DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2006/13

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# Field work summer 2005

Johan M. Bonow, Knud Erik S. Klint & Peter Japsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

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# 1. Summary

Fieldwork in connection with an integrated study of geomorphology and of fracture and fault systems was carried out along the Nordre Isortoq Escarpment in central West Greenland between 1st and 11th of August 2005. The fieldwork was focussed on explaining the pronounced topographical contrast, expressed as an escarpment (*c.* 500 m high), between a low and flat area along the coast and an elevated inland plateau on the top of the escarpment. The main suggestions prior to fieldwork, based on preliminary analysis and previous studies, were that the escarpment was either:

*1) a re-exposed Mesozoic-Paleocene fault scarp.*
This hypothesis would imply that the low and flat area was a remnant of a deeply weathered etch surface, equivalent to the etch surface that has been identified in the Disko Bugt area, north of the study area (Bonow 2005; Bonow et al. 2006b). A down-faulting along the escarpment, prior to onset of formation of the planationsurface in the Oligocene, is necessary to explain the preservation of the etch surface at a low position in the landscape. In support for that suggestion is that previous studies have mapped a major fault immediately offshore, west of the study area (e.g. Chalmers & Pulvertaft 2001).

*2) a Plio-Plestocene erosional feature formed after late Neogene uplift events.*
This would imply that the low relief surface is a 'strandflat', developed after late Neogene uplift of the Oligocene-Miocene planation surface that defines the elevated plateau. Such coastal platforms are common features (e.g. Guilcher et al. 1994). The escarpment is thus an erosional feature, but it's ' almost vertical appearance must be explained.

3) *any combination of these suggested features*.

In the field the faults and fractures were systematically mapped in five selected areas, focussing on the major systems in respective area. The geomorphological investigations focussed on five pronounced landscape features: The elevated plateau, the escarpment, the major valleys, the hill complexes and the low relief area.

The observations made during the fieldwork combined with the record of onshore/offshore geology and existing Apatite Fission Track Analysis (AFTA) data have led us to the conclusion that the escarpment is a young erosional feature for the following reasons:

1. Visual inspection showed that no major fault or fault zone was related to the present location of the escarpment.
2. The area in front of the escarpment is flat and the landforms here consist mainly of minor rock basins and low bedrock ridges. Some residual hill complexes also occur. These landforms are typical for a well developed strandflat.
3. The "open" vertical/sub vertical fault and fracture zones perpendicular to each other forms an orthogonal pattern of vertical columns with a preferential block size in the order of approximately 1 x 1 meter and tens of meters high. The fracture zones are

intensely weathered with abundant sandy–gravelly saprolites. This configuration facilitated an erosional mode of the escarpment with block-fall along a steep face.

4. Removal of material from the foot of the escarpment has been efficient due to a combination of processes. Especially important for the maintenance for the steepness of the escarpment has been the glaciers that run parallel to the escarpment

The fault and fracture systems in the study area are related to similar systems observed north of Nordre Isortoq and around Nassutooq (Nordre Strømfjord). These systems have been correlated to late Cretaceous – Palaeocene extension followed by an Eocene sinistral wrench system during the opening of the Labrador Sea (Wilson et al. 2006). The fault and fracture systems in the study area have been reactivated and opened due to late tectonic uplift in the Neogene that led to the formation of the 100 km wide asymmetric domal structure that culminates at *c.* 1500 m a.s.l. 25 km inland of the coast (Bonow et al. 2006b; Japsen et al. 2006). The re-opening of the fracture systems has facilitated migration of water and hence weathering processes. Loading and unloading of ice-sheets during the late Cenozoic have also contributed to further fracture reactivation.

A major fault zone of possibly Late Cretaceous – Paleocene age (Chalmers et al. 1999; Wilson et al. 2006) was identified at Ikatut, a few km south of the inlet to Nassutooq (Nordre Strømfjord). The fault zone is immediately east of a major extensional fault offshore mapped from seismic data (Chalmers et al. 1999). It is suggested that the fault at Ikatut is part of the same complex.

# 2. Background

This report documents the observations made during fieldwork along the coast parallel n south of Nordre Isortoq, West Greenland, from August 1 to 11 2005. The fieldwork was funded by GEUS and the aim of the fieldwork was to investigate fractures and faults, to make geomorphological investigations and to sample rocks for fission track analysis. The data from the detailed investigations of geomorphology and fracture systems made during the fieldwork are presented in this report.

This study is a direct continuation of the fieldwork and studies that were launched in 2002 and 2003. In 2002 the Danish Scientific Research Council (SNF) project “Neogene uplift, erosion and redeposition in West Greenland – identification of pre-glacial landforms and neotectonic activity” made it possible to obtain some basic ideas about the morphotectonic evolution during the Phanerozoic in West Greenland (Japsen et al. 2002). This study was followed up in 2003 by more specific and detailed fieldwork related to a) the GEUS project “Fracture systems in West Greenland” (Wilson et al. 2006.) and b) the PhD project “Palaeosurfaces and Palaeovalleys on the North Atlantic previously glaciated passive margins – reference forms for conclusions on uplift and erosion” (Bonow 2004) and c) the joint BMP-GEUS project “”Neogene uplift, erosion and resedimentation in West Greenland” (Japsen 2004) (BMP: Bureau of Minerals and Petroleum, Nuuk)

The detailed study presented here is thus part of an overall effort towards integration of the results of all studies of geomorphology, geology, fracture systems and apatite fission-track analysis (AFTA) to construct a regional model for the morphotectonic evolution during the Phanerozoic in central West Greenland.

The overall main objective of the fieldwork was to establish a model which can explain the landforms in the study area based on geomorphological analysis and investigation of fractures and faults. The study area along the escarpment south of Nordre Isortoq, West Greenland (Fig. 2–1), was chosen, because it was regarded as a key area for complementary information to previous investigations. Earlier studies had focused on registrations of fractures within the Nuussuaq Basin and along the coast from Sisimiut to Disko Bugt (Japsen et al. 2002), and from the area immediately north and south of Nordre Strømfjord (Wilson et al. 2006; Fig. 2–1). The study area is also situated in an area where previous geomorphological investigations have failed to clarify the age-relation between the apparent ‘hilly relief’ along the coast and the elevated planation surface inland of the escarpment (Bonow et al. 2006b).

The study area is further a key for understanding the structural development of escarpment formation along the coast in central West Greenland, and particularly interesting here is that the study area is immediately east of a major N-S trending offshore fault of assumed Cretaceous-Palaeocene age (Chalmers & Pulvertaft 2001). It was therefore important to investigate the characteristics of the Nordre Isortoq Escarpment in order to determine its relation to the regional event stratigraphic chronology and to determine its origin and age.


*Fig. 2–1. Regional map with the main study area in the south and the Ikatut area in the north.*

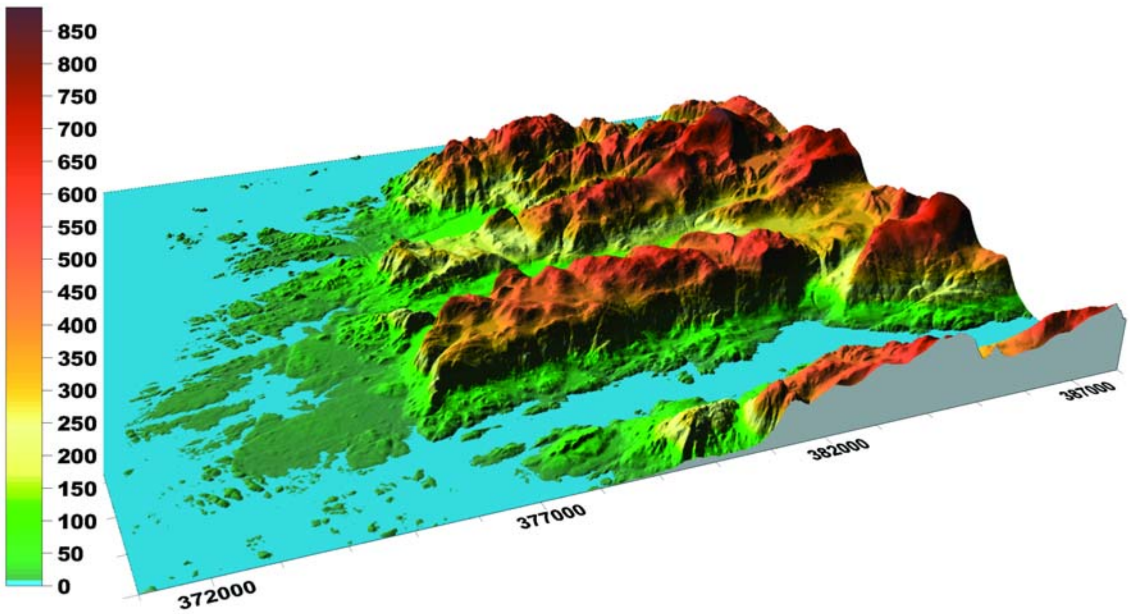



*Fig. 2-2. Overview across the study area with view towards the NNE. The 3D model is based on a grid with 50 m spacing. The escarpment trends N–S, parallel to the coast. Height and distances in metres. Location in fig. 2–1.*

# 3. Morphotectonic and geologic development in West Greenland

Most of West Greenland is part of a denuded Precambrian shield, with mainly Archaean and Proterozoic rocks (Henriksen et al. 2000). The rocks in the Nagssugtoqidian Orogen are predominantly Archaean orthogneisses that were reworked under high grade metamorphism in the Palaeoproterozoic (van Gool et al. 2002). The primary structures are of ductile to semi-ductile nature primarily folded or sheared zones of various types of gneiss. Occasional intrusions of kimberlitic dykes of unknown age occurred in the area. These structures are mainly healed and old fractures and faults have been re-crystallised, while brittle structures such as open faults and fractures are regarded to have formed in a younger shallow, colder and hence more rigid environment. Younger rocks of Mesozoic and Cenozoic age are present offshore, west of the study area and in the Nuussuaq Basin further north (Fig. 3–1).

### 3.1.1 Geology and tectonics in central West Greenland

The region became tectonically unstable during the initial opening of the Labrador Sea and Davis Strait that probably occurred during the Palaeozoic (Chalmers et al. 1999). The fault and fractures occurring north of the field area from Nordre Isortoq to Nordre Strømfjord was thoroughly investigated in 2003 and the primary faults and fractures were correlated to the opening of the Labrador Sea – Davis Strait during the Early Cretaceous to Eocene (Wilson et al. 2006). Sedimentary rift basins started to form west of West Greenland and developed during the Mesozoic and Cenozoic with maximum total sediment thicknesses of around 10 km (Chalmers et al. 1999; Chalmers & Pulvertaft, 2001). A continental margin developed in the Paleocene when seafloor spreading took place in Baffin Bay and the Labrador Sea, and a major strike-slip fault system developed in Davis Strait (Chalmers & Pulvertaft, 2001). The impact of the Iceland Plume is recorded in Cretaceous–Paleocene succession in the Nuussuaq Basin. Here extensive erosion together with development and reactivation of faults took place in latest Cretaceous times followed by uplift and incision of valley systems in the Cretaceous rocks during the early Paleocene (e.g. Dam et al. 1998). The valleys were subsequently drowned and filled with marine Paleocene sediments prior to eruption of thick sub-aqueous basalt, which extruded over large parts of the Nuussuaq Basin later in the Paleocene (Pedersen et al. 2002). Volcanism and subsidence continued until the Eocene (Storey et al. 1998). Offshore West Greenland, Cenozoic sediments reach thicknesses of more than 4 km (Rolle, 1985; Nøhr-Hansen, 2003; Piasecki, 2003). A mid–Eocene unconformity probably marks the end of major fault movements and can be correlated to slowing rates of sea-floor spreading in the Labrador Sea (Chalmers, 2000; Dalhoff et al. 2003).

Uplift of the Nuussuaq Basin in the Neogene has been concluded from the fission track record acquired from the 3 km deep, hydrocarbon exploration well GRO#3 (Mathiesen, 1998; Japsen et al. 2005; Fig. 3–1). The fission track record shows three distinct episodes of cooling that began between 40 and 30 Ma, 11 and 10 Ma and 7 and 2 Ma (Japsen et al. 2005). The two latter episodes included exhumation of rocks and were interpreted as uplift events. They are in agreement with the observations offshore by Chalmers (2000), who found that a >3km thick, post-mid-Eocene, seaward dipping section is truncated by an erosional unconformity close to sea bed west of Nuussuaq, and concluded it had formed substantially after the mid-Eocene and probably during the Neogene. These studies suggest uplift and erosion offshore as well as on the landmass on Nuussuaq during the Neogene. Similar Neogne uplift events are inferred to have occurred south of Disko Bugt based on correlation between regionally developed palaeosurfaces (Bonow et al. 2006a, b).

### 3.1.2 Erosion surfaces in the Precambrian basement

Vast areas of West Greenland are characterised by upland plateaus of low relief, named *planation surfaces*. These plateaus have been interpreted to represent base level governed erosion surfaces, formed prior to uplift events in the Neogene (e.g. Bonow 2004; Bonow et al. 2006a, b; Japsen et al. 2006). Older Mesozoic erosion surfaces have also been identified at mainly low elevations, and have been labelled *etch surfaces* (Bonow 2005; Bonow et al. 2006a, b). These erosion surfaces in Precambrian basement rocks in West Greenland have distinct characteristics, which are closely connected to the relationship between cover rocks of different age. This connection has turned out to be of importance to understand the tectonic development in West Greenland during the Phanerozoic, especially the tectonic development after the cessation of volcanism in the Eocene (Bonow 2004).

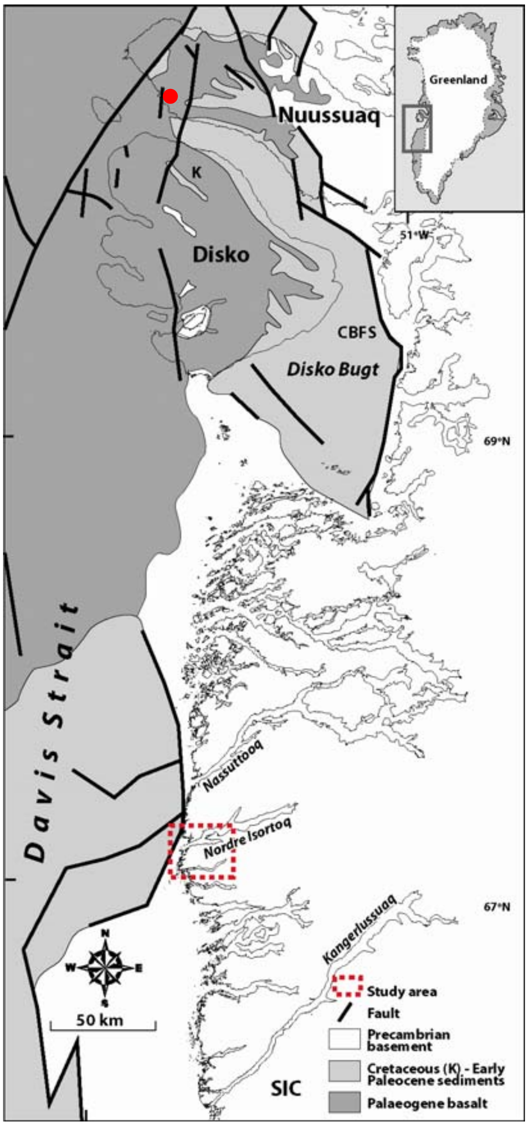



*Fig. 3–1. Precambrian basement and cover rock in West Greenland. Note that the sedimentary Nuussuaq Basin is bounded in the east by a regional fault system and that the major fault is located immediately west of the study area. Red dot - Gro#3-well. SIC - Sukkertoppen Ice Cap. After Bonow (2004).*

Etch surfaces in West Greenland have been formed by deep weathering in the warm and humid Mesozoic- early Cenozoic. The weathering products of the Precambrian basement, the saprolites, are occasionally preserved *in situ* at the weathering front. The weathered surface was covered by Cretaceous sediments and/or Palaeocene basalts and the cover rocks thus constrain the minimum age for this erosion surface (Fig. 3–2).

*Fig. 3-2. The exposed weathering front at Fortunebay, Disko. The fresh gneiss shows characteristic rounded weathering forms. The sandy/gravelly material is the saprolite, and it often retains the original appearance of the gneiss structure. The dark basalt of Palaeocene age is partly covering the weathering front, and confirms the minimum age for the gneiss forms. The gneiss section is c. 1.5 m high.*

The major shape of the etch surface is characterised by an undulating topography with distinct hills or hill complexes rising 100 m above its surroundings (Fig. 3–3). In general bedrock structures become enhanced by weathering and etch surfaces are often severely affected due to the climate conditions in which they are primarily formed. This gives the etch surfaces their distinct topographical shape (Fig. 3–4). Such etch surfaces has been identified, apart from Disko, also on Nuussuaq (Pulvertaft 1979), below sea level in Disko Bugt (Bonow 2005) and south of Disko Bugt (Bonow et al. 2006b).

