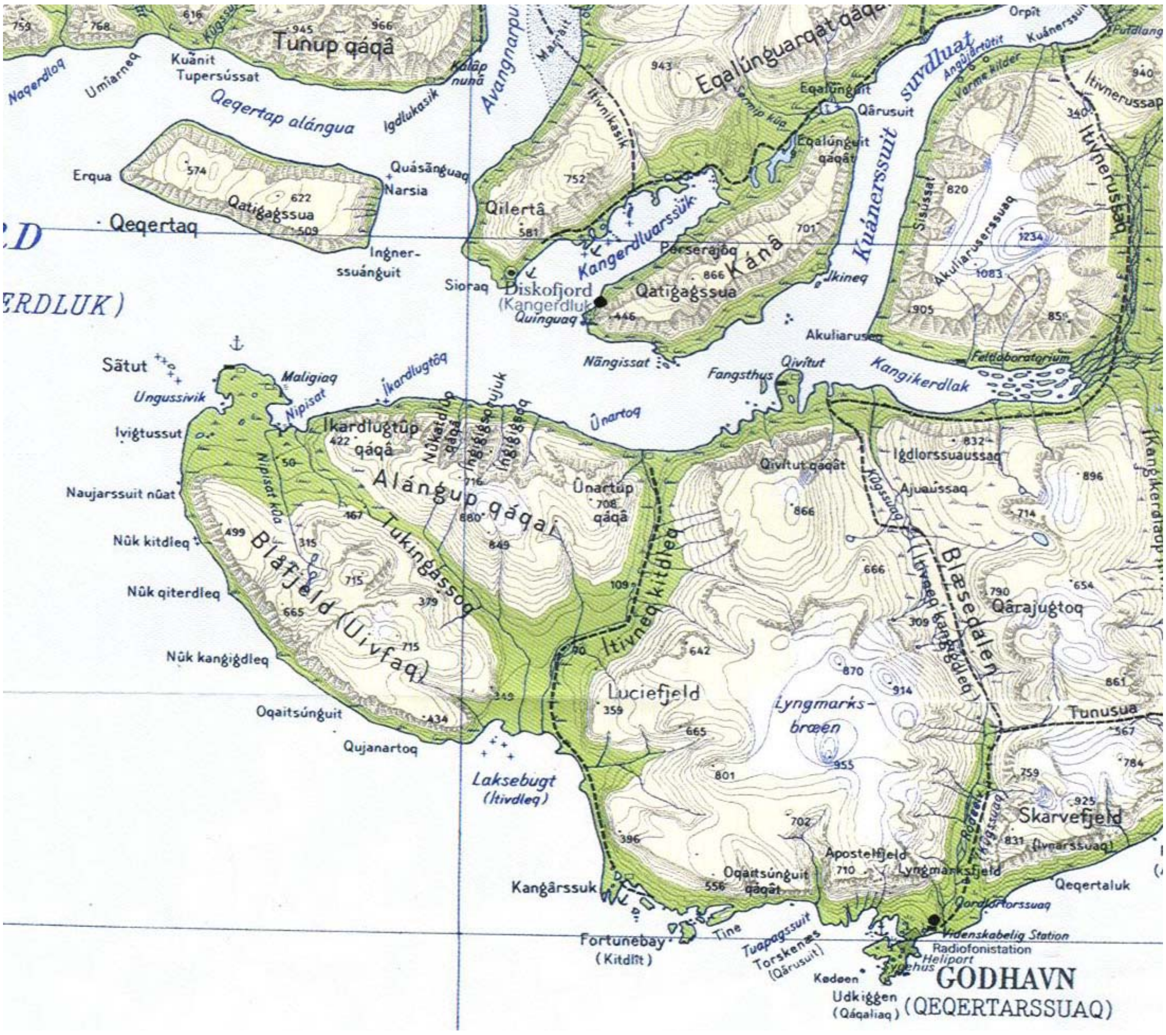


Figure 5-6. *Key map with sample locations in the areas of Arktisk Station (Qeqertarsuaq / Godhavn, 1 FT sample) and Kannaa (Kangerluk / Diskofjord, 2 FT samples). 1:250 000.*

Figure 5-7. *Key map with sample locations in the areas of Palungataaq (E of Saqqaq, FT profile 830 m) and Laksebugt (Arveprinsens Ejland, 1 FT sample). 1:250 000.*

6. Discussion

6.1 Hilly relief

The presence of a hilly relief topography (relative relief 100–300 m) associated with deeply weathered gneiss basement in the Disko Bugt area is an important feature for understanding the development of relief in the Precambrian basement. The weathering mantle (saprolite) is a strong indicator for deep weathering, usually interpreted as an indicator of warm climate (Thomas 1994; Lidmar-Bergström *et al.* 1999). Hilly relief developed by deep weathering has therefore been labelled etch surfaces in Scandinavia (Lidmar-Bergström 1988; 1995; Johansson *et al.* 2001; Olvmo & Johansson 2001).

6.1.1. Hilly relief associated with weathered gneiss and cover rocks

A weathered (etched) surface is documented on south Disko where the hilly relief has been successively exhumed by removal of Paleocene basalts (e.g. the field work locations Fortunebay and Kannaa; Figs A-23; A-26), and on the north side of Nuussuaq where middle Cretaceous (Albian-Cenomanian) fluvio-deltaic sandstone and mudstone rest on deeply kaolinised basement (Pulvertaft 1979; e. g. Chalmers *et al*. 1999). Cretaceous remnants have been identified onshore as far south as the island Grønne Ejland and from seismic sections Cretaceous–Paleocene sediments are interpreted to reach even farther south in south-east Disko Bugt (Fig. 6-1; see Chalmers *et al.* 1999). These Cretaceous–Paleocene cover rocks have thus preserved the etch surface to the present day, and the stratigraphy proves the pre-60 Ma age of this surface. The hilly basement relief on Disko can consequently be considered as a sub-Paleocene etch surface, maybe of Cretaceous age.

6.1.2. Hilly relief with no remnants of cover rocks

Hilly relief is also present onshore south of Disko Bugt, in the Lersletten area. For the purpose of this report we define the Lersletten area as the area reaching (see section 4.3.2 and Fig. 2-1)

- N–S from Aasiaat to just north of Nassuttooq (e.g. the field locality Inugsuk; Fig. A-8; A-10) and
- E–W from Rifkol (e.g. the field localities Rifkol and Alangorssup to the eastern limit of Lersletten.

Neither Cretaceous–Paleocene cover rocks (e.g. resistant remnants such as chert) nor remnants of kaolinised basement (saprolites) have been reported from the Lersletten area. Etching seems to have been a major component in the landscape development as indicated from the similarity between the large-scale hilly relief in the Lersletten area and the sub-Paleocene etch surface on Disko. The proximity between Cretaceous–Paleocene cover rocks and the hilly relief in the Lersletten area also support this view. Consequently, the present land surface in the Lersletten area may be considered as a sub-Paleocene etch surface.

6.2. Planated relief

South of Nassuttooq, a high plain with flat summits and shallow valleys is dissected by a few deep valleys and fjords (Fig. 6-2). This high plain replaces the hilly relief in the Lersletten area and is present between Nassuttooq and Sukkertoppen Iskappe (Figs 6-3, 6-4):

- From north the planated summit level rises from an altitude of 600–700 m around Nassuttooq (e.g. the field localities Iterlak (Figs A-9; A-12) and Naujarssuit to 1000–1200 m south of Kangerlussuaq, just east of Sukkertoppen Iskappe.
- A transition zone coincides with the Nordre Strømfjord Shear Zone just north of Nassuttooq.
- Along the west coast, the high plain is terminated by a major escarpment (e.g. the field locality Natarnivingup; Fig. A-6).