*Fig. 3–3. The partly stripped etch surface on southern Disko consists of distinct hills in Precambrian basement (background), forming a 'hilly relief', which recently have been re-exposed from the Palaeogene basalt that can be seen in the foreground. Photograph across Fortunebay and Disko Bugt towards the south.*

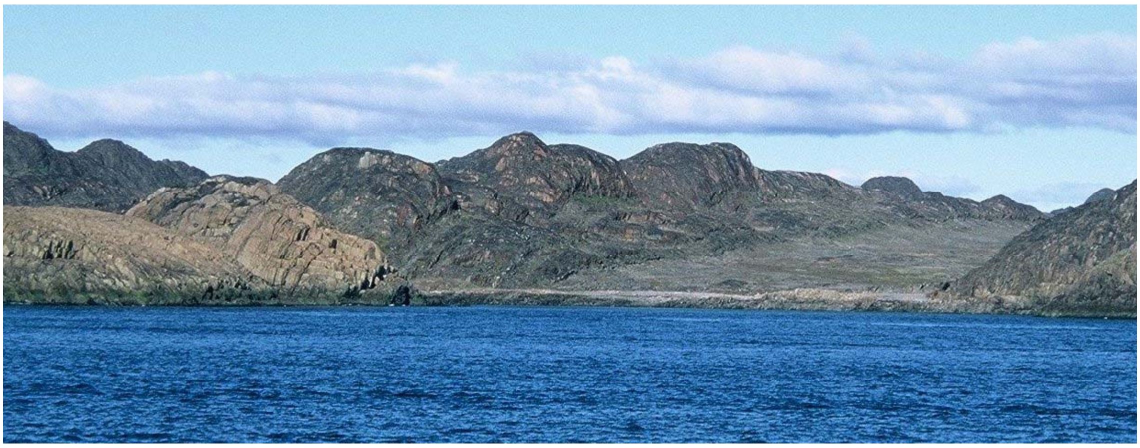


*Fig. 3–4. The stripped etch surface close to Ikatut, a few kilometres north of Nassuttooq (Nordre Strømfjord). Removal of all cover rocks due to late uplift has re-exposed the Precambrian basement, which appearance is the characteristic 'hilly relief'. Total stripping of cover rocks occurs almost exclusively in formerly glaciated areas.*

The basement exposed away from the areas with cover rocks are on the contrary characterised by flat surfaces with limited relative relief (the planation surfaces) (Figs 3–5; 3–6; 3–7; 3–8). These surfaces make up the summits of crustal blocks and are tilted in various directions (e.g. Bonow et al. 2006a, b). They have occasionally been dissected by valley systems, especially in areas where they are highly elevated.

On Nuussuaq the planation surface rises from 500 m a.s.l. in the east to 2000 m a.s.l. in central Nuussuaq, cutting across the Eocene basalt. This relation shows that the erosion surface developed after the basalt flows ended. The basalts on Disko are also planated (Fig. 3–8). Because the planation surfaces can be correlated and mapped regionally from Nuussuaq to Sukkertoppen Ice Cap, this age can also be suggested in these areas where no cover rocks are preserved. In the area south of Disko the planation surface cuts off the etch surface which is more inclined emerging form the Disko Bugt, and this also confirms the planation surface age to the Cenozoic (Bonow 2004, Bonow et al. 2006a, b).

Originally planation surfaces must have formed sub-horizontally, because the tilt will cause rivers to incise and the relief to rejuvenate subsequently eroding a new surface down to the base level. Consequently, formation of such regionally developed surfaces must have occurred close to base level. Thus they cannot form as tilted plains and their present high position and tilt indicate that the have been tectonically uplifted during a late stage. The planation surfaces in West Greenland are thus under destruction.

*Fig. 3–5. The planation surface south of the Sukkertoppen Ice Cap. The planation surface has been slightly dissected by valley systems. Detail from oblique aerial photograph 507B-S-51, 1948. Photo towards the SSW. © Kort & Matrikelstyrelsen, Denmark.*

*Fig. 3–6. The planation surface at Nassuttooq (Nordre Strømfjord) forms a consistent line along the horizon at c. 600 m a.s.l.. Photo towards the north.*

*Fig. 3–7. The planation surface at Arveprinsens Ejland (c. 700 m a.s.l.). Photo towards the south–east, taken 6 km east of Saqaq, Nuussuaq.*

*Fig. 3–8. The planation surface at Disko (background) (c. 1000 m a.s.l.). Photo towards the south–west, taken 6 km east of Saqaq, Nuussuaq.*

# 4. Geomorphological observations

The study area is located on lowlands at Kangarssuk, approximately 20 km north of the town Sisimiut (Figs 2–1; 3–1; 4–1). The low relief coastal platform, the escarpment and the planation surface at high elevation along the coast have earlier been identified in an overview study, but as previously mentioned the age relationship between the landforms south of Nassuttooq – including the study area – is unclear (Bonow et al. 2006b).

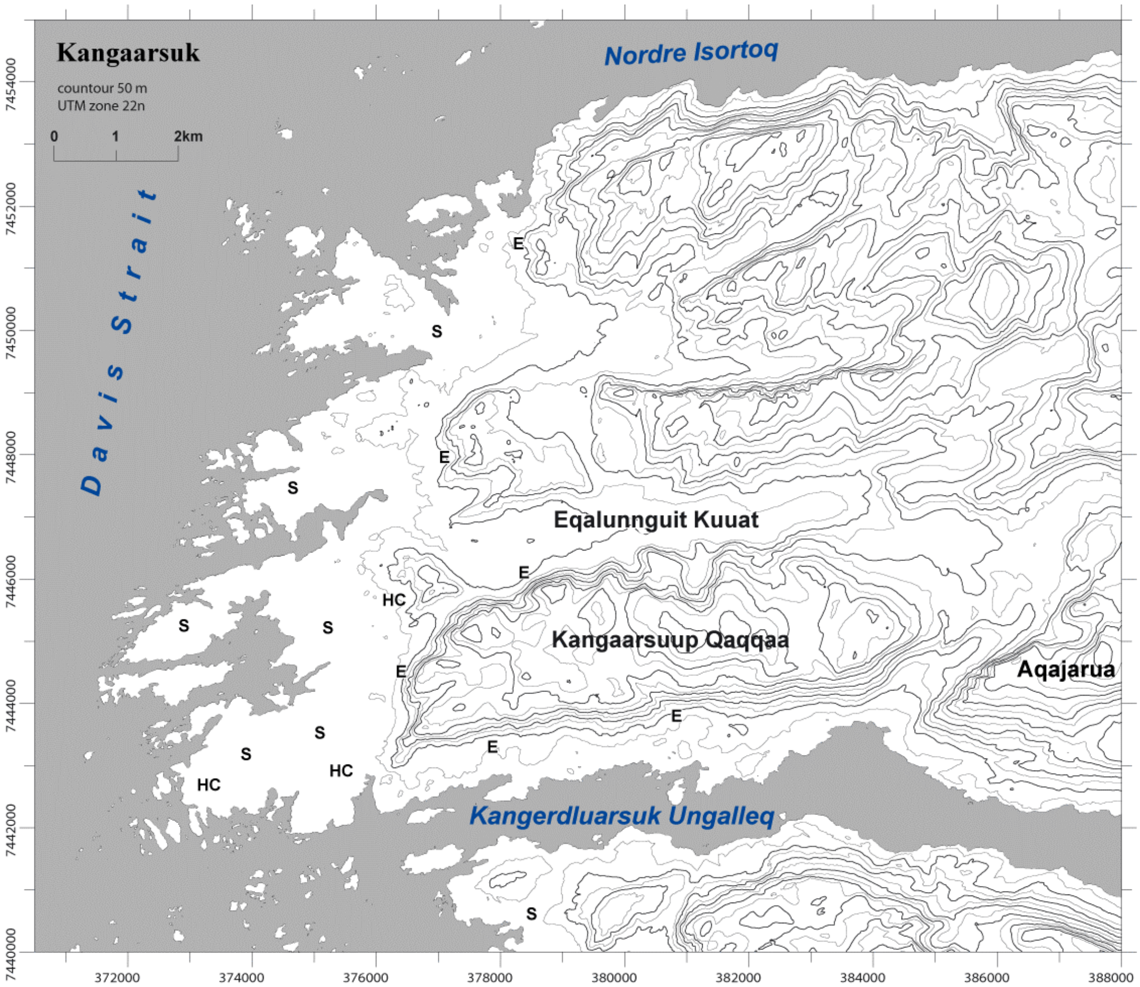



*Fig. 4–1. Map illustrating the main landforms in the study area with its major landform types. The highly elevated plateau and the valleys are clearly seen. S – Strandflat, HC- Hill complex, E – Escarpment. For location see fig 2–1 and 3–1.*

Low relief areas along the coasts of the northern North Atlantic are common features (e.g. Guilcher et al. 1994). The term ”strandflat” was introduced by Reusch (1894), refereeing to the coastal platform and islands in Norway characterised by low relief, uneven topography, partly submerged and with unknown or complex origin. Reusch identified the strandflat along the Norwegian coasts and islands. It has been suggested that the Norwegian strandflat includes both re-exposed sub-Cretaceous relief and younger forms (Peulvast 1988, Holtedahl 1998).

## 4.1 Aim, questions and methods

Two different relief types occur in the area, separated by an escarpment, namely a low-lying area with hills in the west and a planation surface at high elevation (above 600 m a.s.l.) in the east. The relative age of these two major landscape types could be established north of the study area. Here the hilly relief was found to be of etch character with an origin in deep weathering during the late Mesozoic-Palaeocene (Bonow 2005), while the planation surface was found to be younger and of Cenozoic age because the etch surface is cut off by the less inclined planation surface (Bonow et al. 2006b). In the study area, the low-lying area cuts off the planation surface and this thus suggests that the age relationship is the other way round.

Why is there a fundamental difference regarding the topography between the study area and the area north of Nassuttooq and which is the relationship between the two landform types? Three possible explanations have been identified:

1. The low-relief surface west of the escarpment is an etch-surface, equivalent to the surface on Disko and in the Lersletten area. This explanation requires a down-through of the hilly relief surface along the escarpment prior to the formation of the planated relief and thus to preservation of the etch surface by Cenozoic cover rocks. This would have preserved the etch surface until re-exposure by late Neogene uplift and implies that the escarpment reflects a tectonic fault.
2. The low-relief surface is a so-called “Strandflat” developed during the Plio-Pleistocene by backward erosion from the coast, and thus younger than the planation surface. The hills identified on this surface are thus young, but have similar characteristics as the etch-surface farther north. No fault along the escarpment is required to explain the present topography, but a major fault must be present offshore, because the Precambrian basement is found 3 km below sea level immediately west of the present coastline according to interpretation of seismic data (Chalmers 2000).
3. The low relief area is a complex landform with inherited sub-Cretaceous/sub-Palaeocene landforms, glacial forms and landforms developed by “strandflat” processes. The escarpment may partly be formed by a fault, and partly by backward erosion.

The detailed geomorphological investigations are based on field documentation (photographs, samples of weathered rock), inventory (clefts, weathering forms) and interpretation of landforms (aerial photographs, detailed digital terrain model).

A new detailed digital terrain model covering the study area was constructed as part of this project together with Hans F. Jepsen, GEUS. The model is based on high precision, digitised black/white aerial photographs at the scale 1:40.000 (see appendix for details). The landforms were described and analysed by aid of the digital terrain model.

## 4.2 General description of landforms

The area has five main landscape types (Fig. 4–2):

1) the high plateau, with minimum elevations from *c.* 650 m above sea level (a.s.l.),
2) the north-south trending escarpment, *c.* 500 m high,
3) the dominating east-west valleys,
4) the extensive, low-relief coastal platform,
5) the hill complexes on the coastal platform.

There are also minor landscapes forms overprinting the large-scale landforms such as weathering mantles (saprolites) and roche moutonées. The main landscape types were investigated in detail.

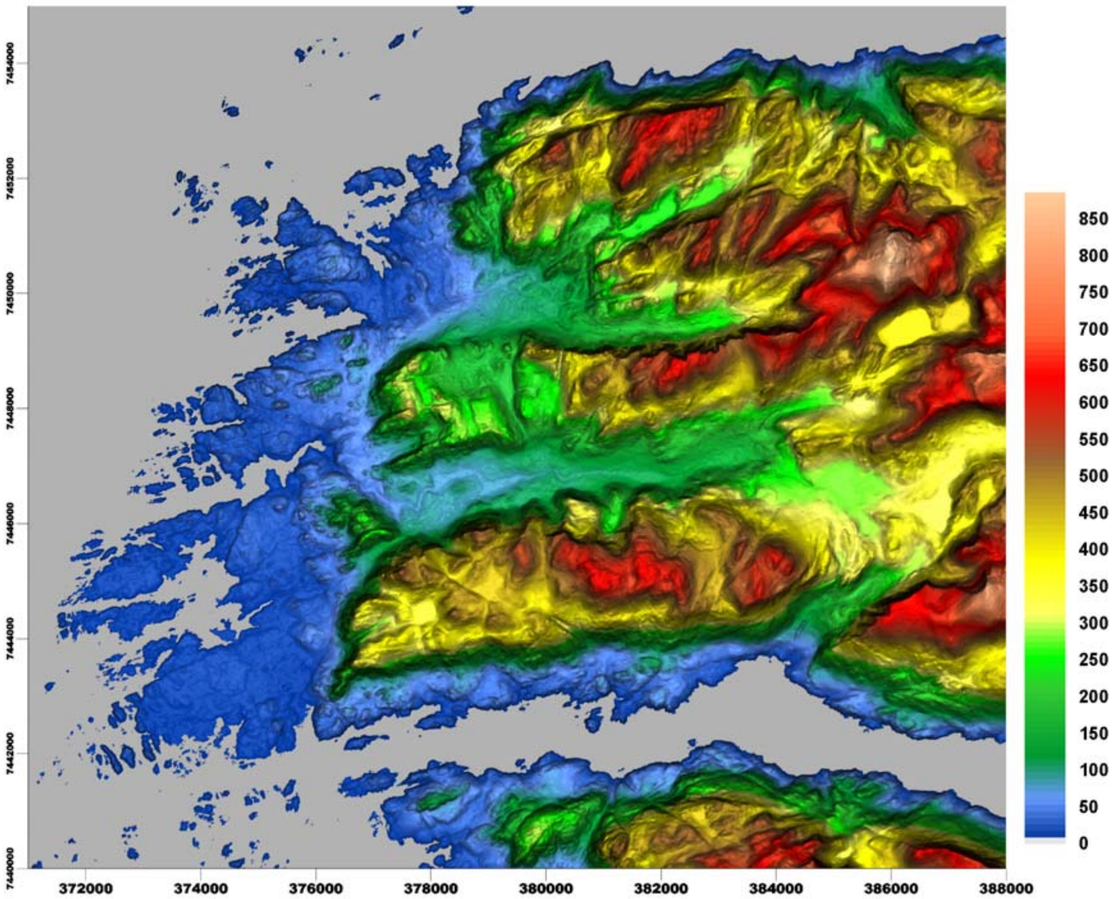



*Fig. 4–2. 3D model with topography combined with vertical shading over the study area. The vertical shading enhances the slopes. The major landforms and bedrock structures can clearly be seen. The escarpment (mainly green) separates the low relief coastal plain (blue) from the elevated plateau (yellow-brown-red), but also along the fjords. Coherent areas consisting to the planation surface can only be identified in the east (light brown-pink). Note the numerous hills both on the coastal plain and along the fjord valleys.*

### 4.2.1 The elevated plateau

The elevated eastern part of the study area is dominated by a well defined undulating plateau with low relative relief. It is part of a planation surface of regional importance that has been mapped in an overview study in central West Greenland (Bonow 2004). In the study area the planation surface is bordered by an escarpment in the west, the Kangerdlurssuk ungatdleq fjord in the south and Nordre Isortoq fjord in the north and towards the escarpment it is cut by valleys; e.g. Eqalunnguit Kuuat (Fig. 4–1). The plateau is tilted with increasing elevation towards the east. In the east it is well preserved while close to the escarpment the plateau is generally obliterated. Here, only the highest summits reach the plateau level, but no coherent surface is preserved here (Fig. 4–3). The rock surface is overprinted by medium-scale glacial erosional forms, but glacial indicators such as striae and chattermarks are lacking. Instead much of the rock is heavily weathered and has been decomposed to a thick gravelly saprolite, occasionally up to 1 m thick. This weathering has destroyed the glacial surface (Fig. 4–3).

*Fig. 4–3. Panorama view looking NW-N-E (left to right) from on top of the escarpment at c. 500 m a.s.l.. To the left, the dissected planation surface ends with the N-S trending escarpment (arrow). In the central part of the photo, a small lake lies in the bottom of a former glacial cirque. This shows that glacial erosion has locally contributed significantly in destroying the planation surface. To the right is the Kangerluarsuk Ungalleq fjord, which is deeply incised in the well preserved planation surface that stretches out toward the east and is seen as line in the horizon.*

### 4.2.2 The escarpment

In general the escarpment is well defined and can be followed north-south across the study area (Figs 4–1; 4–2; 4–4) and along the fjords, but it is also a regional feature, which can be followed along most of West Greenland’s coast. In the study area the escarpment wall rises 400 to 500 m above its foot. The upper part of the escarpment wall is almost vertical, guided by vertical joints, and it ends abruptly with a sharp knick-point, as the planation plateau extends inland.