The highest area is located west of Sukkertoppen Iskappe, where summits reach 1850 m a.s.l., while local high mountains reach 1400 m a.s.l. south of Nordre Isortoq.

The planated relief appears to continue to the north, east of Disko Bugt, and reaches altitudes over 1000 m in eastern Nuussuaq (e.g. the field locality Palungataaq; Figs A-35; A-36). From Palungataaq near Saqqaq we observed that the plain dropped in altitude towards the south along the eastern side of Disko Bugt (east of the Cretaceous Boundary Fault System) to *c.* 550 m a.s.l. south of Qasigianguit (east of Lersletten where summits reach 200–300 m a.s.l.; Fig. 6-1). The Cretaceous Boundary Fault System has been mapped offshore as far south as Qasigianguit on the basis of seismic data (Chalmers *et al.* 1999). However, based on geomorphology, it is possible that the fault system has a continuation onshore, east of Lersletten. If the fault system is present onshore, direct observation of faults may be difficult due to widespread Quaternary covers (Henderson 1969).

On eastern Nuussuaq the planated relief cuts across bedrock of Paleocene basalt and of Precambrian basement on both the western and eastern side of the Cretaceous Boundary Fault in the Saqqaq Valley (Fig. 6-5).

The summit altitude between Sukkertoppen Iskappe and Nassuttooq declines towards the north where the relief may by correlated to the summit level in the Lersletten area (Fig. 6-3). It is possible that this summit level represents the level of a primary surface from which all other relief is developed (cf. the sub-Cambrian peneplain in Scandinavia; e.g. Elvhage & Lidmar-Bergström (1987), Lidmar-Bergström (1996).

6.3. Development of the bedrock relief

6.3.1. Preservation and exhumation of the hilly relief

The preservation of the hilly relief in the Lersletten area indicates that a Cretaceous–Palaeogene cover can only have been removed recently in the geologic history. The hilly relief is generally below 300 m a.s.l. and may thus have been buried below such cover rocks. Cretaceous–Paleocene siliciclastic sediments reach an altitude of *c.* 500 m a.s.l. on eastern Disko with thick Palaeogene basalts on top. It can also be noted that summits above 500 m only occur south of Nassuttooq, and not in the Lersletten area The exhumation (re-exposure) of the hilly relief in Lersletten area is likely to be the result of fluvial erosion of cover rocks after a Neogene uplift event. The relief was finally shaped by glacial erosion. The timing and magnitude of this hypothetical pre-glacial erosional event may eventually be confirmed by thermochronological analysis.

6.3.2. Timing of formation of the planated relief

The absolute time for development of the planated relief in the study area can not be determined from the available observations, but hopefully the thermochronological analysis will help to clarify this issue. Two different scenarios can account for the fact that a hilly relief is not present in the area from Nassuttooq to Sukkertoppen Iskappe and east of Disko Bugt:

1. The relief was planated subsequent to the etching of the exposed basement in the Disko Bugt-Lersletten area. Parts of the areas with planated relief may have been exposed to deep weathering during the Cretaceous.
2. Palaeozoic–Mesozoic cover rocks were present in the area during the formation of the etch surface in the Lersletten area. These cover rocks protected a Precambrian peneplain from deep weathering processes.

In eastern Nuussuaq, the planation event must have occurred during the Cenozoic (case 1). Here the planated relief cuts across bedrock of Paleocene basalt and Precambrian basement on the western and the eastern side of the Cretaceous Boundary Fault in the Saqqaq Valley (Fig. 6-8). On westernmost Nuussuaq the planated relief even cuts across Lower Eocene basalt and the planation event may thus have been initiated during Late Eocene–Oligocene times.

The high lying planated relief identified in eastern Nuussuaq may eventually be correlated along the eastern side of Disko Bugt with the planated summit relief south of Lersletten as discussed above (Fig. 6-1). In this scenario, mid-Cenozoic fluvial erosion in the area around Nassuttooq might have had a base level of *c.* 750 m above present sea level as indicated by the level of the flat summits. The etched basement in the Lersletten area would not have been exhumed and planated due to a Cretaceous–Palaeogene protective cover, up to *c.* 750 m thick. However, south of the Lersletten area any etch surface would have been obliterated during a Cenozoic planation event (case 1).

The second of the above scenarios indicates that at least parts of the planated relief between Nassuttooq and Sukkertoppen Iskappe were protected by Palaeozoic–Mesozoic cover rocks during the Cretaceous. The Fossilik Ordovician outlier, south of Sukkertoppen Iskappe (Stouge & Peel 1979; Fig. 2-3) documents the presence of a former Palaeozoic cover in West Greenland. The existence of a Palaeozoic cover is further supported by the occurrence of redeposited Ordovician(?) fossils in Cretaceous sediments on Disko (Pedersen & Peel 1985) as well as offshore West Greenland, e.g. in Neogene sediments in Qulleq-1 well (S. Piasecki pers. comm..).

The magmatic intrusions in the southern part of the area are important for the reconstruction of the development of bedrock relief. Three intrusions are especially important: the Safartoq carbonatite complex (*c.* 600 Ma), the Qaqqaarsuk carbonatite complex (*c.* 170 Ma) and Sukkertoppen dyke swarm, near Manitsoq (55 Ma) (Larsen & Rex 1992; Larsen *et al*. 1999). The preserved upper part of the Safartoq carbonatite complex is interpreted to have been close to the surface immediately after its intrusion and this would indicate that not much cover rock was present in the early Palaeozoic (Peel & Secher 1979; K. Secher pers. comm.). However, during the Jurassic, cover rocks may have been present above the Qaqqaarsuk carbonatite complex as estimated from the relation between the intrusion and the host rock (K. Secher pers. comm.). The cover rocks assumed to be present during the Jurassic intrusion event must therefore also have included Palaeozoic rocks if the age of the volcanic event at Fossilik is simultaneous with the Qaqqaarsuk intrusion (L. M. Larsen pers. comm.)

6.3.3. Evidence for Neogene surface uplift

Two large-scale landforms are important for understanding the long-term development in West Greenland, viz: The planated relief with its shallow valleys at high elevation and the deeply incised valleys which have dissected the planated relief along the flanks. The incised valleys are narrow (e.g. along the flanks of Angujartorfiup Nuna) where they are not pathways for glacial outlets (Fig. 4-2). The appearance with the narrow valleys therefore indicates a development mainly by fluvial processes (e.g. Bonow *et al.* in press).

The high plain with incised valleys indicate a late change in base level, either by eustatic sea level change or tectonic uplift (cf. the *Palaeic relief* in southern Norway, Reusch 1901; Wråk 1908; Ahlmann 1919; Lidmar-Bergström *et al.* 2000). The height differences of c. 1 km between the planated relief and the present base level make the tectonic alternative more probable. Tectonic uplift is thought to be the main cause for triggering valley incision, and generally more important than climatic change (cf. Ahnert 1970).

The incised valleys therefore indicate that the planated relief was uplifted during pre-Quaternary times in the investigated area. These valleys appear to have been glacially re-shaped along certain sections. We thus suggest that the uplift occurred during the Neogene on the basis of these relative ages derived from observations in the study area. Similar conclusions about Neogene uplift based on large-scale landforms and valley development have been suggested for the mountains of southern Norway (Ahlmann 1919; Lidmar-

Bergström *et al.* 2000; Bonow *et al.* in press). One can speculate that a tentative quantification of the timing of surface uplift could be post-10 Ma to account for the observed mismatch between the shallow valleys at high elevation and those valleys that are deeply incised.

Magnitude and timing of surface uplift was particularly evident from observations on Nuussuaq (Figs 6-8, 6-6) and Disko:

- Central Nuussuaq: Valleys on the south coast have a bottom level at *c*. 1 km a.s.l. Above this level, the landscape is characterised by alpine relief in Paleocene basalts with summits up to 2 km a.s.l.
- Westernmost Nuussuaq: The relief cuts across Eocene basalts and is generally situated lower than 1 km a.s.l. The relief is undulating with shallow valleys.
- Eastern Nuussuaq: The planated relief is well defined at *c*. 1 km and cuts across Paleocene basalt and Precambrian basement.
- Disko: A smooth summit surface occurs above 1 km.

We suggest that the following model can explain the relief on Nuussuaq, where a tentative timing is indicated to clarify the succession of events. Se also section 6.4.2 and Fig. 6-8:
Eocene: Lower Eocene basalts on west Nuussuaq are downfaulted along the Itilli Fault, mainly prior to the mid-Eocene when sea-floor spreading ceased in the Labrador Sea (Chalmers 2000).
?Oligocene: Planation of relief with a base level around 1 km above present sea level.
Neogene: Surface uplift of *c*. 1 km and development of deeply incised fluvial valleys.
Present: Glacial reshaping of planated relief and valleys during the Quaternary.

The suggested hypothesis of 1 km of surface uplift of Nuussuaq is in agreement with the occurrence of marine Upper Cretaceous sediments *c*. 1 km above sea level (Birkelund 1956). Our hypothesis, furthermore, suggests that the timing of this uplift can be narrowed from post-65 Ma to post-(?)10 Ma. A Neogene uplift event is in agreement with studies of structural relations and basin modelling from Nuussuaq (Mathiesen 1998; Chalmers 2000). Note that landslide in year 2000 at Paatuut occurred just 10 km west of Kingittoq; the slide may have been the immediate result of geomechanical instability, but according to the analysis presented here, the Paatuut-Kingittoq area is likely to be affected by neotectonic activity (Pedersen *et al. 2001)*.

Nuussuaq is a key area for the understanding the succession of events in West Greenland. The youngest deposits in the region are found here, and hence it is here that one can place the narrowest constraints on the timing of bedrock development and the relief in Nuussuaq and hence in other areas. The onset of erosional events (cooling) may be constrained by thermochronological analysis of basement samples that were collected in summer 2002 (Palungataaq locality).

6.4. Sketches of the possible development of the bedrock relief

Several of the geological and geomorphological observations made during the field work and available from the literature have been compiled to suggest possible stages in the development of the bedrock relief in central West Greenland (Figs 6-3, 6-4, 6-8). As indicated above, the absolute time for development of the planated relief in the study area cannot be determined from the available observations, and the extent of Palaeozoic cover rocks through geological time is speculative. The sketches are included to illustrate key points in the discussion.

6.4.1. North-south profile, Fig. 6-7

600 Ma / Late Precambrian: The surface of Precambrian bedrock was denuded to a flat surface, maybe with residual hills. The Safartoq carbonatite complex was intruded.

450 Ma / mid-Palaeozoic: Palaeozoic sediments covered large parts of central West Greenland as evidenced by the Fossilik outlier south of the profile and redeposited fossils on Disko.

100 Ma / Cretaceous: The basement was exposed in the Disko Bay–Lersletten area and suffered kaolinitic weathering leading to the development of an undulating hilly relief. Presence of Palaeozoic cover rocks south of the Kangerlussuaq prevented kaolinitic weathering of the basement in that area (case 2 of the above scenarios). The Qaqqaarsuk carbonatite was intruded c. 170 Ma through these cover rocks explaining why the near-surface part of the carbonatite is not preserved. The exposed bedrock in the Disko Bugt area is assumed to have been more elevated than the covered bedrock around Sukkertoppen Iskappe to the south. In this case, the present rise in topography of c. 1 km from Lersletten to Sukkertoppen occurred during the Cenozoic. This case is assumed in the following profiles.

50 Ma / Eocene: Cretaceous–Palaeocene rifting led to deposition of a thick siliciclastic cover in the Disko Bugt area. Today these deposits reach c. 500 m a.s.l. on Disko and may have covered the Lersletten area as far south as Nassuttooq (Ndr. Strømfjord) where the bedrock relief is higher than 500 m. During the mid-Paleocene and Early Eocene continental flood basalts covered much of the northern area.

10 Ma / Neogene: Mid-Cenozoic (?Oligocene) planation occurred after Eocene rifting in the Labrador Sea and Palaeozoic cover rocks to the south were removed leading to the formation of the Paleic relief in its present form. Offshore, this phase of planation is represented by absence of Oligocene sediments in wide areas and by deep erosion of the Eocene strata (A.B. Sørensen pers. comm.).

Present: Neogene surface uplift shifted the planated relief to its present position about 1 km above sea level south of Kangerlussuaq and in the northern part of Disko Bugt. Incision of deep valleys was initiated by this tectonic uplift and the fluvial valleys were reshaped by glacial erosion during the Quaternary. The large-scale landscape in the high plain around Angujartorfiup Nuna east of Sukkertoppen Iskappe did not suffer notable glacial erosion. This area must therefore have been high prior to the Quaternary glaciations.

6.4.2. East-west Nuussuaq profile, Fig. 6-8

10 Ma / Neogene: Mid-Cenozoic (?Oligocene) planation occurred after Eocene rifting in the Labrador Sea leading to the formation of a planated relief close to sea level. Note that the Vaigat Formation (underlying the marker horizon, m_M) only is present west of Kingittoq (Gieseckes Monument). In this interpretation, the block to the east was a structural high during the Palaeocene eruption of the Vaigat formation. This is supported by the downwards displacement of Cretaceous strata to the west of Kingittoq (see Chalmers *et al*. 1999).

Present: Neogene surface uplift shifted the planated relief to its present position about 1 km a.s.l. Note the flexure of the marker horizon, m_M, with a relative down-sagging to the east of about 400 m (Pedersen & Dueholm 1992) – a reversal relative to the previous movements of the Kingittoq fault (cf. Chalmers *et al*. 1999).

Neogene surface uplift: The estimated uplift has a regional component of *c*. 750 m superimposed by 100 km wide additional domal uplift of 750 m, 1500 m in total just west of Kingittoq. The inclination of the domal feature towards the east is rather steep and leaves open the possibility of Neogene faulting at Kingittoq. The inclination and the amplitude of the domal feature match the structure of the marker horizon at the base of Niaqussat Member on eastern Disko (Fig. 6-9, Pulvertaft & Larsen 2002).