Typical forms along the rock wall are rock pillars as well as more or less detached boulders (Fig. 4–5). Well-rounded forms occur along horizontal and vertical joints and fractures (Fig. 4–6). Weathering has penetrated along the vertical joints, but in detail the escarpment wall consists of a mix of fresh and deeply decomposed rocks. The weathering is of gravelly type, with a rusty, red-orange colour. Occasionally the weathering occurs in pockets, which are almost totally surrounded by fresh, unweathered rock (Fig. 4–5).

*Fig. 4–4. The Nordre Isortoq Escarpment from the west. The almost vertical cliff wall rises 400-500 m above its foot. A knick-point separates the top of the escarpment from the low relief plateau that extends inland towards the east (see fig. 4–3).*

*Fig. 4–5. Typical rock pillar with rounded weathered forms at the escarpment wall. The weathering has clearly penetrated along fractures. Note the pocket with deeply weathered rock (arrow) beneath the large block of fresh rock.*

*Fig. 4–6. Gravelly weathering with spherodial weathering-forms along fractures and joints at the escarpment wall. The contact between fresh and weathered rock is sharp.*

Thick talus has formed at the foot of the escarpment as a result of rock-fall of large boulders, detached from the vertical joints (Fig. 4–7). The boulders are generally formed as square-blocks with well defined sides, but their corners are most often well rounded. Spheroidial weathering has affected some of these boulders, whereas the outer layer is totally decomposed, its core consists of fresh rock (Fig. 4–8). In this area some of the wider joints have been stripped from weathering products by running water. No large faults could be observed here (see also chapter 5).

*Fig. 4–7. The southern part of the escarpment towards the south. Rock falls have generated a thick talus slope.*

*Fig. 4–8. Large blocks with spherodial weathering. While the outer part is totally decomposed, the core consists of fresh rock.*

### 4.2.3 The major valleys

*Kangerluarsuk Ungalleq:* The valley is heading from east towards west. It has a somewhat unusual appearance for a fjord valley, as its deep water filled part is flanked by a 500 to 1000 m wide rock platform of low relative relief at about 10-20 m a.s.l. (Fig. 4–9). There is however no doubt that large amount of glacial ice have once been present in the valley, e.g. indicated by a series of large end-moraines far out in the fjord (below the water surface) at the entrance of the valley between Kangaarsuup Qaqqaa and Aqajarua (Fig. 4–1). The platform is best developed on the northern shores of the fjord. The platform ends by a steep E-W escarpment leading up to the high plateau.

*Fig. 4–9. The Kangerluarsuk Ungalleq fjord towards the east. The over-deepened water-filled part of the fjord is bordered by a bedrock platform with hills. In the background remnants of the high plateau can be seen.*

The rock platform along the fjord is characterised by irregular topography. Hill complexes rises 20 to 30 m above a smooth surface, consisting of till, covered by marine and talus material (Fig. 4–9). The hills have been remoulded by overriding ice, which has detached and removed thick sheet slabs. Despite this severe erosion from overriding glaciers, the rock surfaces are irregularly decomposed to a gravelly saprolite, similar in character to those identified on the escarpment.

*Eqalunnguit kuat:* The valley is wide and its bottom is cut more than 300 m below the surrounding plateau. In the outermost parts the valley bottom is covered by up to 50 m thick glacifluvial delta deposits, which can be followed far into the valley. Several terraces mark a successive lowering of a former base level and minor streams partly dissects these deposits. The major stream has probably cut down to the bedrock. The valley sides are mainly bare or are covered only by thin till. Although the valley is mainly glacial in character, the general impression is that severe glacial erosion has not occurred here.

### 4.2.4 The hill complexes

*General shape and size:* Three hill complexes, formed in gneiss, were investigated, two close to the escarpment and one in the south-westernmost part of the study area (Fig. 4–1; 4–10).

*Fig. 4–10. A part of the hill complex at the mouth of Eqalunnguit kuat valley.*

The hills are limited by joints dominantly in 2 directions, viz. NE-SW and NW-SE (Fig. 5–1). The individual hills are up to 50 m high from its foot and rise abruptly from the almost flat surroundings. The hills are up to 200 m in diameter. Most of the hills are asymmetrical and appear slightly rounded. Large sheet slabs have been detached or removed. Their thickness and shape are determined by sub-surface fractures, parallel to the hill surface (Fig. 4–11).

*Weathering:* The rock surface of the hills is mainly fresh, but there is also heavily weathered rock. Across considerable areas the rock has disintegrated to a gravelly saprolite, up to 1 m thick (Fig. 4–12). This type of weathering is neither bounded to any specific part of the hills nor is it obviously connected to any particular rock type prone to weathering.

*Fig. 4–11. One of the hills in the southwestern hill complex, which rises c. 20 m above its surroundings. Large sheetslabs have been detached from the hill and their thickness is controlled by sub-surface fractures, parallel to the hill surface. Gravelly weathering occurs close to the hill crest.*

*Fig. 4–12. Heavily decomposed rock occurs in all kinds of positions in the landscape. Note the sharp contact with unaltered rock.*

*Clefts:* Some of the hills are cut through by clefts, mainly heading east-west. The clefts are up to a few metres wide, 100 m long and up to 10 m deep, and have generally vertical walls. Sediments cover their bottom and the bedrock beneath have not been observed. The upper part of the cleft walls is often rough, while in its lower parts the surface is generally smoother. Occasionally boulders with generally sharp edges are present within the clefts. No signs of glacial activity could be identified within the clefts. (Fig. 4–13), See also Fig. 5–14.

*Fig. 4–13. A 10 m deep cleft divide the hill in two (shown by arrow).*

### 4.2.5 The low-relief area (strandflat)

The topography of the several km wide coastal platform west of the escarpment is characterised by low relief close to the present sea level. The relative relief is generally less than 5 m, apart for the described hill complexes, which rise considerably above the main surface. This surface has thus all the geomorphological attributes for a typical strandflat (Fig. 4–14).

In detail the surface is slightly undulating with small bedrock ridges running east-west and the lower parts occupied by shallow lakes or wet bogs. Areas with gravelly weathering occur commonly in the strandflat area. Along the boundary between the hills and the strandflat, a sediment slope has developed (Fig. 4–15).

*Fig. 4–14. The low-relief strandflat in front of the escarpment. It is characterised by small basins in between low bedrock ridges. The relative relief is less than a few metres. Photograph towards the north.*

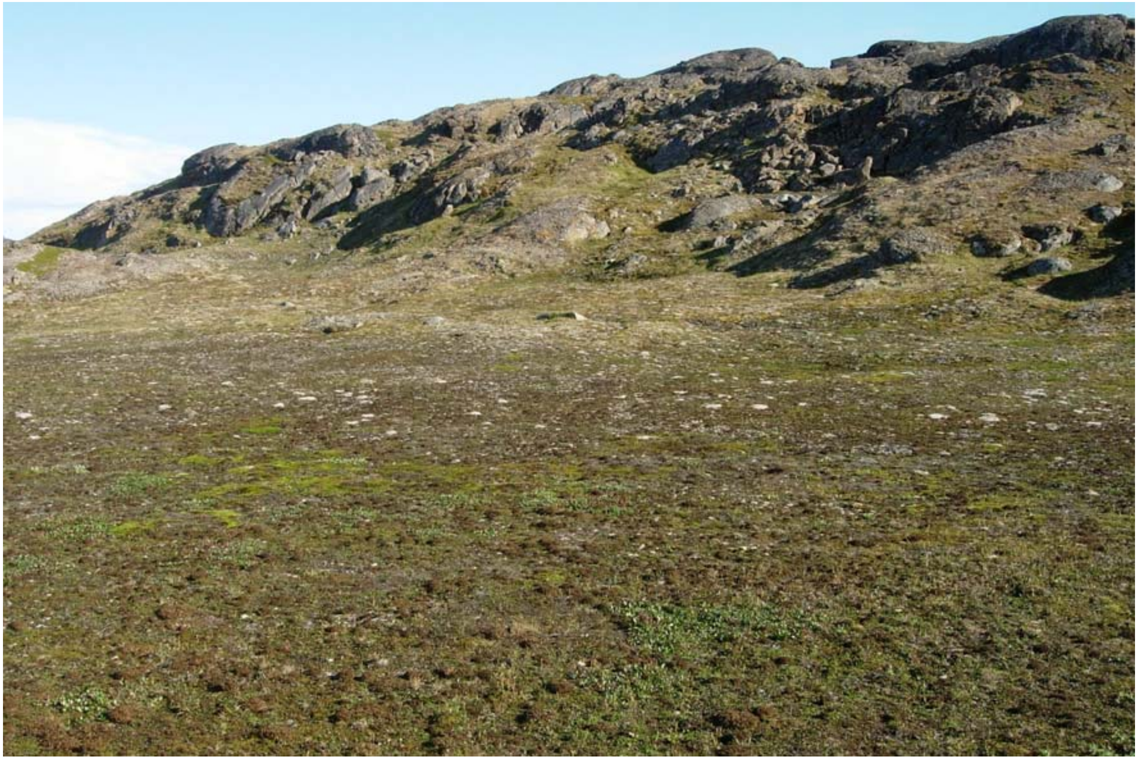


*Fig. 4–15. A sediment slope consisting of weathered material, located at the boundary between a hill complex and the strandflat.*

## 4.3 Summary of geomorphological observations

The most important observations for interpretation of the large-scale landform development within the study area are that:

- the planation surface at high elevation could be identified in the eastern part of the study area. Close to the escarpment the planation surface is obliterated, but the present summits are probably not far below the level for the old planation surface.
- the present position for the escarpment is not along a major fault.
- gravelly weathering has resulted in up to one metre thick saprolites. This weathering has affected both bedrock and boulders at all positions in the landscape.
- the low relief area below the escarpment is characterised by low bedrock ridges, minor rock basins and residual hill complexes, landforms which are typical for a well developed strandflat.

# 5. Fracture and fault characterisation

Uplift of the basement is closely related to fault zones either by formation of new faults or by reactivation of older fault zones. An important part of the fracture/fault analysis of an area is the identification of major lineaments that may constitute such fault zones. Visual inspection of the lineaments may therefore add important information regarding the mode of faulting. Since fault zones constitute weakness zones they are normally deeper eroded than the surrounding area. The faults are accordingly often buried under loose material and poorly exposed. In this case only related fractures in the vicinity may reflect the fault pattern. The measurement of fractures is therefore a key element in deducing the tectonic and erosional history of the area.

## 5.1 Background

Different types of fractures and faults forms in relation to a certain stress field, either as systematic sets of parallel fractures/faults with a distinct orientation, or in some cases as more irregular non systematic fractures with an overall random orientation. Systematic fractures thus forms “families” of fractures with special characteristics that may be related to distinct tectonic processes (Pollard & Aydin 1988; Klint et al. 2004.)

### 5.1.1 Fractures

Fractures include all brittle failures such as joints, fissures, cracks, veins, etc. which are not a fault, bedding or cleavage, and which is 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.

The classification of fractures is primarily based on the orientation of the fractures. Once classified as systematic or non-systematic the fracture properties (density/size distribution) may be calculated for the individual fracture systems, and a more detailed classification related to other characteristics such as fracture shape and size may be included in the classification, by comparison with the characteristics of the different fracture types.

### 5.1.2 Faults

Faults are failures where a distinct displacement has taken place between two slip planes, often with a development of striations on the surface (slickensides). Faults may be classified as either:

- Normal faults (extensional dip slip fault)
- Reverse faults (compressive dip slip fault)
- Thrust faults (low-angle reverse fault)

- Transverse strike-slip faults that may be either dextral (opposite plane move to the right) or sinistral (opposite plan move to the left).
- Oblique faults (Where both strike slip and dip slip occurs). Resultant vector shows net slip.

## 5.2 Methods

During the fieldwork, more than 240 fault and fractures were recorded in five key areas. Abundant structural data were collected for statistical/structural analysis. The work included:

- Characterisation of fault systems in terms of:
    1. –orientation
    2. –kinematics
    3. –fault surface characteristics
    4. –mineralization
- Event stratigraphy – relative ages of deformation phases.
- Structural analyses to determine kinematic patterns, especially mode of deformation such as extension, compression, transtension, transpression, etc.

### 5.2.1 Fracture/fault measurement technique

Fractures were measured along traverses typical along lineaments that were selected from aerial photos. The exact position of each location was recorded on a handhold GPS. The Way Points (WP) obtained were transferred to a map sheet. Generally at least two traverses perpendicular to each other were measured in each selected area in order to collect a representative population of fracture/faults. Each fracture/fault was measured and the following parameters were described:

*Order/System:* The fractures were classified as 1$^{st}$ and 2$^{nd}$ order fractures, with the 1$^{st}$ order fractures as the dominating fractures (in general 10-100 m scale), 2$^{nd}$ order fractures were less dominating fractures often connecting 1$^{st}$ order fractures (in general between 1 and 10 m). The size scale is however relative, and in some cases where the 1$^{st}$ 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 parallel fractures could be recognized in the field it was given a number as system 1 fractures and another set system 2 etc.

*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 was 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, quartz, epidote, or preferential growth of other crystals on the surface showing the slip direction. The direction of the slickensides was measured on fault-surfaces. Special types of fractures such as conjugating shear-fractures, en echelon fractures, plumose jointing etc. were noted if positively identified.

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

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

### 5.2.2 Data analysis

All structures were plotted in a stereographic projection and analysed. Clusters with systems of parallel fractures or faults were grouped as single systems or related systems depending on their other characteristics such as surface texture, shape and mineralization. A interpretation were made for each area and correlation between the different areas revealed which systems were regional distributed and which were of a more local origin.

### 5.2.3 Lineament analysis

Lineaments were deduced from two sources, Aerial photos in 1:40.000 scales and from elevation models. A detailed lineament map was deduced from the aerial photos (Fig. 5–1), while the elevation model revealed the large scale lineaments (Fig. 5–2).

Based on the aerial photos five areas were selected for more detailed investigations (Fig. 5–2). The areas were selected in order to verify all major lineaments represented within the area. Because of the relatively short field campaign focus was directed towards major fractures and fault systems, and not so much towards the calculation of statistical fracture properties (fracture density and size distribution), which demands much more data.

Fracture frequencies were however evaluated on a number of locations by counting fracture trace frequencies or by systematically taking overlapping photos of long exposures. Most of the measurements were accordingly collected along traverses.

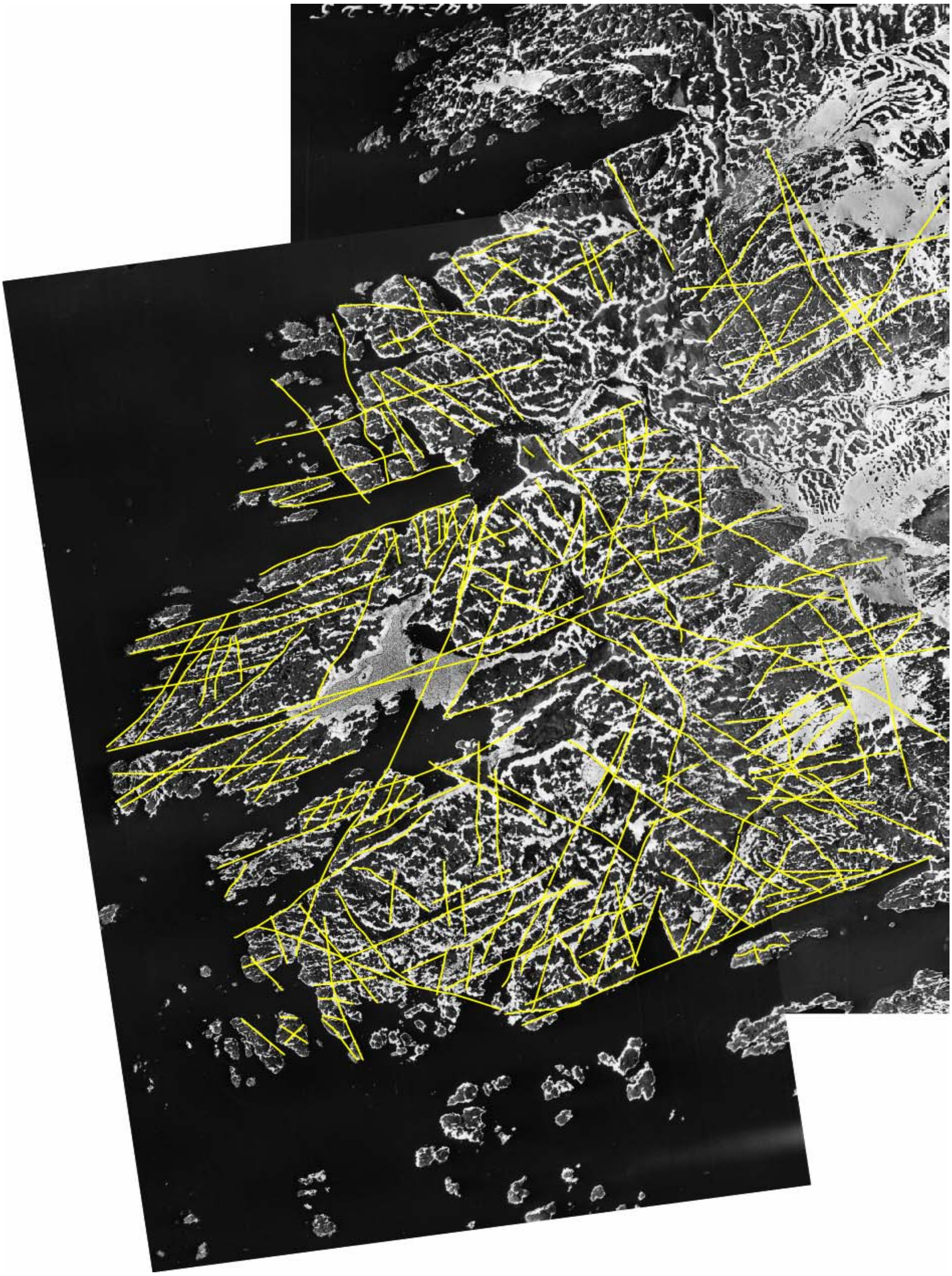


*Fig. 5–1. Aerial photos of the field area with distinct lineaments interpreted in yellow. These photos formed the basic mapping sheet during the field investigations. For location see fig 4–1 and 4–2.*