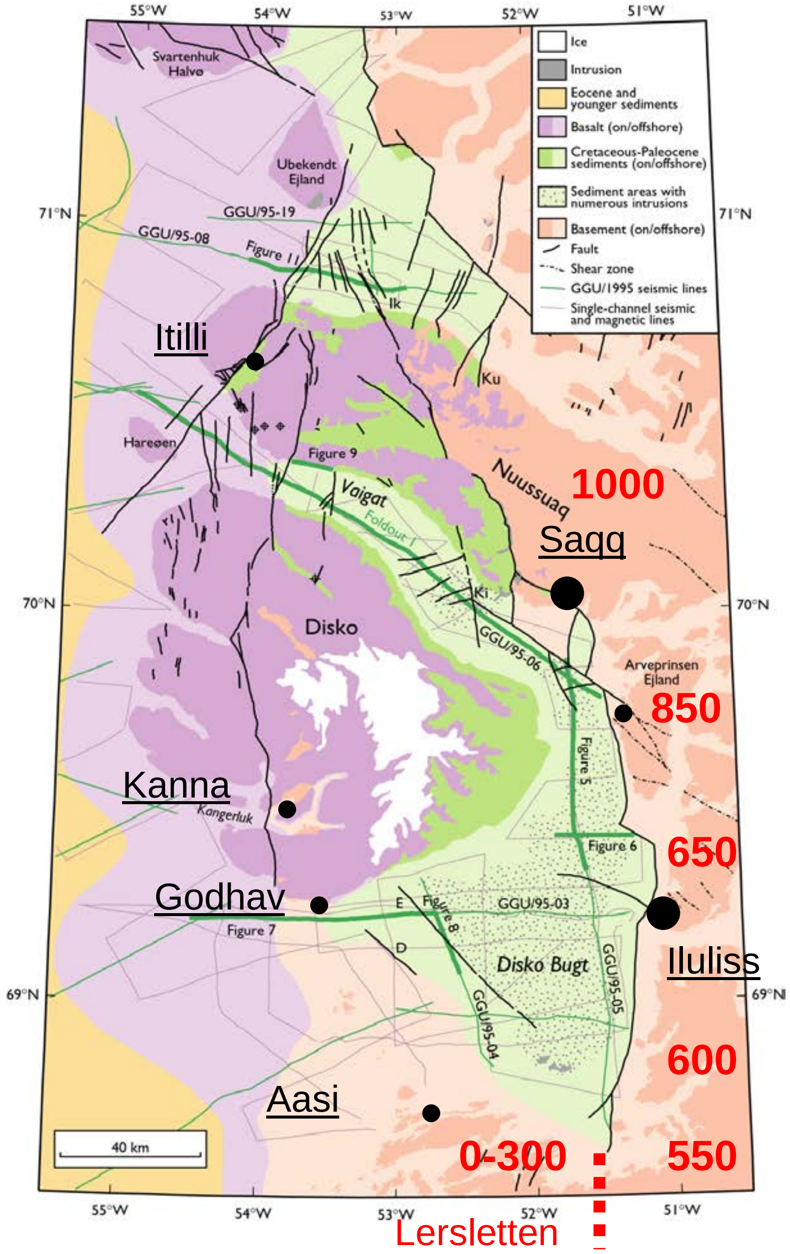


Figure 6-1. *Geology of the Disko-Nuussuaq area (from Chalmers et al. 1999). Note the gentle inclination of the Paleic relief (east of the CBFS) towards the south. The low-lying Lersletten is clearly distinguished from the higher basement east of the extrapolation of Boundary Fault mapped from seismic data onshore.*

Red numbers: Flat basement tops reflecting the approximate level of the Paleic Relief (altitude in metres).

Information related to the 2002 field work:

Small circle: 1 fission track sample.

Large circle: 2-5 fission track samples.

Underlined place names: Field work locations.

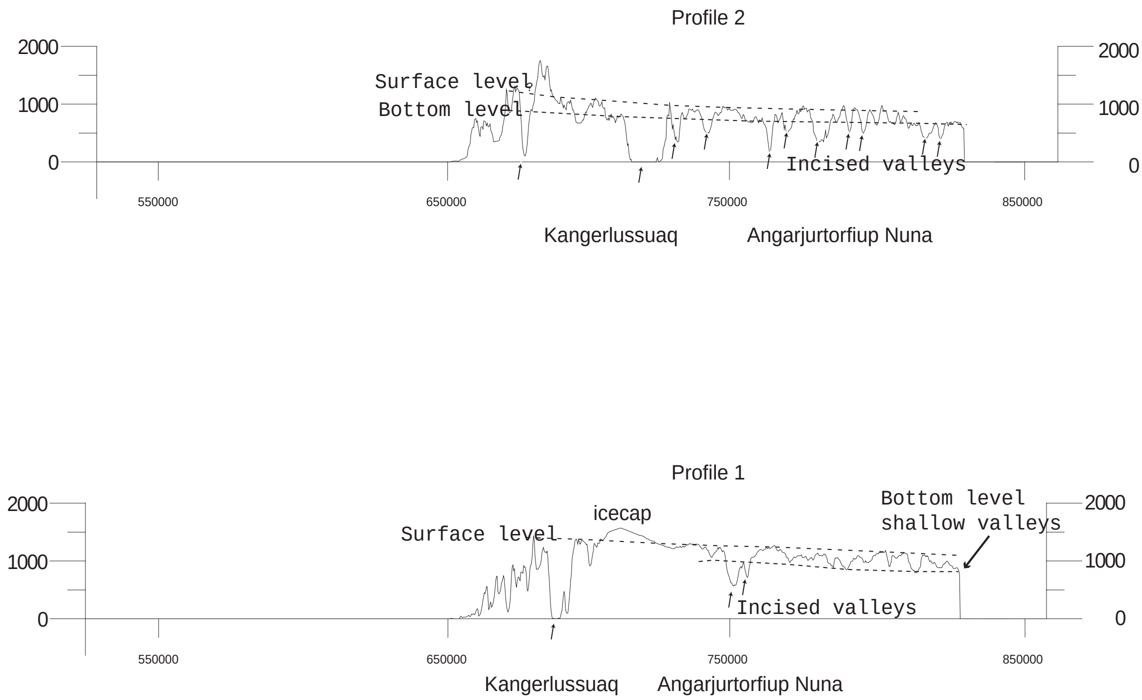


Figure 6-2. *West-East profiles over Sukkertoppen-Angujartorfiup Nuna. The summit and the bottom level for shallow valleys have been reconstructed. Location of Fig. 4-1.*

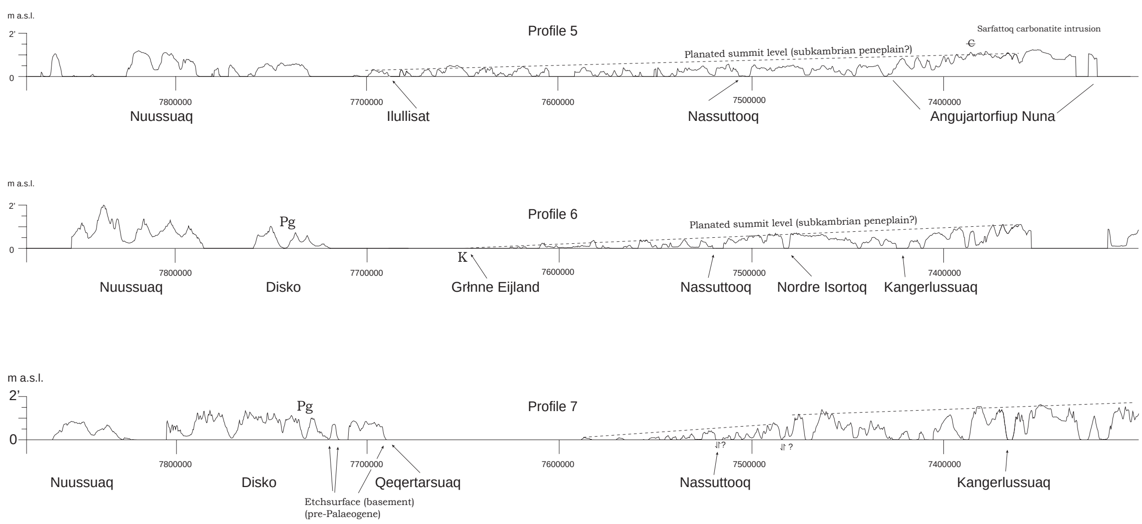


Figure 6-3. *Possible interpretation of an etch-surface in the Lersletten area and of a preserved sub-Cambrian peneplain in the area south of Nassuttooq (cf. Fig. 6-4). Location of profiles in Fig. 4-1.*

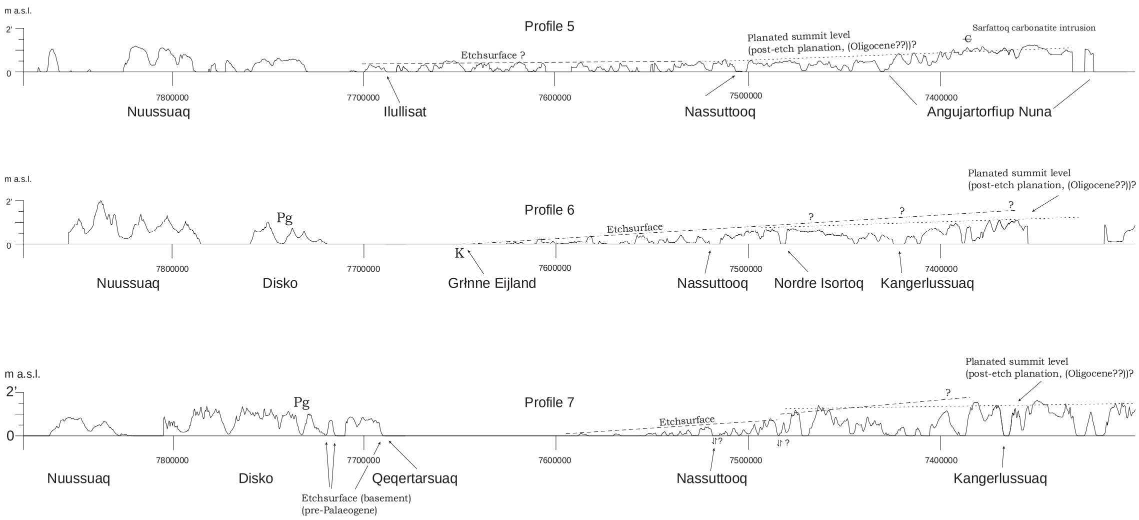


Figure 6-4. *Possible interpretation of an etch-surface in the Lersletten area and a younger planation surface in the area south of Nassuttooq. (cf. Fig. 6-3). Location of profiles in Fig. 4-1.*

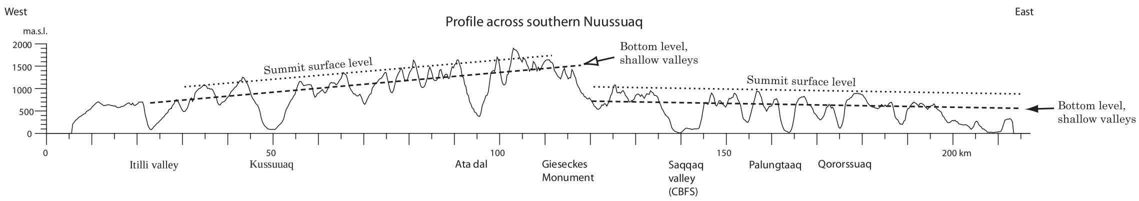


Figure 6-5. *Interpreted surface and bottom level on Nuussuaq. Note that the Saqqaq fault can not be seen in the landscape.*

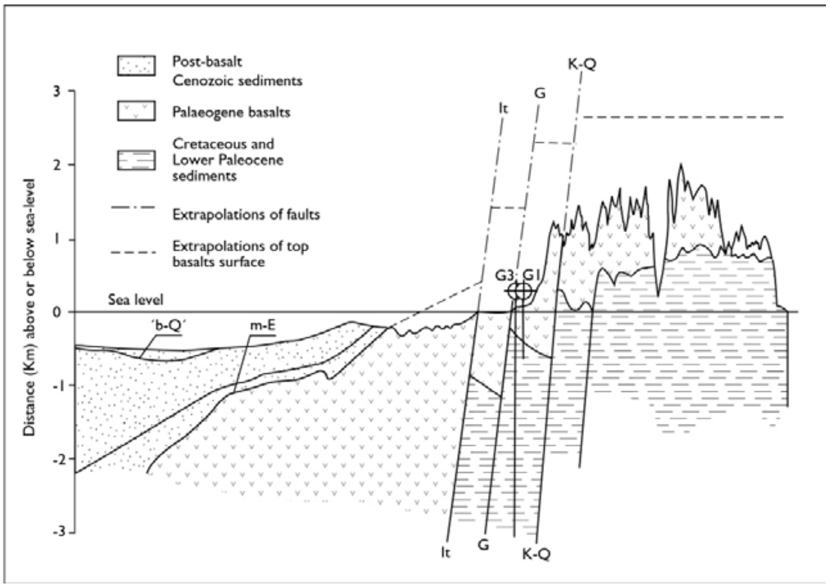


Figure 6-6. *Composite cross-section from west of Disko and Nuussuaq and along the southern coast of Nuussuaq (from Chalmers 2000). The western part of the cross-section is based on an offshore seismic line and the eastern part on the profile published by Pedersen et al. (1993). The top basalt surface is seen to be tilted from -2 km offshore to almost 3 km above sea level onshore; c. 2 km of this difference is due to faults active during post-basalt times. The residual relief of c. 3 km was suggested by Chalmers (2000) to be due to Neogene uplift.*