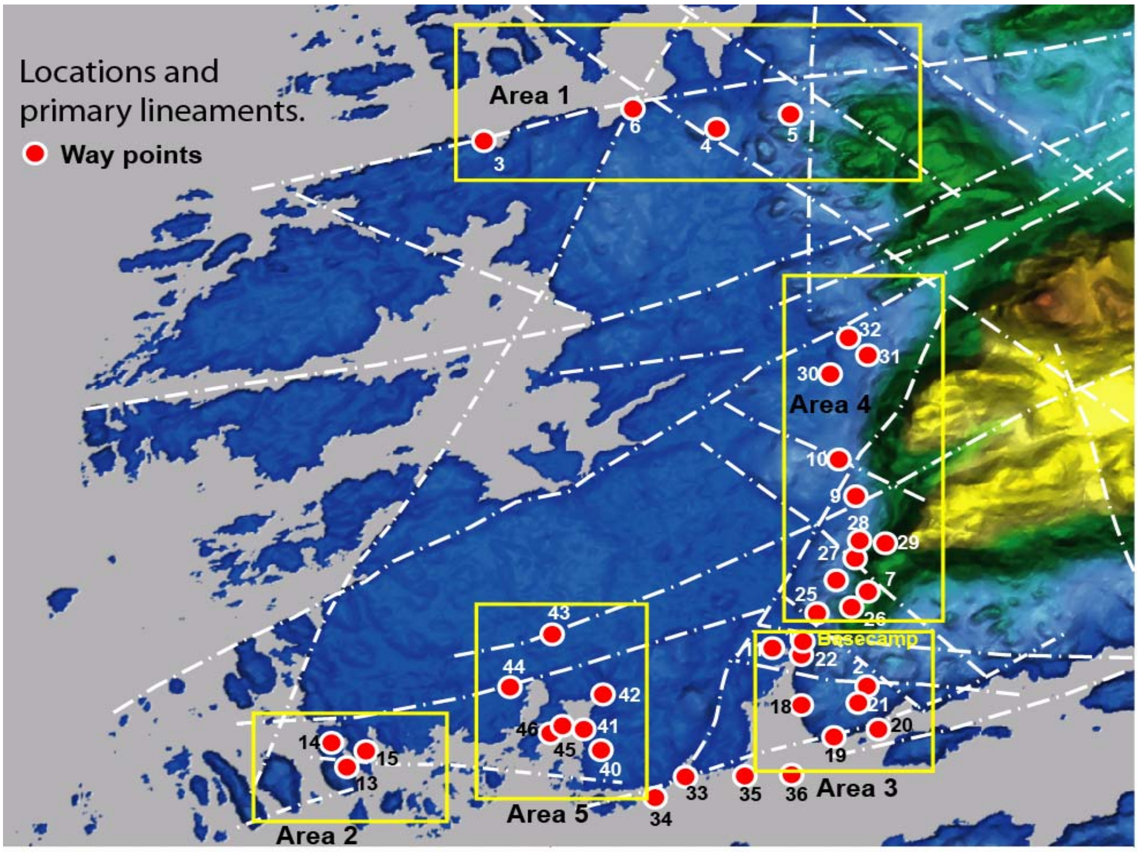



*Fig. 5–2. Locations of waypoints (red circles) referring to distinct observation points and primary areas subjected to more detailed investigations. Major lineaments are furthermore outlined.*

## 5.3 Site descriptions

### 5.3.1 Area 1

Area 1 is situated along the ESE-WNW trending fjord/valley system that truncates the escarpment in the northern part of the area (Fig. 5–2 and 5–5). The transect was laid out to crosscut some of the major lineations in the area, especially the lineament parallel to the fjord and one very dominant lineament striking SW-NE. Only major fractures, crevasses and faults were measured during the traverse. Five fracture/fault systems were deduced from the field investigations.

System 1 is regarded as the youngest fault system in the area. It consists of major sinistral strike slip faults that can be traced more than 6 km through the area. It generally strikes between 10-20° (Fig. 5–3) and truncates all other structures in the area.

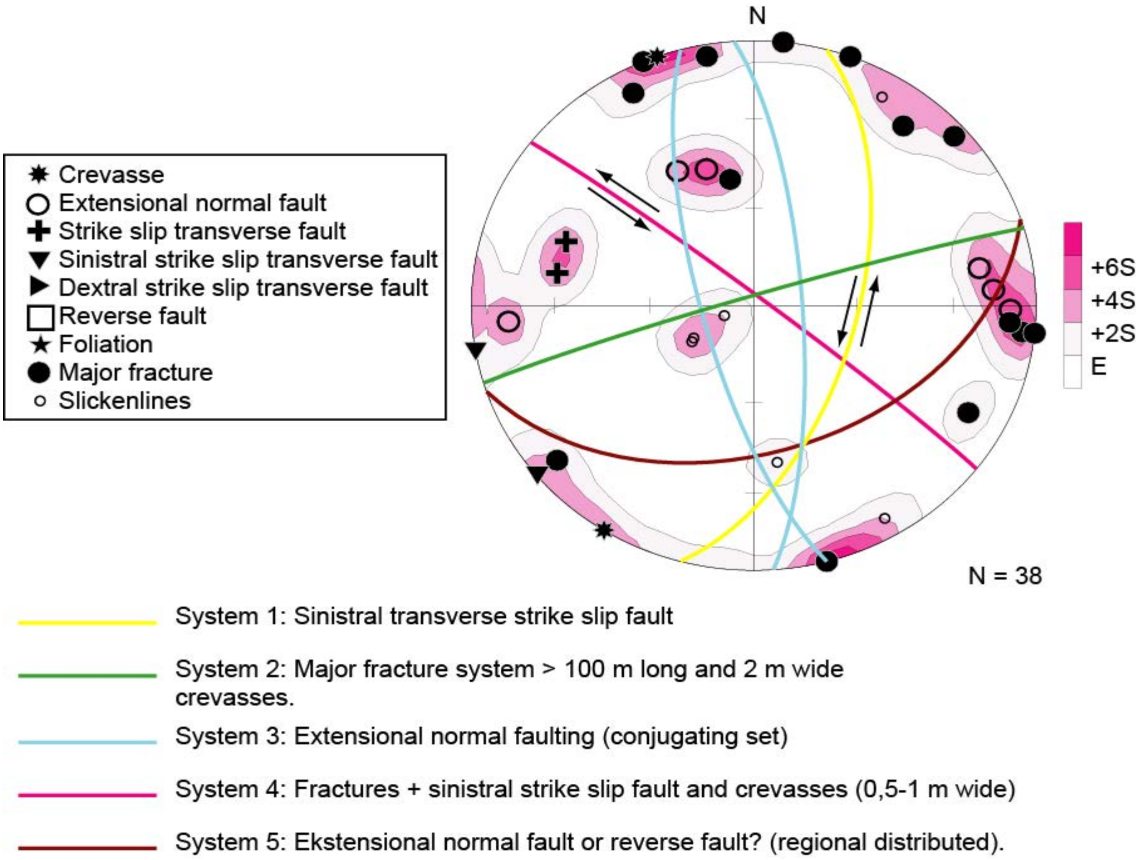



*Fig. 5–3. Fracture and fault data from area 1.*

System 2 consists of a major vertical fracture system striking 70-80° that forms large straight crevasses (Fig. 5–4a). This system is parallel to the major inlets and fjords in the area and outlines some of the largest lineaments within the area.

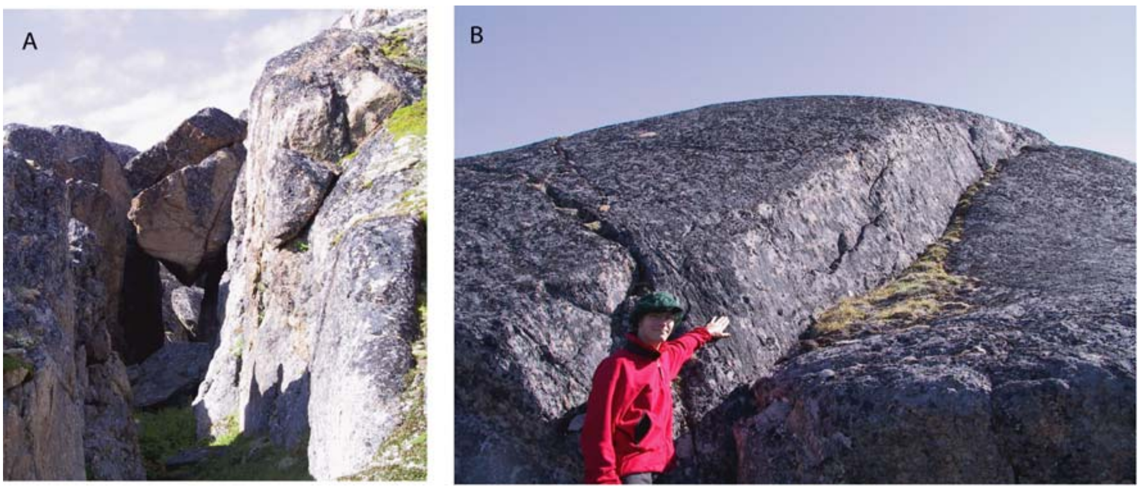



*Fig. 5–4. a) Crevasse in area 1. The width is more than 2 m and the length of the crevasse exceeds 100 m. b) Normal fault truncated by system 2 fracture.*

*Fig. 5–5. View across the E-W trending valley that truncates the escarpment in area 1. Note the "mega step like" geometry that is outlined by fracture system 2 and the smooth wellrounded glacierpolished surface. Glaciers were moving from right to left.*

System 3 consists of a series of extensional normal faults striking almost N-S with a dip of approximately 75$^{o}$ towards west (Fig. 5.4b). The faults are restricted to a narrow zone in the foot hills, and the displacement is generally small (< 1m).

System 4 constitutes both major faults, crevasses and one oblique sinistral transverse fault striking 140°. This fault is part of a regional distributed fault system that correlates to major lineaments that may be traced across the escarpment for several kilometres.

System 5 consists of oblique faults striking ~70° and dipping ~45° SE. The faults have a smooth surface with weakly developed dip slip striations, but it was difficult to establish a direction of the resistance and the faults may be either reverse or normal. This system seems have a regional distribution throughout the area and may accordingly be connected to a regional stress field.

### 5.3.2 Area 2

Area 2 is situated in the westernmost part of the area (Fig. 5–2). A series of very distinct E-W trending lineaments were investigated. Three fracture/fault systems were deduced from the field investigations (Fig. 5–6):

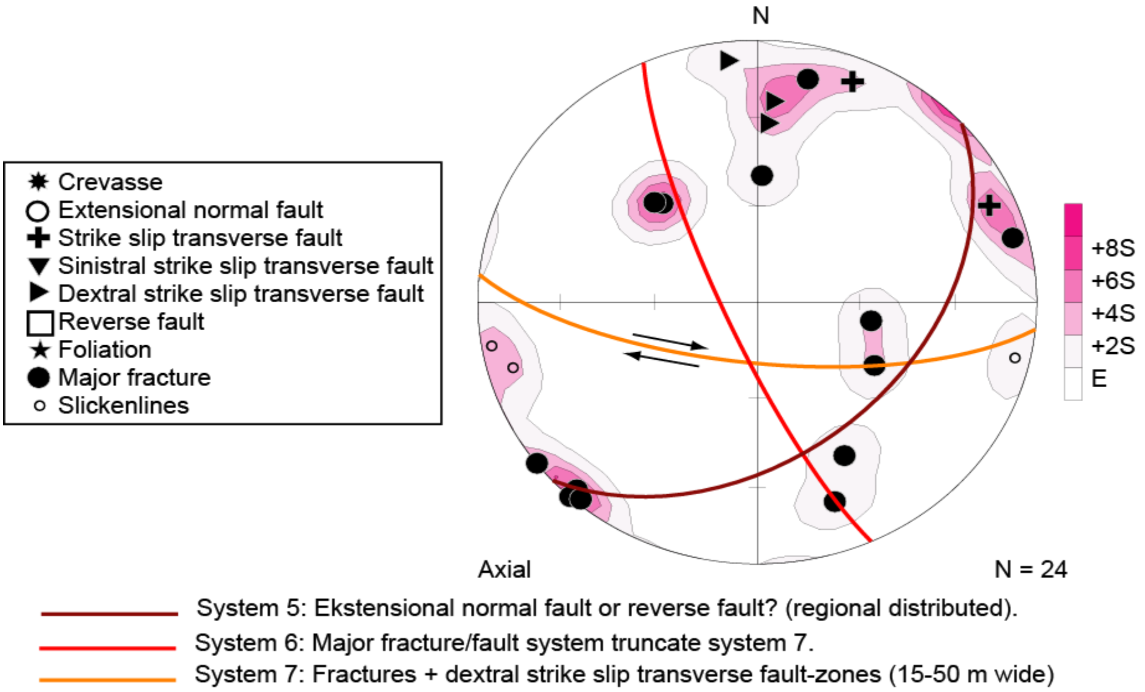



*Fig. 5–6 Fracture and fault data from area 2.*

System 5: One system of major planar fracture planes striking ~45° and dipping 45°SE appears on several places within area 2. This fracture system corresponds well to the system 5 fracture/fault system recorded at the other locations in the area, but no cross-cutting relations to system 6 and 7 were observed.

System 6: Distinct lineaments oriented 156°/80°SW is truncating the major dextral transverse fault system 7 without being displaced of the fault. It is accordingly younger than the faults and represents a relatively young fracture system.

System 7: Consist of major dextral transverse strike slip faults. The faults are generally forming large planar fault planes striking ~96° dipping ~70° S (Fig. 5–7). The fault zones forms ~15 meter wide lineaments with a general orientation between 90 and 115°.

*Fig. 5–7. System 7. Dextral transverse fault planes in area 2.*

### 5.3.3 Area 3

Area 3 is situated south of the base camp along the eastern part of the small inlet (Fig. 5–2). A series of very distinct oblique faults were measured and primary lineaments on a traverse along the primary E-W trending fjord were recorded. Four fracture/fault systems were deduced from the field investigations (Fig. 5–8). The area is dominated by a dark mica-rich foliated gneiss 60°/78°SE, which may partly control the formation of fracture system 8.

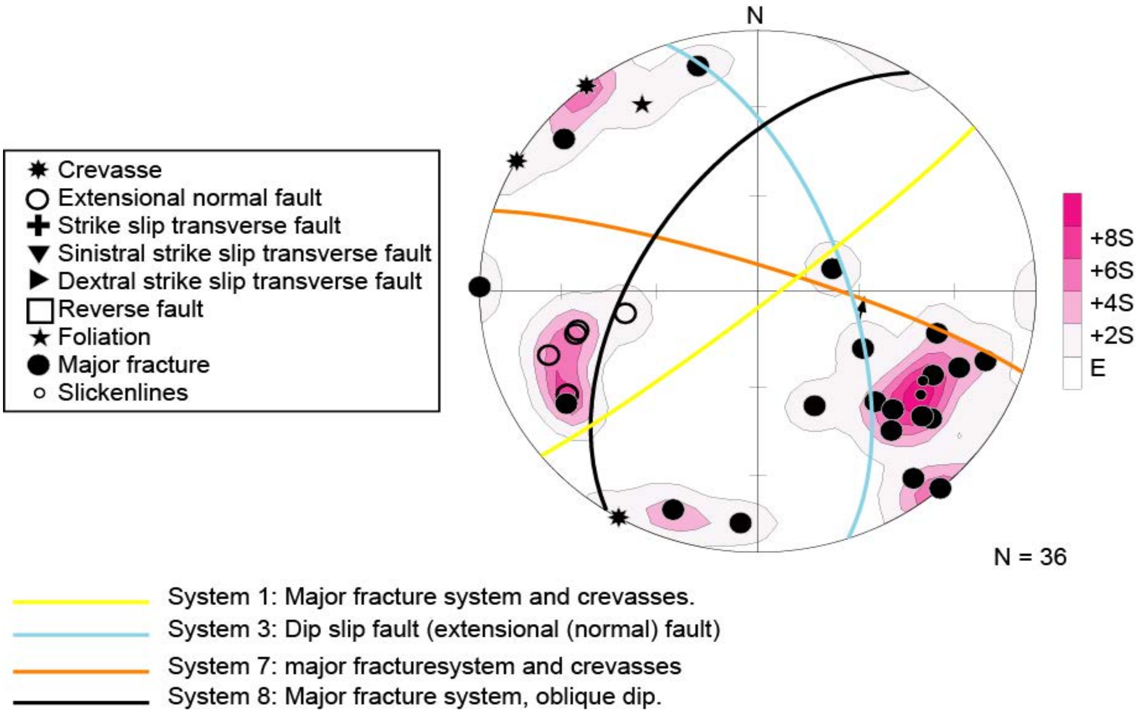



*Fig. 5–8. Fracture and fault data from area 3.*

*Fig. 5–9. Dip-slip faulting along system 3 fault planes from area 3.*

System 1: A number of lineaments consisting of characteristic crevasses and major fractures striking NE-SW dominate the area. The fracture system may be related to the system 1 fault/fracture system although no sinistral displacement has been observed.