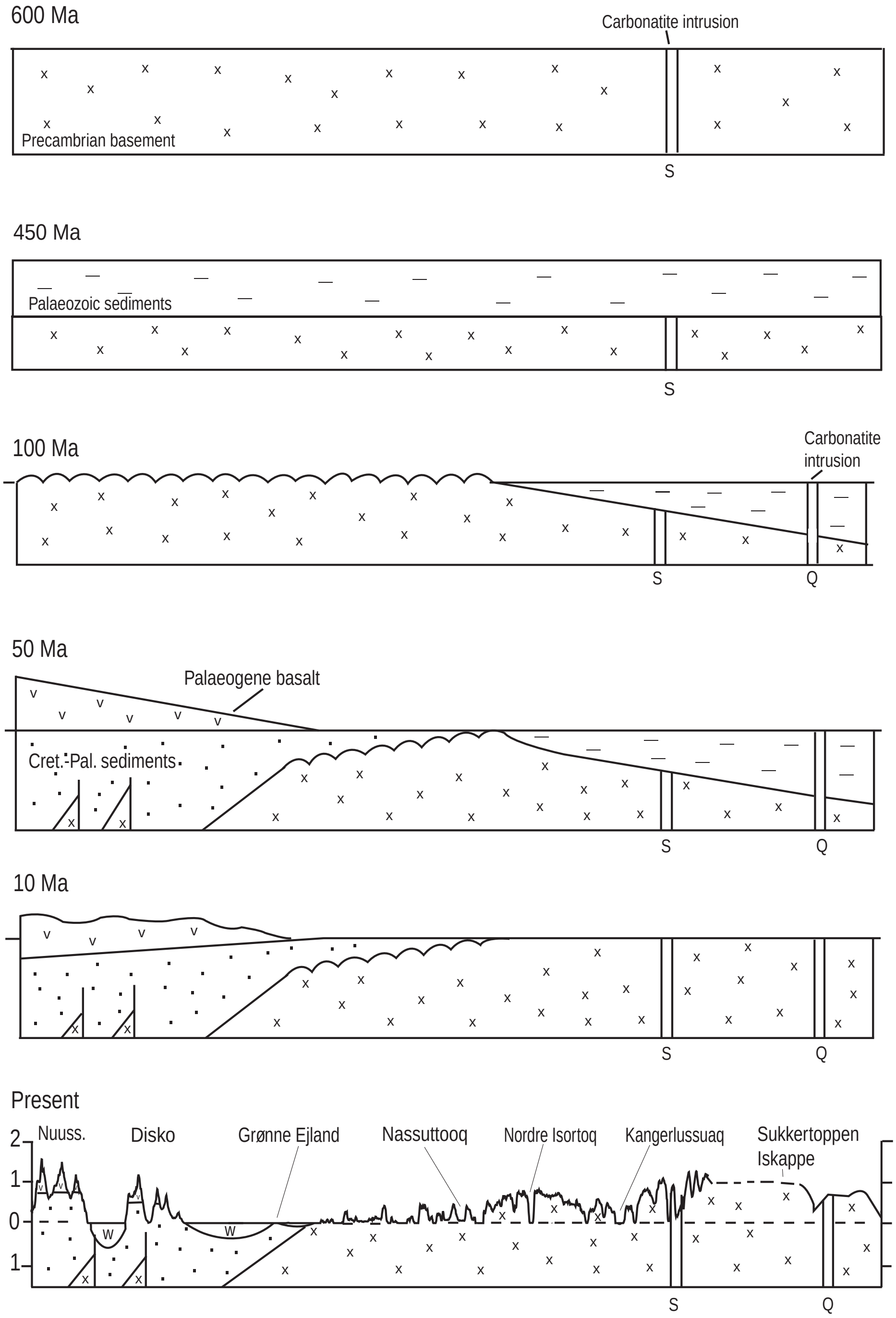


Figure 6-7. *Illustration of a possible development of bedrock relief in central West Greenland between Nuussuaq and Sukkertoppen Iskappe along profile 6 in Fig. 4-1 (see the section 6.4 for details). The stratigraphy along the present-day profile is modified after Pedersen et al. (1993), Chalmers et al. (1999) and Henriksen et al. (2000).*
S: Safartoq carbonatite complex, intruded at c. 600 Ma; evidence for near-surface conditions at time of intrusion preserved (K. Secher pers. comm.).
Q: Qaqqaarsuk carbonatite complex, intruded at c. 170 Ma; the near-surface part of the carbonatite is apparently not preserved (K. Secher pers. comm.).
w: water .

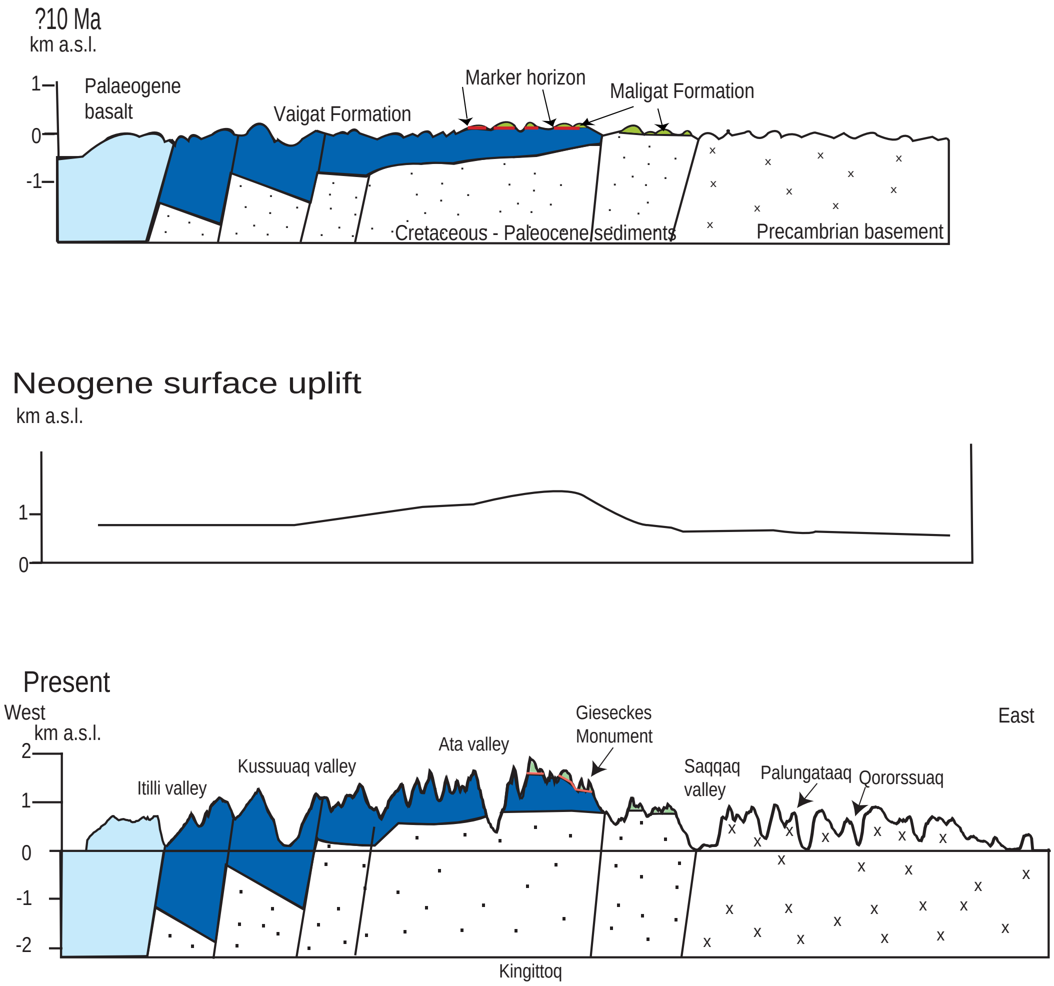


Figure 6-8. *Illustration of a possible development of the bedrock relief along the southern coast of the Nuussuaq (location on Fig. 4-1; topographic profile shown in Fig. 6-5).*

- *10 Ma reconstruction based on flattening of the marker horizon (red), m_M, at the base of the Paleocene Maligat Formation (west of Kingittoq; Pedersen et al. 1993) and on the assumption that the shallow valleys represent the pre-Neogene base level.*
- *Neogene surface uplift is estimated as the difference between the present summit surface and the reconstructed mid-Cenozoic planated surface.*
- *Stratigraphy along the present-day profile modified after Pedersen et al. (1993) and Chalmers (2000).*

A suggested late uplift of c. 1 km explains the position of valleys c. 1 km above sea level in central Nuussuq. The model is in agreement with the occurrence of upper Cretaceous marine sediments at the altitude of c. 1 km (Birkelund 1956). Note the down-sagging to the east of the marker horizon (c. 400 m) west of Kingittoq where Cretaceous sediments are downfaulted to the west (see Chalmers et al. 1999).

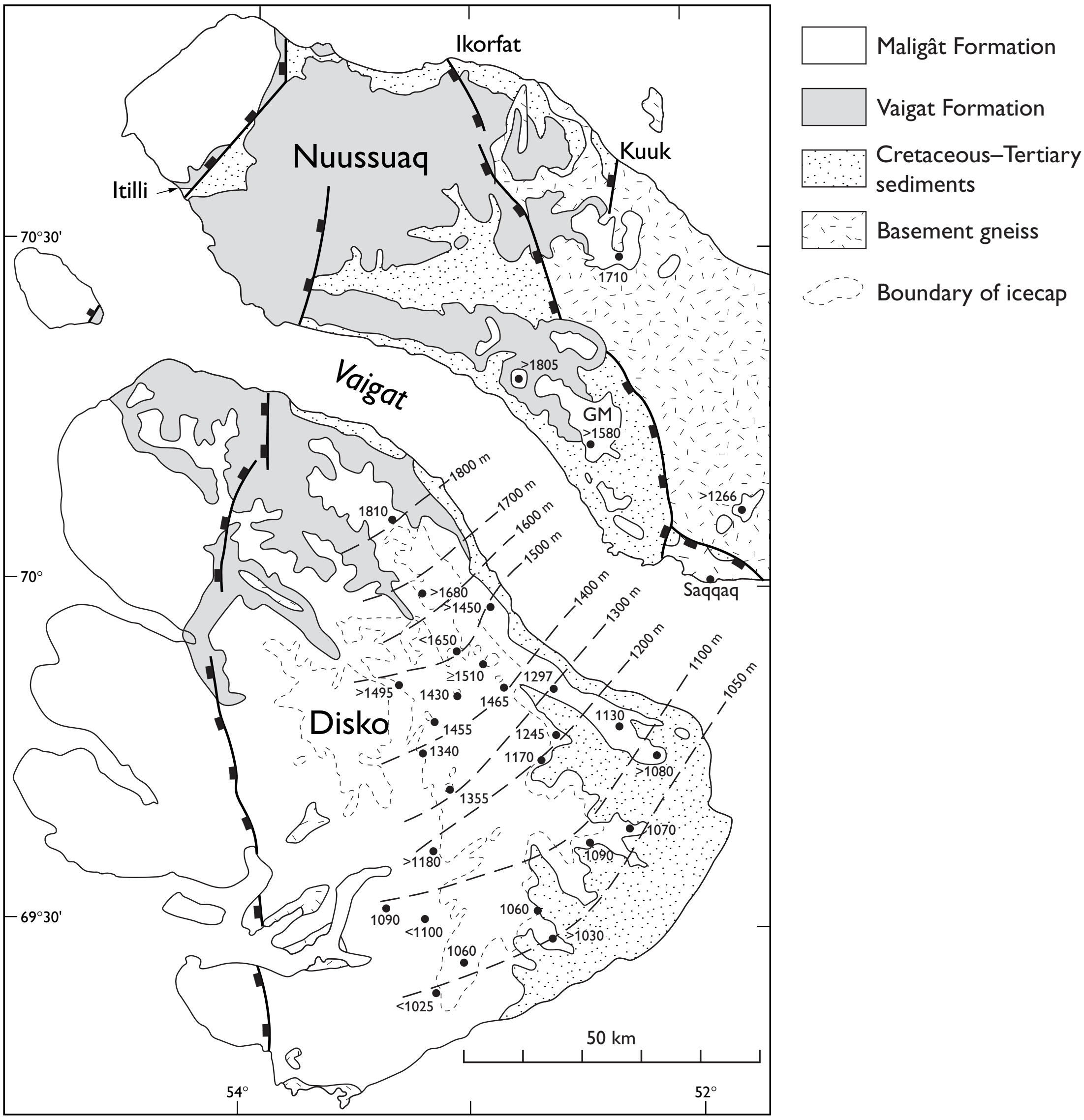


Figure 6-9. *Contours for the base of base of the Niaqussat Member / top of the Nordfjord Member in NE Disko. GM: Gieseckes Monument. From Pulvertaft & Larsen (2002) (slightly modified after Larsen & Pedersen 1992). The inclination of this surface matches the eastern side of the Neogene domal feature interpreted along southern Nuussuaq (Fig. 6-8).*

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Maps

Precambrian geology between Qarajaq Isfjord and Jakobshavn Isfjord, West Greenland, 1:250 000, Grønlands Geologiske Undersøgelse 1994.

Sheet 3 Søndre Strømfjord – Nûgssuaq, Geological map of Greenland 1:500 000, Geological Survey of Greenland 1971.

67 V.1 Nord Agto, Geologisk kort over Grønland 1:100 000, Grønlands Geologiske Undersøgelse 1984.

67 V.2 Nord Ussuit, Geologisk kort over Grønland 1:100 000, Grønlands Geologiske Undersøgelse in prep.

69 V.1 Nord Mellemfjord, Geologisk kort over Grønland 1:100 000, Grønlands Geologiske Undersøgelse 1984.

69 V.1 Syd Uiffaq, Geologisk kort over Grønland 1:100 000, Grønlands Geologiske Undersøgelse 2000.

69 V.3 Nord Ataa, Geologisk kort over Grønland 1:100 000, Grønlands Geologiske Undersøgelse 1995.

70 V.1 Nord Agatdal, Geologisk kort over Grønland 1:100 000, Grønlands Geologiske Undersøgelse 1974.

Appendix: Photos

Figure A-1. *Location map for photos in Appendix.*

Figure A-2. *The undulating relief at Angujartorfiup Nuna, east of Sukkertoppen Iskappe (GEUS photo jbw2002c14 and jbw2002c15).*

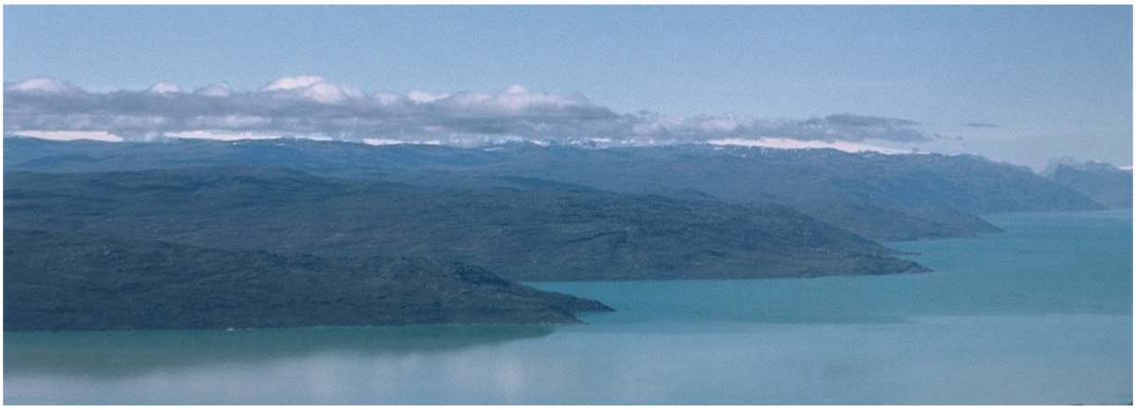

Figure A-3. *The Kangerlussuaq cut through the high Sukkertoppen Mountains (GEUS photo jbw2002c28).*

Figure A-4. *The landscape between Kangerlussuaq and Sisimiut is drumlinised with many lakes and wet bogs (GEUS photo jbw2002c29).*

Figure A-5. *A well-preserved summit level at ~800 m a.s.l. east of Sisimiut is cut by deep, U-shaped fjord valleys (GEUS photo jbw2002c42).*

Figure A-6. *The coastal platform, cut in gneiss, is of Strandflaten type. The escarpment is 600 m high and the summits of the Palaeic relief in the background reaches 700 to 1000 m a.s.l. (GEUS photo jbw2002c55).*