System 3: The most distinct structure in the area is a system of major planar dip slip fault planes striking N-S (~160°/65°E) (Fig. 5–9). The fault-planes have weakly developed slickensides with a small displacement. It was difficult to record the mode of faulting, but extensional normal faulting seems to dominate.

System 7 is represented by major E-W striking lineaments. Deep crevasses and major fractures were recorded, but no dextral strike slip displacement. The fractures are however regarded to have formed during the same event, as system 7 faults in area 2.

System 8 consisted of a system of major planar oblique fractures striking ~71° and dipping 64°NW.

### 5.3.4 Area 4

Area 4 is situated north of the base camp along the escarpment (Fig. 5–2). Several primary lineaments were investigated on a traverse along the escarpment. Special attention was paid to the escarpment parallel features and the general spacing of the primary fracture/fault systems.

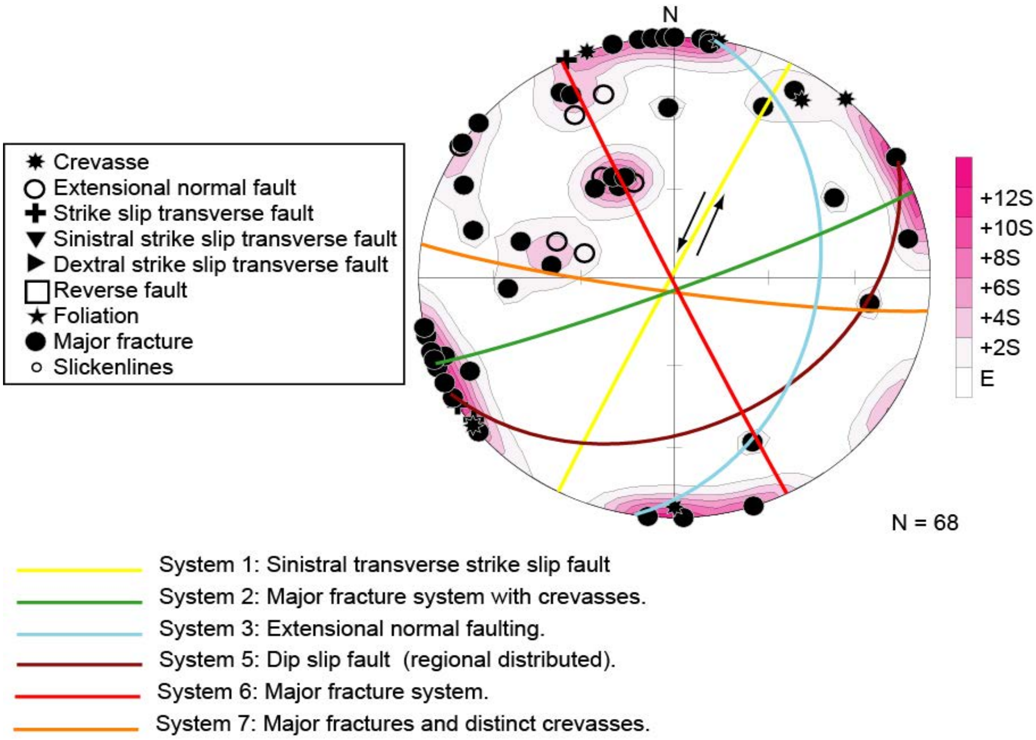



*Fig. 5–10. Fracture and fault data from area 4.*

Six primary fracture/fault systems were deduced from the field investigations (Fig. 5–10). They were categorized as systems 1-2-3-5-6-7.

*Fig. 5–11. Strongly fractured outcrops along the escarpment in area 4. Note the primary vertical orientation of the fractures. The typical spacing of the major fractures range around 1-2 meter. This area is strongly affected by erosion and scour marks from glaciers parallel to the escarpment (Fig. 6–2) indicate removal of eroded material.*

System 1: A number of lineaments consisting of major fractures striking NE-SW are correlated to the system 1 fracture/fault system.

System 2: A distinct system of fractures formed vertical/sub-vertical fractures striking 70-80°. These fractures typically had spacing between 20 cm and 4 m with an average spacing of 1.5 m.

System 3: The N-S striking system 3 faults were sparsely distributed within the area. Only two N-S trending extensional faults were identified along the escarpment striking ~8° dipping 66°W. Although no crosscutting relations were detectable and no magnitude of displacement was measurable, the faults are regarded to have relatively small displacements in the order of less than 1 m. Evidence of major faults capable of creating the escarpment was not identified.

*Fig. 5–12. Faults (system 5) comprise oblique dip-slip faulting striking ~60° dipping ~40°SE in area 4.*

System 5: One of the most distinct structures in the area is a system of major planar dip slip fault planes striking ~60° dipping 40°SE (Fig. 5–12). The fault-planes have weakly developed slickensides with a small displacement. It was difficult to record the mode of faulting, but extensional normal faulting seems to dominate.

System 6: Distinct fractures forming a second system of vertical/sub vertical fractures striking 150-160° with an average spacing between 1-2 m are outlining the dominating blocks in this area. These fractures are correlated to system 6.

System 7: Major fractures and crevasses striking 95-110° are correlated to the system 7 elsewhere.

Especially system 2 and 6 fractures (green and red system) formed large vertical columns of rocks with dimensions close to 1-2 by 1-2 m and tens of meters high (Figs 4–6; 5–11). This fracture configuration facilitates steep slopes with erosion by rock-fall and general backwasting processes rather than a general downwasting process.

### 5.3.5 Area 5

Area 5 is situated south-west of the base camp along the southern coast flanking the primary fjord (Fig. 5–2). The area is dominated by gneiss with a N-S striking foliation dipping 20°E. The topography is generally flat with hilly relief outlined by numerous lineaments. Distinct faults and fractures were measured and primary lineaments were recorded during recognisance in the area.

Five fracture/fault systems were deduced from the field investigations (Fig. 5–13).

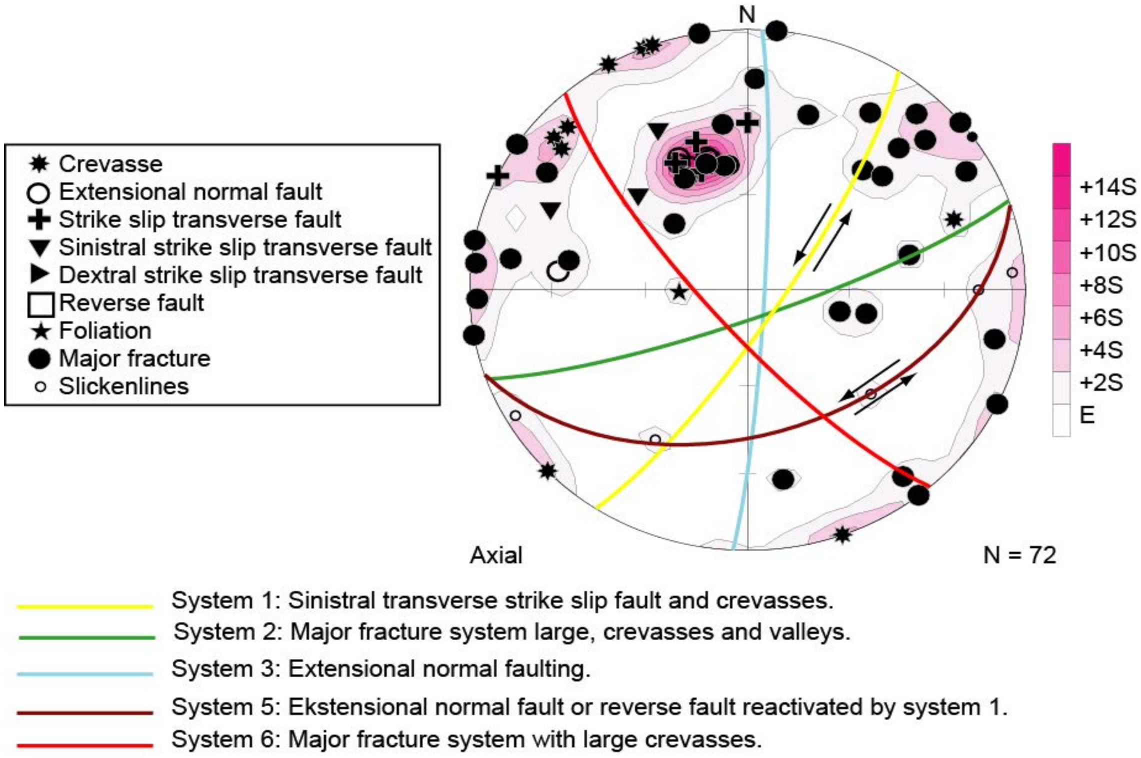



*Fig. 5–13. Fracture and fault data from area 5.*

System 1: The faults and fractures of system 1 are outlined by prominent crevasses striking ~30° with strike slip faults showing sinistral strike slip movements. These lineaments crosscut all other structures in the area and are accordingly the youngest structure in this area. The system 1 faults offset the older structures in the magnitude of one meter.

System 2: A secondary system of distinct crevasses outlines the topography of the system 2 lineaments with vertical fractures striking 60-80°. The most distinct lineament was striking 68° and could be traced for several km (Fig. 5–14).

System 3: One extensional fault striking 6° dipping 58°W were recorded. A less prominent vertical N-S striking fracture system is related to the system 3 faults.

System 5: The area is dominated by oblique planar dip slip fault planes striking ~70° dipping 44°SE with slickenlines dipping 42° towards 156°. The faults are regionally distributed. The fault planes show reactivations of strike slip movements that are clearly related to the system 1 faulting.

System 6: Fracture system and crevasses striking 130-140°.

*Fig. 5–14. System 2 lineaments outlined by crevasses striking ENE-WSW.*

## 5.4 Fracture/fault analysis

Totally 8 fracture/fault systems may be deduced from the field investigations.
Of these systems 1-2-3-4-6-and 7 corresponds well with 6 major systems of lineaments in the area (Fig. 5–15). All these lineaments are related to vertical or sub-vertical

fracture/faults systems, while the oblique dip slip faults and fractures from system 5 and 8 shows no influence on the topography of the area.

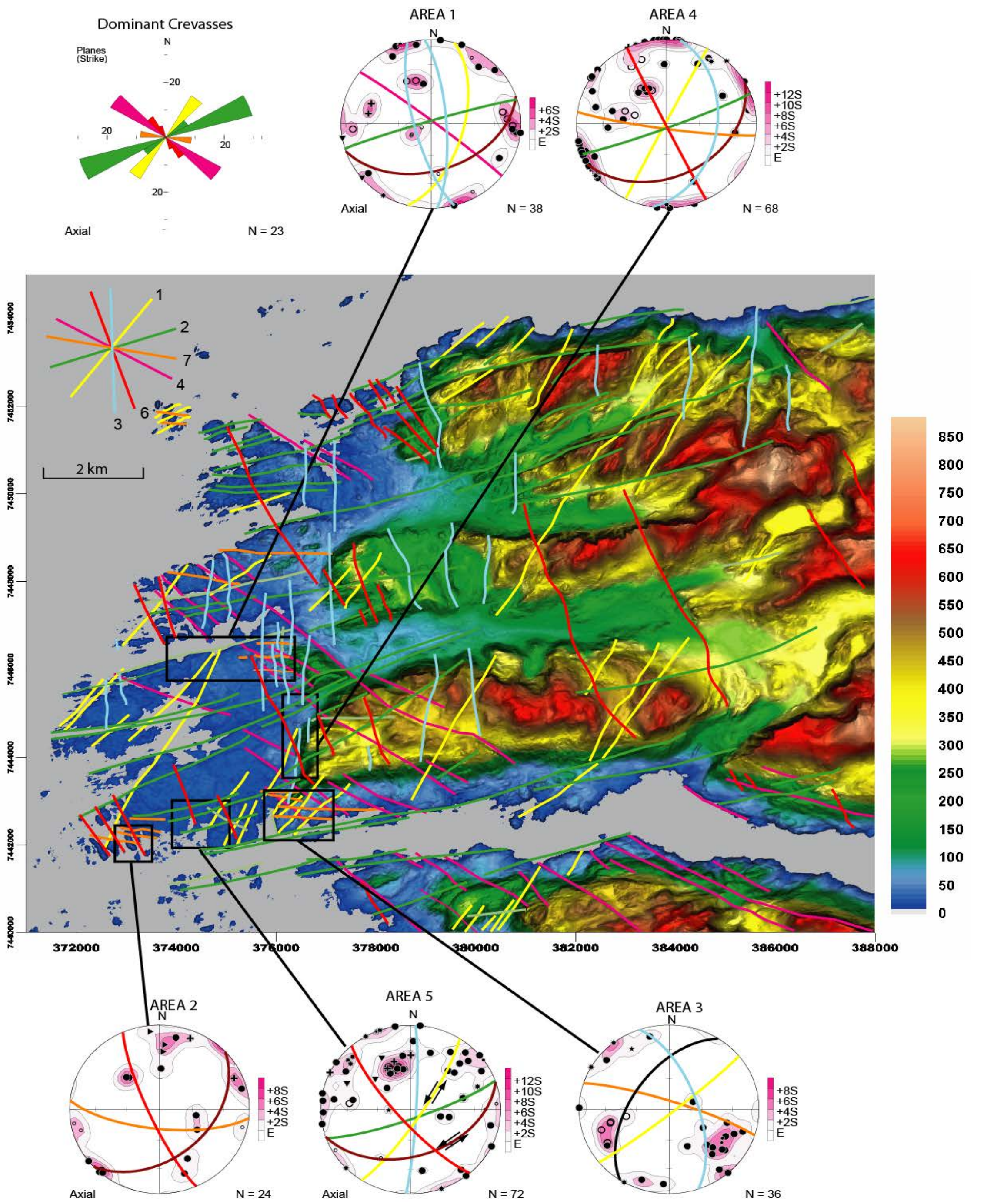



*Fig. 5–15. General fracture and fault distribution in the area.*

Especially systems 1-2-4-6 forms distinct crevasses and outline the face of the escarpment, while the system 2 extensional faults have minor influence on the topography. The relation between the faults and fractures are outlined in fig. 5–16.

## 5.4.1 Local event stratigraphy

The order of formation of the fractures was investigated from cross-cutting relations. It is evident that several of the systems have been reactivated and a clear order of events is accordingly difficult to establish.