Figure A-7. *Hilly relief topography characterises the area between Nassuttooq and Aasiat. The summit level can only be identified as small remnants of the highest hills (GEUS photo jbw2002c63).*

Figure A-8. *Detailed view of the hilly relief along the coast at Inugsuk, NW of Nassuttooq (GEUS photo jbw2002c64).*

Figure A-9. *The summit level is continuous towards the north. Photograph from Iterlak overlooking Nassuttooq (GEUS photo jbw2002c83).*

Figure A-10. *Hills and basins are clearly structurally controlled. Photograph at Inugsuk, NW of Nassuttooq (GEUS photo jbw2002c123).*

Figure A-11. *Nassuttooq is situated in the border area between the well-preserved summits and the hilly relief (GEUS photo jbw2002c132).*

Figure A-12. *The flat summit surface at Iterlak, S of Nassuttooq (700 m a.s.l.) continue towards the south (GEUS photo jbw2002c151).*

Figure A-13. *The Sukkertoppen Iskappe is resting on a high (>1200 m a.s.l.) undulating plain (GEUS photo jbw2002c155).*

Figure A-14. *A great escarpment is present on the western side of Sukkertoppen Mountains. The Strandflaten is a few kilometres wide (GEUS photo jbw2002c193).*

Figure A-15. *Undulating hilly relief in gneiss is exhumed from on overlying Palaeogene basalt on Disko (GEUS photo jbw2002c217).*

Figure A-16. *Large clefts (N-S) with weathered joints and tor-like pillars at Fortunebay, Disko (GEUS photo jbw2002c223).*

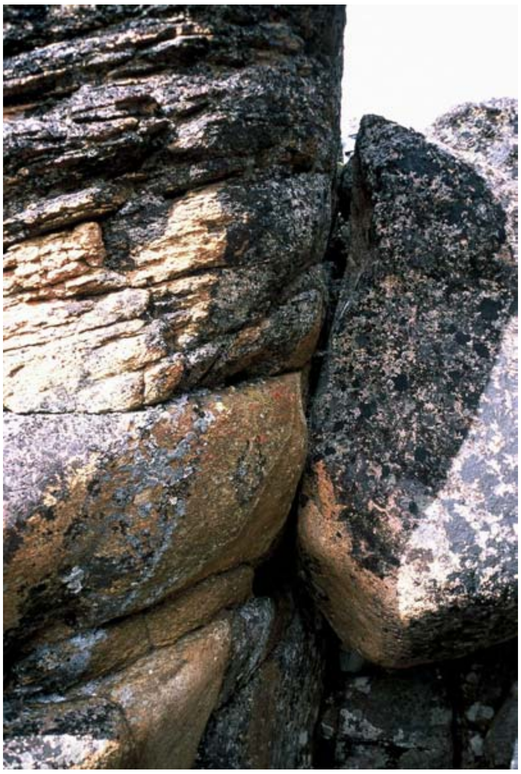

Figure A-17. *Rounded weathered joints and development of corestones, at Fortunebay, Disko (GEUS photo jbw2002c224).*

Figure A-18. *Weathering pits in a vertical wall in one of the clefts, Fortunebay, Disko. In one of the pits sand was encountered (GEUS photo jbw2002c226).*

Figure A-19. *Basalt/gneiss primary contact at Fortunebay, Disko (GEUS photo jbw2002c229).*

Figure A-20. *Deeply weather gneiss in direct contact with basalt. The gneiss-hill to the left is fresh. Fortunebay, Disko (GEUS photo jbw2002c231).*

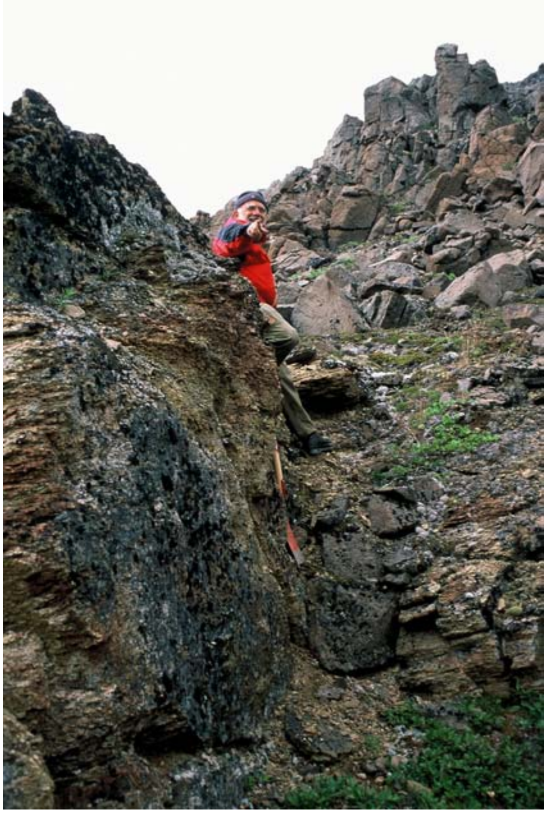

Figure A-21. *The saprolite (weathered material) is 2.5 m thick, Fortunebay, Disko (GEUS photo jbw2002c235).*

Figure A-22. *Gneiss corestones stripped from saprolite in the basalt/gneiss contact, Fortunebay, Disko (GEUS photo jbw2002c237).*

Figure A-23. *Hilly relief in gneiss with a relative relief of about 100 m, Fortunebay, Disko (GEUS photo jbw2002c239).*

Figure A-24. *Saprolite sample site (sample no4791-29, t. samples) at Fortunebay, Disko (GEUS photo jbw2002c244).*

Figure A-25. *Roche moutonnées along Kangerluk, Disko. Ice-movement is towards the left. The sheet slabs structurally control the development of the roche moutonnées (GEUS photo jbw2002c292).*

Figure A-26. *Hilly relief with a relative relief of 200 m has been exhumed from a basalt cover of Palaeocene age at Kanaa, Diskofjord (GEUS photo jbw2002c299).*

Figure A-27. *The exhumed hilly relief has to different degrees been reshaped by glacial erosion along Kannaa, Diskofjord (GEUS photo jbw2002c302).*

Figure A-28. *A great escarpment above 1100 m a.s.l. follows along the Itilli valley, NW Nuussuaq (GEUS photo jbw2002c312).*

Figure A-29. *The steeply NW dipping basalt layers on NW Nuussuaq (GEUS photo jbw2002c313).*

Figure A-30. *The wide Itilli valley in NW Nuussuaq with an incised V-shaped valley at its bottom (GEUS photo jbw2002c315).*

Figure A-31. *The low sloping coast, on the south coast of W Nuussuaq, west of Itilli valley (GEUS photo jbw2002c324).*

Figure A-32. *A cliff characterises the coast east of Itilli valley, south coast of Nuussuaq (GEUS photo jbw2002c331).*

Figure A-33. *The high undulating plain on NW Nuussuaq. The plain cut across the layering of Eocene basalts (GEUS photo jbw2002c337).*

Figure A-34. *A surface cut across the Cretaceous boundary fault system. The bedrock is gneiss in the foreground and basalt/sandstone is present on the far side of the fault system (GEUS photo jbw2002c351).*

Figure A-35. *A continuous summit level (gneiss) towards the east from Saqqaq (GEUS photo jbw2002c354).*

Figure A-36. *Summit surface of eastern Nuussuaq (gneiss) (GEUS photo jbw2002c363).*

Figure A-37. *The summit surface of eastern Nuussuaq cut across the Cretaceous boundary fault system in the centre of the picture (GEUS photo jbw2002c364).*