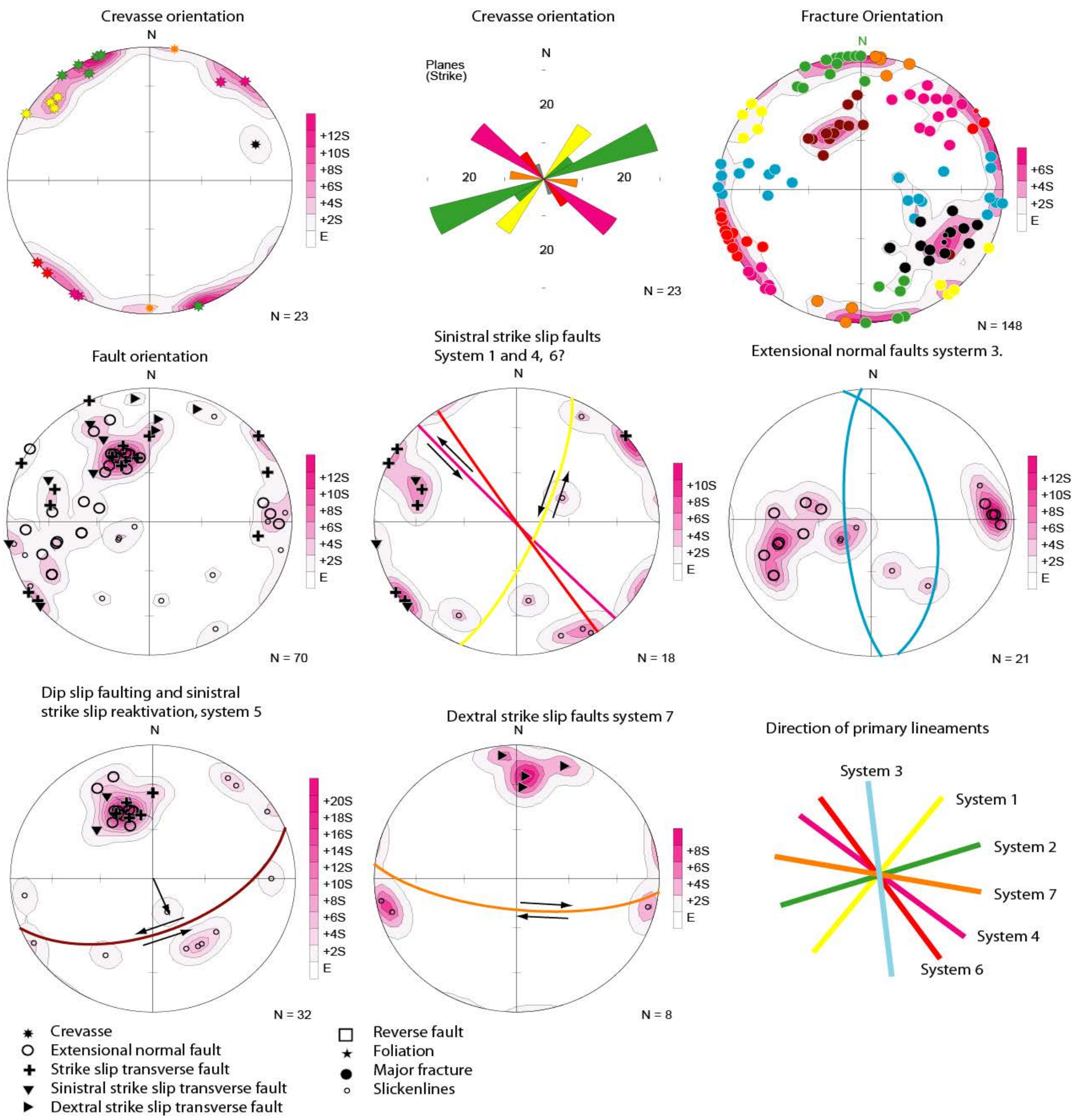



*Fig. 5–16. Plot of all fracture/fault systems within the study area.*

The number of fault/fracture systems related to each area is outlined in fig. 5–16. The figure shows that not all systems were represented in the different areas, but especially system 1-2-3-4-5-6 seems to be regionally distributed while system 7-8 seems to be more locally distributed. The order of formation is suggested as follows:

- System 1 (sinistral transverse faults) is regarded to be the youngest fault system. This system crosscut all other structures in the area.
- System 2 fractures may be the second youngest since it is only truncated by system 1 faulting. It may however also belong to an older reactivated system since it clearly outlines the fjords.
- System 3 (extensional faults) is sparsely distributed and less dominant, but seems to be the second or third youngest lineament wherever it occurs. It may also have been reactivated during the late uplift events.
- System 4 and system 6 may constitute one system, but especially in area 1 the systems seems to be separated in two. No direct crosscutting relations have been observed.
- System 5 is very difficult to place in chronological order. The oblique faults and fractures belonging to the system 5 are clearly truncated and reactivated by system 1 faults. But the orientation and regional distribution of this fault system indicate a possible compressive stress field that may be of much older origin than the system 1 and 3 faults. This fault system is clearly restricted to this area, while system 1-2-3-4-6 may be correlated to similar systems north of the study area, in the Nordre Isortoq and Nordre Strømfjord area (Wilson et al. 2006).
- System 6 is regional distributed and crosscut system 7 and is accordingly younger than this.
- System 7 consists of dextral strike slip transverse faulting sub parallel to the major fjords. This system has no cross cutting relationships with other than system 6, but both system 6 and 7 could be younger than system 3.
- The system 8 oblique fractures are only observed in area 3. It may be developed as a conjugating fractures system to the system 5 fault planes. It is older than the system 3 faults, but may be a local feature.

AREA 1

System 1: Sinistral transverse strike slip fault
System 2: Major fracture system > 100 m long and 2 m wide crevasses
System 3: Extensional normal faulting (conjugating set)
System 4: Fractures + sinistral strike slip fault and crevasses (0,5-1 m wide)
System 5: Extensional normal fault or reverse fault? (regionally distributed)

AREA 2

System 5: Extensional normal fault or reverse fault? (regionally distributed)
System 6: Major fracture/fault system truncate system 7
System 7: Fractures + dextral strike slip transverse fault-zones (15-50 m wide)

AREA 3

System 2: Major fracture system and crevasses
System 3: Dip slip fault (normal extensional fault)
System 7: Major fracturesystem and crevasses
System 8: Major fracture system, oblique dip

AREA 4

System 1: Sinistral transverse strike slip fault
System 2: Major fracture system and crevasses
System 3: Extensional normal faulting
System 5: Dip slip fault (regionally distributed)
System 6: Major fracture system

AREA 5

System 1: Sinistral transverse strike slip fault
System 2: Major fracture system > 100 m long and 2 m wide crevasses
System 3: Extensional normal faulting (conjugating set)
System 5: Dip slip fault (regionally distributed)
System 6: Major fracture system with large crevasses
System 7: Fractures + dextral strike slip transverse fault-zone

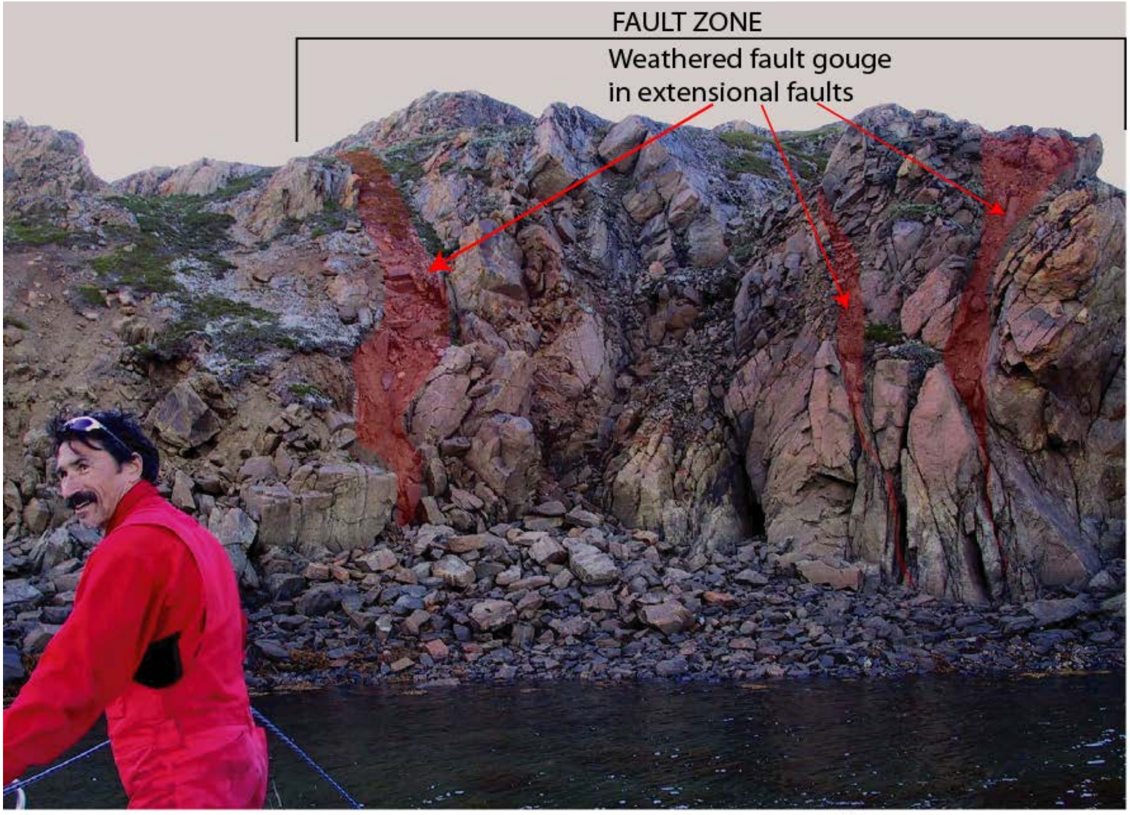
All fracture/fault systems

System 1: Sinistral transverse strike slip fault
System 2: Major fracture system and crevasses
System 3: Extensional normal faulting (conjugating set)
System 4: Fractures + sinistral strike slip fault and crevasses
System 5: Dip slip fault (regionally distributed)
System 6: Major fracture system with large crevasses
System 7: Fractures + dextral strike slip transverse fault-zone
System 8: Local major fracture system (area 3 only), oblique dip

*Fig. 5–17. Distribution of the fracture/fault systems within the individual areas.*

## 5.4.2 Area 6 Ikatut ("Point Chalmers")

The onshore area near Ikatut (Fig. 2–1) a few km south of the inlet to Nordre Strømfjord is identified close to the major faults offshore mapped from seismic data (Chalmers et al. 1999) (Fig. 3–1). Characteristic curved lineaments on aerial photos could indicate the presence of major extensional faulting, but foul weather prevented inspection during the field season 2003. It was accordingly investigated during one day's fieldwork in 2005.



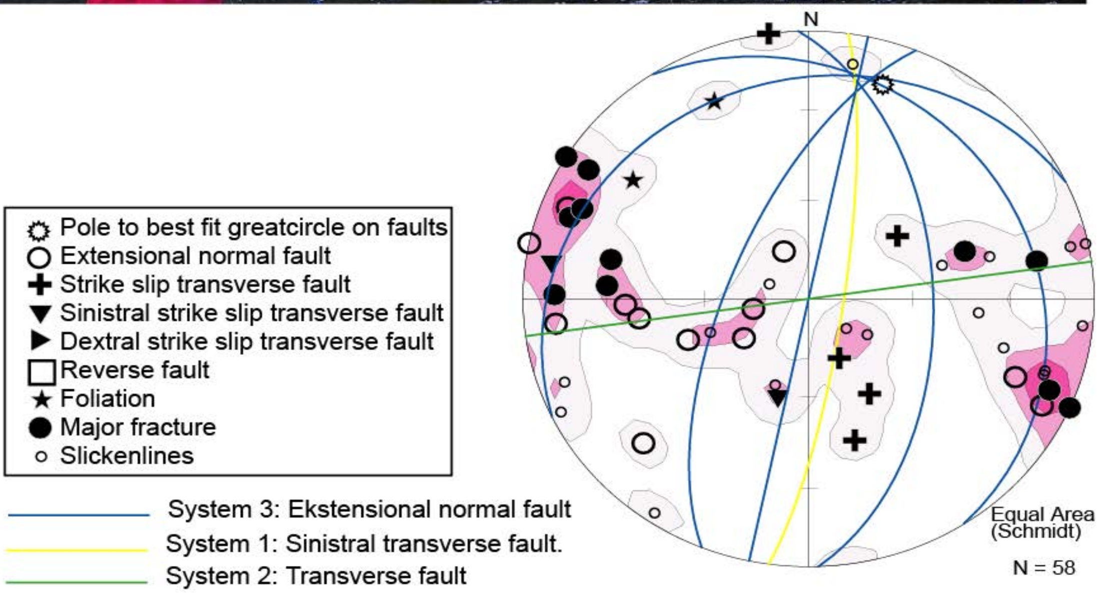




*Fig. 5–18. Fault and fracture data from Ikatut ("Point Chalmers").*

A 3 km long traverse was investigated and major faults and fracture systems were recorded. The area is dominated by a relative low relief with foliated ortho-gneisses. The general foliation is dipping gently towards SE. The gneiss is extremely weathered and highly fractured compared to Kangarssuk further south. One oblique sinistral transverse fault striking NNE-SSW may be related to the Ungava wrench faulting (Wilson et al. 2006) and one vertical transverse fault striking E-W was recorded.

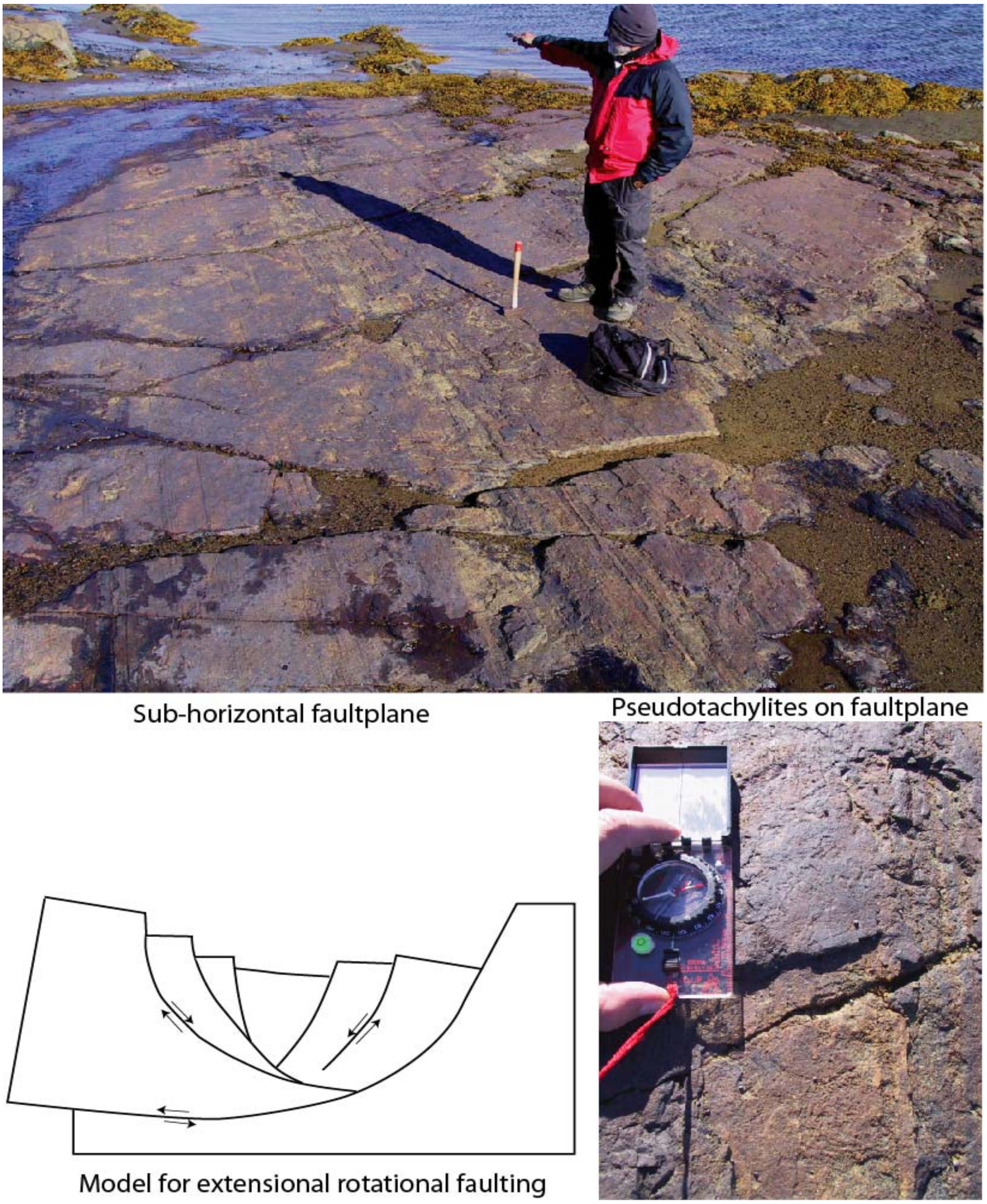



*Fig. 5–19. Sub-horizontal fault plane with pseudotachylites at Ikatut. Rotational extensional faulting along listric fault planes may result in the formation of low-dipping fault planes. Hanging wall has been moving towards WNW.*

Generally the whole area is dominated by multiple NNE-SSW striking fault planes sometimes with fault gauge in strongly weathered crushed fault zones (Fig. 5–19).

Most of the faults were interpreted as extensional faults with a general NNE-SSW strike and steep to almost horizontal dipping fault planes. The orientation of the faults follows a curvature around an axis oriented 17/18°.

The large horizontal fault planes with 0.5-2 cm thick pseudotachylites on the surface may have three origins.

1. foot-wall flats in a thin or thick skinned thrust fault complex. The hanging-wall has been moving towards WSW.
2. an oblique lateral ramp connected to a major transverse E-W trending strike slip fault (San Andreas fault type).
3. a rotational N-S trending extensional fault with a listric fault plane and development of antithetic extensional faults dipping towards E (Fig. 5–19).

We favour the last for the following reasons. 1. The lineament curvature deduced from aerial photos implies normal faulting along curved fault planes dipping towards W. 2. This point of the coast is situated only a few km from a major offshore extensional fault-zone with several km down faulting of the Pre Cambrian basement. 3. No tectonic events corresponding to suggestion 2 and 3 have been documented in this area. From a preliminary point of view this fault zone may be correlated to extensional faulting in Late Cretaceous – Paleocene (Wilson et al. 2006). Further investigations are however recommended for solving the complex fault patterns in the area.

## 5.5 Correlation to the regional tectonic events in the region.

Most of the brittle structures within the research area correlate with the brittle structures investigated North of Nordre Isortoq (Wilson et al. 2006) (Fig. 5–20).

System 3 extensional faulting fits in a 3D strain zone with complex quadrimodal fault patterns related to the Mid Cretaceous/ Early Paleocene extensional faulting. This system may also account for the system 6 fractures.

System 1 sinistral transverse faults are accordingly correlated to a complex 3D wrench system formed during the Ungava Transform fault. Both system 4, 6 and system 7 fit in a tectonic suite with system 1. The oblique system 5 faults may furthermore be related to regional compression in a NW – SE direction if the faults are regarded reverse.

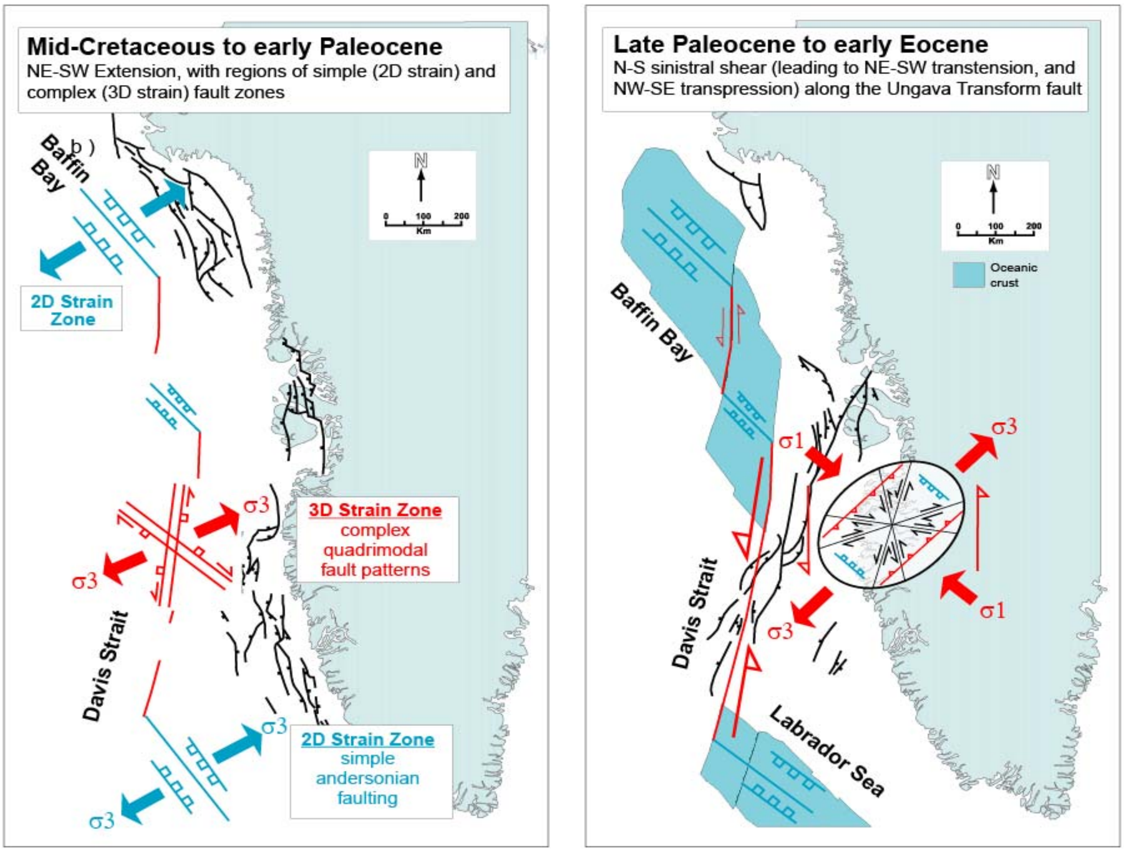



*Fig. 5–20. Tectonic evolution of central West Greenland during Mid Cretaceous to Late Paleocene/early Eocene. After Wilson et al (2006).*

## 5.6 Summary of the fault fracture observations

The most important observations for interpretation of the faults and fractures within the study area are that:

- The fault pattern and sense of movement may reflect the stress fields that govern the opening of the Labrador Sea – Davis Strait.
- The absence of a major extensional fault zone along the escarpment does not support the theory that the formation of the escarpment is related to direct faulting.
- The fault and fracture configuration (spacing, orientation and size) indicate that especially system 1-2, and 4-6 have participated in the formation of the escarpment by weathering and erosion.
- The open mode of the system 1-2 and 4-6 fault and fractures may have been caused by a later reactivation of the fractures.

# 6. Origin and development of the Nordre Isortoq Escarpment: a discussion

The Nordre Isortoq Escarpment marks the boundary between the two main topographical features in the study area: the elevated plateau and the low relief strandflat. The escarpment is not a linear feature but follows a zigzag trace which is controlled by E-W oriented fjords and valleys. Here we will discuss the landscape evolution in and to put it in a regional geological context by integrating the observations concerning geomorphology together with the observations of the faults and fracture systems.

In previous publications we have argued that the elevated plateau is an Oligocene planation surface that was uplifted during two episodes in the late Neogene (Bonow et al. 2006b; Japsen et al. 2006), whereas the low relief areas just south of Disko Bugt is a stripped sub-Cretaceous etch surface (Bonow 2005). The landform configuration in the study area is incompatible with both these suggestions, because the low area here cuts into the planation surface, thus suggesting that this topographical difference has developed after the formation of the planation surface (see also section 4.1).

Down-to-the west movements along a fault or a segmented fault trace along the escarpment is one hypothesis for explaining the relation between the strandflat and the plateau. The fault and fracture analysis gives no support to this idea. Furthermore no significant faults were identified across the escarpment where it intersects the east–west trending Kangerluarsuk Ungalleq fjord either. The bedrock is exposed along the fjord and could thus be investigated both inland of the escarpment and up to 4 km in the coastward direction. This outstanding possibility for investigating the structure of the bedrock along a transect perpendicular to the escarpment only leaves the possibility that the escarpment is an erosional feature.

The large fault structures observed at the field location Ikatut, *c.* 30 km north of the main study area, support this conclusion because of the significant difference between the large fault zone and the minor faults along the escarpment at Nordre Isortoq (Fig. 2–1).

The high-lying plateau landward of the escarpment is dissected and has most probably also been eroded to some degree. Anyhow the plateau raises in elevation inland with a culmination in the mountains of Nordre Isortoq at c. 1500 m a.s.l. (Figs 2–1; 6–1). This means that the plateau along the coast tentatively can be linked with plateau further inland (cf. palaeosurface mapping: fig 4 in Bonow et al (2006b)). The inland plateau has been identified as a planation surface (the upper planation surface, the UPS) that was graded to sea level until its development was interrupted by another uplift event (Bonow et al. 2006b). The initial erosion phase began sometime between 36 and 30 Ma (Japsen et al. 2006). The UPS was uplifted during two phases at c. 10 Ma and some time between 7 and 2 Ma (Japsen et al. 2006). The latter of these phases that probably occurred during the Pliocene, is the dominant phase in the Nordre Isortoq area (Fig. 6–1). The overall configuration of the upper planation surface is thus an asymmetric, domal structure that culminates in the high mountains 25 km east of the study area and which is more than 100 km wide in the east-west direction. The base of the Miocene deposits offshore may be correlated with a tentative reconstruction of the UPS. The reconstruction shown in fig 6–1 is defined along a 20 km wide corridor by the maximum topography for the Nordre Isortoq profile near the coast. The implication of this is that the mountains at Nordre Isortoq were formed by uplift during the late Neogene and that the escarpment consequently primarily developed after the uplift events, probably during Plio-Pleistocene times.

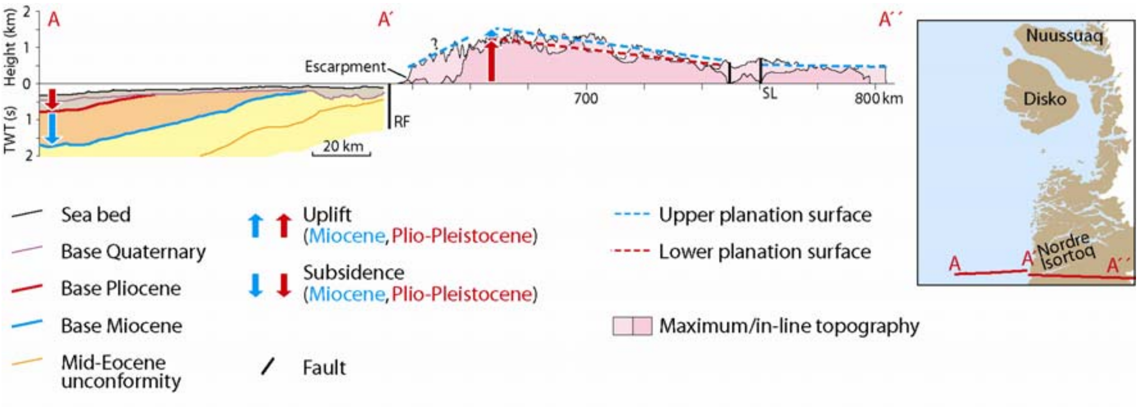



*Fig. 6–1. Onshore-offshore correlation. Present-day profiles across Nordre Isortoq (AA'A'') reveal uplift of the upper planation surface onshore and subsidence offshore during the Neogene. Note that late Cenozoic erosion along the coast near Nordre Isortoq has resulted in a c. 500 m high escarpment. Interpretation of seismic lines AA': GGU92-13 (C. Andersen personal communication). RF: Rift fault (c. 65 Ma). SL: Sisimiut Line. TWT: Two-way traveltime (1 s ≈ 1 km). From Japsen et al (2006).*

If the escarpment is a young erosional feature, the low relief area can not be a preserved etch surface that was recently stripped from protective cover rocks. In the Disko Bugt area the etch surface has been identified as older than the planation surface (Bonow 2005), that have reshaped former hilly relief areas to planation surfaces, for example south of Disko Bugt (Bonow et al. 2006b). Similarly an etch surface in the study area could only have been preserved in a down-faulted position relative to the planation surface if cover rocks had protected the etch surface from the erosion in the Oligocene. The suggestion that no faulting have occurred along the escarpment is in agreement with the idea that the low relief surface in the study area is a young feature developed after the uplift events in the late Neogene and consequently developed into a strandflat.

The strandflat has developed in the coastal zone close to sea level. The processes are unknown in detail, but must have involved a combination of glacial-, periglacial- and marine processes. The strandflat has probably developed during the Plio–Pleistocene and the individual processes may have had more importance in some periods. At present mechanical weathering seems to be the most important agent as evidenced by the abundant presence of up to 1 m thick gravely saprolites (Fig. 4–5). However, the thick saprolites occur in all positions of the landscapes and therefore it is difficult to understand how all this weathering can be post-glacial and thus formed by recent or ongoing processes during a few thousand years. The strandflat was probably covered by a major, erosive ice sheet as late as 11000 years ago. The lower parts of the strandflat must also have been submerged for considerable time prior to the post-glacial isostatic rebound (e.g. Long & Roberts 2003). That post-glacial uplift has occurred is evident by a sequence of uplifted delta-terraces in the study area. Consequently, the weathering products can here only have had a few thousand years to develop. It is however, also possible that the bedrock has been weathered in pre-glacial or inter-glacial times (subsequent to the late Neogene uplift) via the extensive and open fracture systems that was identified in the area during the field work.

Fig. 6–2 shows the interpreted development and timing of the fracture systems observed within the field area. The primary faults and fractures are related to the rifting event between Canada and Greenland in mid Cretaceous – Early Eocene (Wilson et al. 2006) (Fig. 6–2a-b). Neogene uplift and formation of a flexure or domal structures along the continental margin may have reactivated the existing fracture systems into more open mode fractures that would have facilitated increased migration of water and subsequent weathering processes. Especially system 1-2 and 4-6 seems to outline the most conspicuous crevasses and the dominant escarpment faces (Fig. 6–2e).

The theory with the opening of fracture systems is supported by the observation of weathering in well-defined pockets at depths well below the surface, where the weathered pockets are surrounded by unaltered rock (Fig. 4–12). During the glaciations the ice-sheets have without a doubt removed saprolites and rock slabs (Fig. 4–11), but at the same time the erosion has probably exposed deeper parts of the weathered bedrock-column, exposing new pockets of deeply weathered rock.

The escarpment has kept its steepness mainly due to the vertical system 2 (green) and system 6 (red) fractures (Fig. 5–11) that truncate the whole area almost perpendicular to each other and facilitate the formation of huge vertical columns of rocks with a typical dimension of 1-2 meter in diameter and tens of meters in height. This fracture configuration clearly facilitates infiltration of water and subsequent mechanical weathering processes. This has enabled erosion of the escarpment by rock fall of metre-thick columns of rock, which during interglacials formed talus fans. During the glaciations the loosened materials as well as the large boulders have effectively been removed, not only by the major west-flowing glaciers but also by escarpment-parallel ice-flow as indicated by observed striae (Fig. 6–3). The steep slope has thus been continuously rejuvenated. The elevated shorelines along the escarpment document subsequent periods of high sea level, during which finer material may have been removed by wave actions.

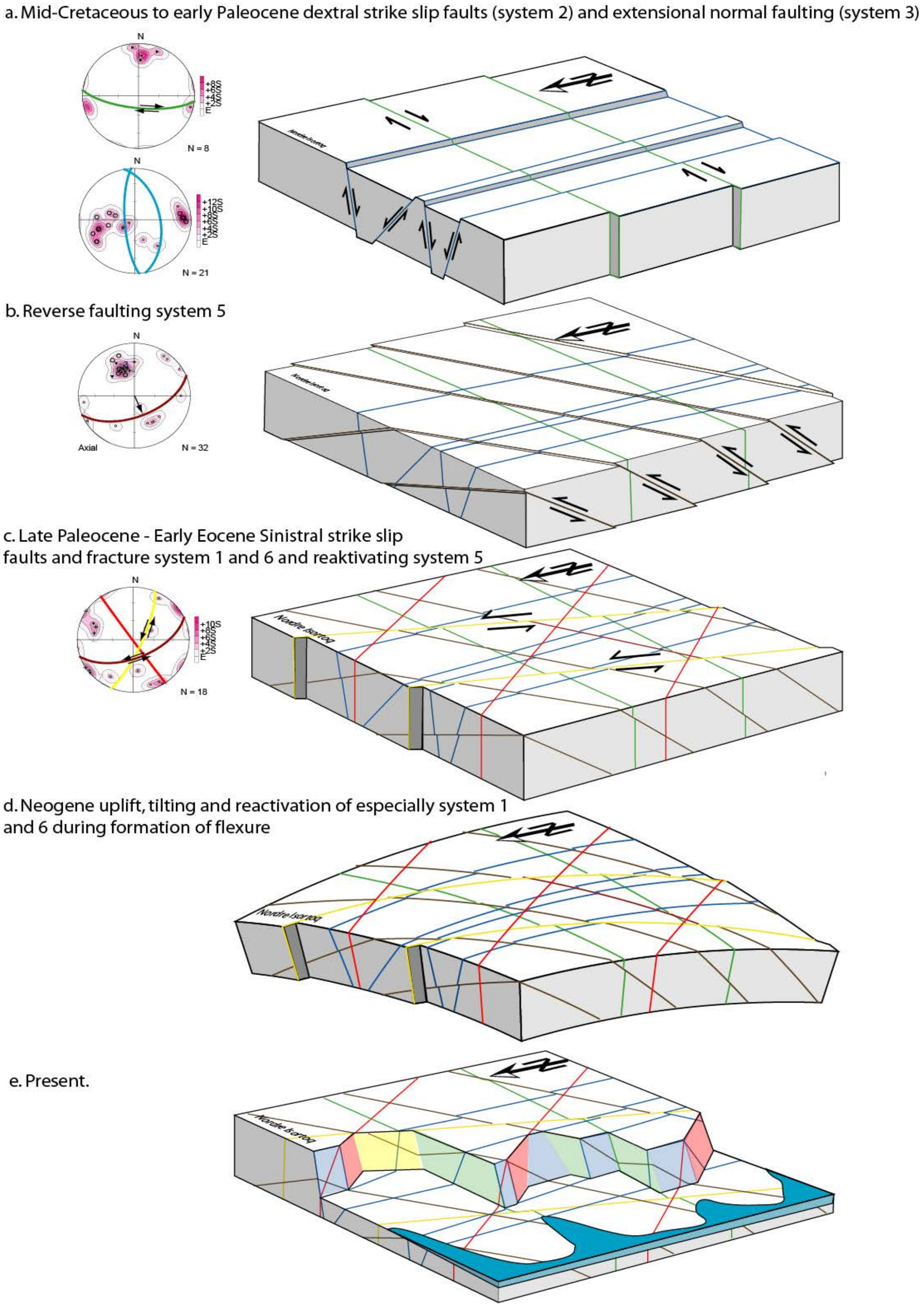



*Fig. 6–2. Inferred development of the fracture and fault systems since the Cretaceous in combination with uplift in the late Neogene and the Plio-Pleistocene escarpment development. a) Mid Cretaceous - Early Cretaceous. Dextral strike faults (green, -system 2) and extensional normal faulting (blue, -system 3) formed in response to*

*the initial opening of the Baffin Sea and Davis Strait. b) Early Paleocene–late Eocene. Rotation of the stress fields results in oblique reverse faulting (brown, -system 5). c) Sinistral strike slip faults (yellow, -system 1) developed during Late Paleocene-Early Eocene overprints the Early Paleocene–late Eocene system 5 (brown). The red fracture (system 6) is possibly generated during the same event. d) Neogene uplift after c.10 Ma. Uplift and formation of a flexure or domal structure results in localised extensional reactivation and opening of the primarily vertical fracture/faultsystems 1-2 and 4-6, enhancing weathering especially along these fracture/fault systems. e) Present. The strandflat develops in front of the escarpment, which maintains its steepness and appearance due to the major fracture systems.*

*Fig. 6–3. Striae parallel to the escarpment with probable ice flow towards the south (right).*

The characteristic landforms of the strandflat, e.g. isolated hills and hill complexes, are very similar to those of the proven sub-Cretaceous etch surface to the north (south of Disko Bugt). The results here show that it is not possible to use single disciplines alone to decide the origin and the timing for the formation of the central West Greenland landscapes.

## 6.1 Constraints on the pre-rift development from AFTA data

The suggested model for the development of the escarpment can lead to further conclusions because we have information about the palaeo-temperatures from Apatite Fission-Track Analysis (AFTA) data that are available from a number of rock samples in the Nordre Isortoq region (Fig. 6–4; Green 2004; see Japsen et al. 2006). In particular AFTA data are available for a height profile at the southern coast of Nordre Isortoq (samples 850-2, -3, -4; at 0, 290 and 570 m above sea level – red circle) as well for a strandflat sample (sample 891-28), just 2 km to the west of the lowermost sample from height profile which was taken from the base of the escarpment.

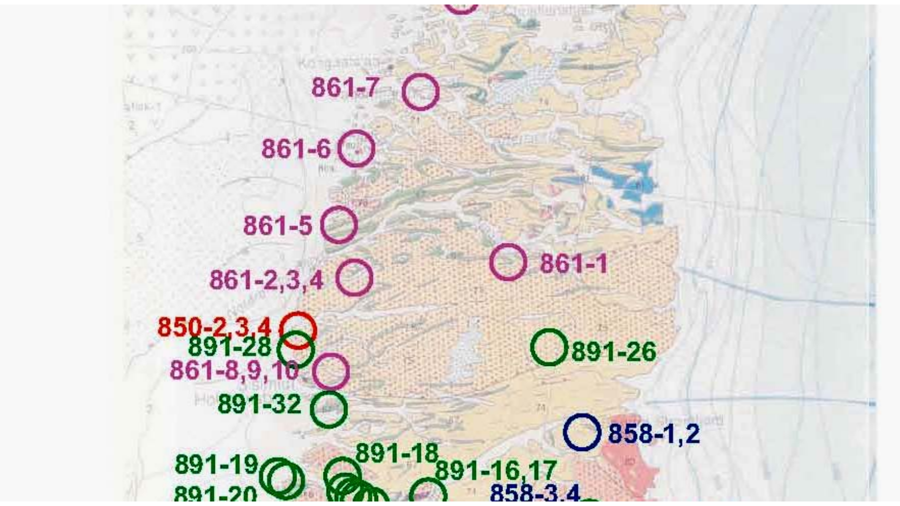



*Fig. 6–4. Sample locations with respect to regional geology for samples analysed from Nordre Isortoq region for different Geotrack Reports (#850 – red text; #858 – blue text; GC861 – magenta text; GC883 – orange text; GC891 – green text)(Green 2004).*

The data show a lateral variation of the estimated palaeotemperature for these samples for the Late Jurassic cooling event (starting between 160 and 150 Ma)(Fig. 6–5): >125ºC for the coastal sample whereas the samples inland of the escarpment indicate temperatures of 100-115ºC and 100-120ºC. Far from the coast palaeo-temperatures are estimated to <100ºC. Correspondingly, fission-track ages are younger towards the coast where minimum values are c. 150 Ma compared to c. 400 Ma further inland (Fig. 6–6). This lateral variation thus reflects the increase in Late Jurassic palaeotemperatures towards the coast (and Triassic, not shown).

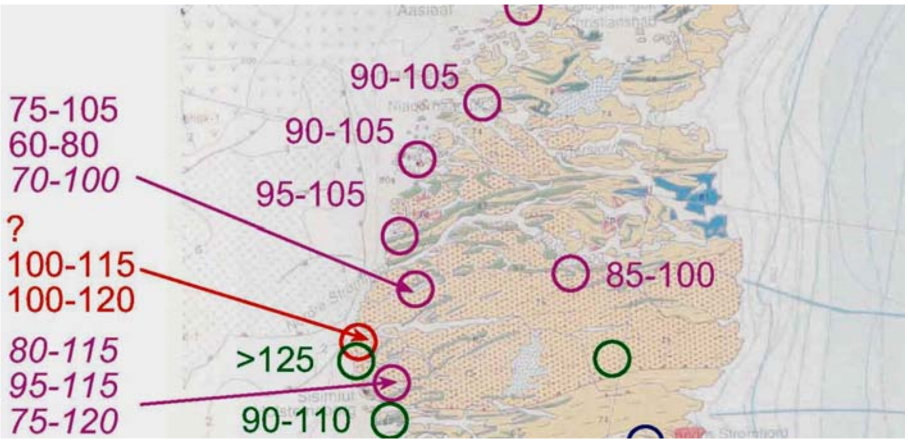



*Fig. 6–5. Estimated paleotemperatures in individual samples prior to the Late Jurassic (160-150 Ma) cooling episode in the Nordre Isortoq region (Green 2004). Palaeotemperatures increase towards the present coast (less than 100ºC inland to more than 125ºC along the coast). These palaeotemperatures correspond to a significant, but wide range of cover-rock thicknesses depending on the palaeogeothermal gradient (which is unknown). Numbers in columns indicate vertical profiles.*

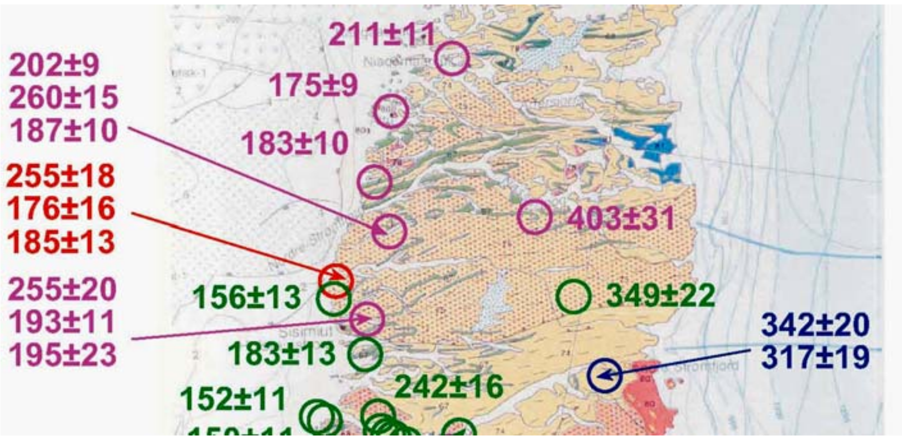



*Fig. 6–6. Fission-track ages (Ma) from the Nordre Isortoq region (Green 2004). Numbers in columns indicate vertical profiles. Note the clear trend of younger ages towards the coast (from c 400 to c. 150 Ma). Numbers in columns indicate vertical profiles.*

In contrast to these east-west variations there do not appear to be any clear tendency in the estimated palaeotemperature for the Eocene-Oligocene cooling event (starting between 36 and 30 Ma) (Fig. 6–7). Palaeotemperatures are about 60 to 70ºC across the region corresponding to a cover of c. 2 km above the present surface assuming a geothermal gradient of 30ºC/km.

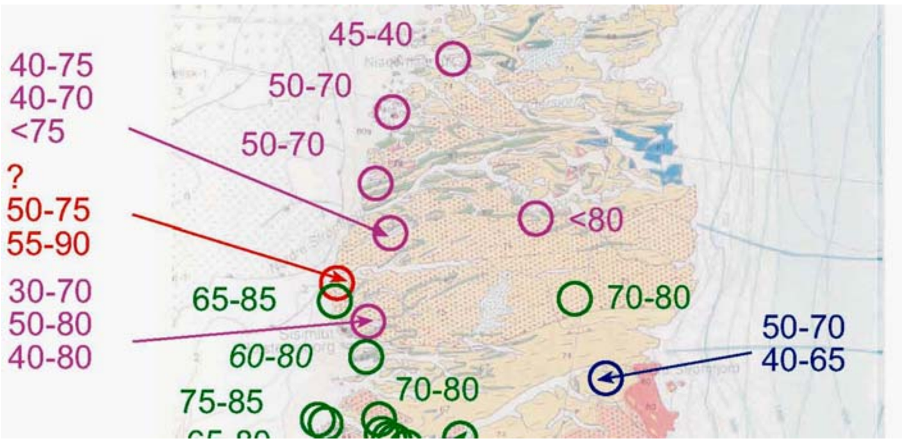
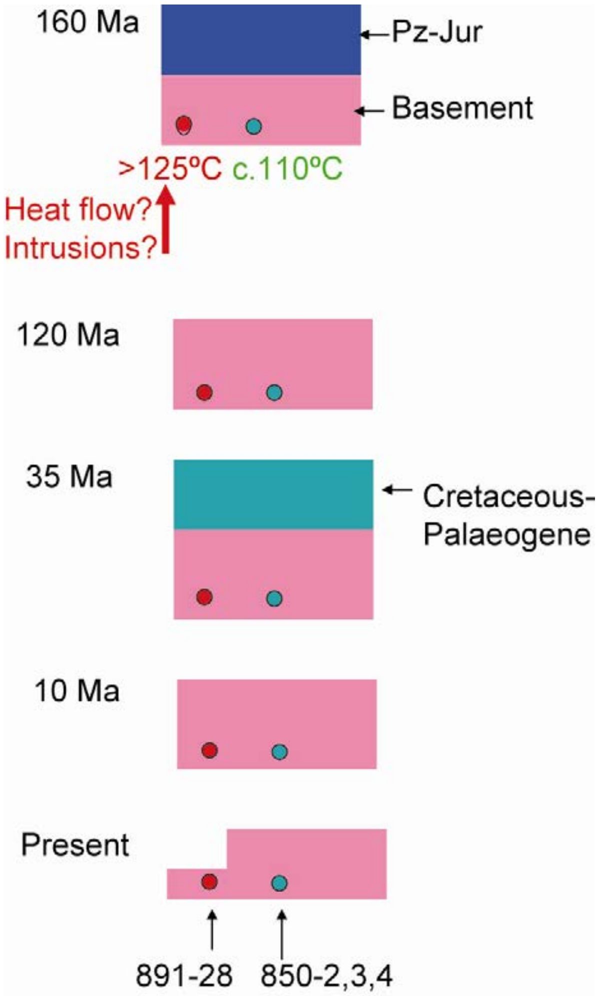



*Fig. 6–7. Estimated paleotemperatures in individual samples prior to the Oligocene (36-30 Ma) cooling episode in the Nordre Isortoq region (Green 2004). Palaeotemperatures are about 60 to 70ºC across the region corresponding to a cover of c. 2 km above the present surface assuming a geothermal gradient of 30ºC/km. Numbers in columns indicate vertical profiles.*

If we combine these observations based on AFTA data with the conclusion from the fieldwork that there is no major fault related to Nordre Isortoq Escarpment we can establish the series of events shown in fig. 6–8.




*160 Ma*: AFTA data indicate much higher palaeotemperatures prior to the Late Jurassic cooling event near the coast. As no faulting is observed along the present escarpment, the temperature difference is suggested to be due increased heat flow towards the west.

*120 Ma*: Possibly removal of all sedimentary cover and development of an etch surface in the basement rocks.

*35 Ma*: Deeper burial of the samples by some 2 km of cover including Cretaceous-Paleogene sediments.

*10 Ma*: Final development of the planation surface prior to late Neogene uplift.

*Present*: Erosional escarpment formed below the planation surface.

*Fig. 6–8. Cartoon of the possible development of the bedrock across the Nordre Isortoq Escarpment (west to east).*

The cartoon illustrates that – because there are no fault movements – there is no evidence for lateral variations in the thickness of cover rocks across the escarpment during the Mesozoic. Consequently the estimated differences in Late Jurassic palaeotemperatures (and in fission track ages) must be related to an increase in heat flow towards the west where Late Jurassic doming, exhumation and thermal activity is inferred to have predated the Cretaceous rifting (Japsen et al. 2006; cf. Bott, 1981).

# 7. Conclusions

- The Nordre Isortoq Escarpment is a young erosional feature, which is not formed by faults or differential weathering.
- The steepness of the escarpment is controlled by the orientation of the fractures in combination with removal of eroded material by glaciers, where glacial transport along the escarpment was especially important.
- The low area on the coastward side of the escarpment is a strandflat, formed after the late Neogene uplift of the planation surface.
- The event stratigraphical model in the area is in general agreement with the tectonic history of the area further north although faulting is significantly weaker at this position as for example near the Nassutooq (Nordre Strømfjord) inlet.
- The open-mode fractures were probably formed as a consequence of the flexure or domal uplift in the Neogene, which reactivated and opened existing faults and fractures.
- Repeated glaciations in the late Cenozoic may have accelerated the weathering by reactivation of the structures due to loading and unloading of glaciers.
- AFTA data indicate much higher palaeotemperatures prior to the Late Jurassic cooling event near the coast. The temperature difference is suggested to be due increased heat flow towards the west and not due to deeper burial due to faulting.

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# 10. Appendix

The following nine aerial photographs (black/white) at the scale 1:40.000 were used for the digital terrain model: 264Q219; 264Q220; 264Q221; 264Q222; 264Q223; 264R0269; 264R0268; 264R0267 and 264R0266.

The aerial photographs were scanned to a resolution where one pixel in the black/white photo is equivalent to 0.70 m. Pairs where set up in a stereographic model, using a Socet Set software package from BAE Systems Ltd. The coastline and islands was manually digitised from the 3D stereographic models in a Digital Photogrammetric Workstation that also was used to extract the terrain model. This resulted in a high-resolution digital terrain model with 50 m grid. The DEM was used in figs 2-2, 4-1, 4-2, 5-2, 5-15 and A1.

*Table 1. Sample location. All coordinates in UTM zone 22W, except sample 451919 which is in zone 21W.*

| Sample nr. | utmx | utmy | m a.s.l. | Date | Name | Locality | Region | Comment * = Afta |
|---|---|---|---|---|---|---|---|---|
| 451901 | 377374 | 7443975 | 406 | 05-aug | pj | Kangaarsuup Qaqqaa | | * |
| 451902 | 375792 | 7442844 | 0 | 05-aug | kesk | Kangaarsuk camp | Sisimiut | 'Kimberlite' |
| 451903 | 373195 | 7442115 | 0 | 06-aug | pj | Kangaarsuk camp SW | Sisimiut | * |
| 451904 | 373195 | 7442115 | 10 | 06-aug | pj | Kangaarsuk SW | Sisimiut | Weathered material |
| 451905 | 375962 | 7442479 | 0 | 06-aug | kesk | Kangaarsuk | Sisimiut | Pseudotachylyte |
| 451906 | 372928 | 7442913 | 0 | 06-aug | jbon | Kangaarsuk | Sisimiut | 'Kimberlite' |
| 451907 | 376148 | 7443096 | 67 | 07-aug | pj/kesk | Kangaarsuk Hill | Sisimiut | Pseudotachylyte |
| 451908 | 376203 | 7443023 | 77 | 08-aug | jbon | Kangaarsuk Hill | Sisimiut | Sediment from cleft |
| 451909 | 379101 | 7442762 | 0 | 08-aug | pj | Kangerlluarssuk Ungalleq | Sisimiut | *Fjord traverse, - 3 km |
| 451910 | 378012 | 7442434 | 0 | 08-aug | pj | Kangerlluarssuk Ungalleq | Sisimiut | *Fjord traverse, - 2 km |
| 451911 | 376932 | 7442494 | 0 | 08-aug | pj | Kangerlluarssuk Ungalleq | Sisimiut | *Fjord traverse, -1 km |
| 451912 | 376072 | 7442219 | 0 | 08-aug | pj | Kangerlluarssuk Ungalleq | Sisimiut | *Fjord traverse, 0 km |
| 451913 | 375653 | 7442111 | 0 | 08-aug | pj | Kangerlluarssuk Ungalleq | Sisimiut | *Fjord traverse, +0.1 km |
| 451914 | 374625 | 7442318 | 0 | 08-aug | pj | Kangerlluarssuk Ungalleq | Sisimiut | *Fjord traverse, 1 km |
| 451915 | 384315 | 7443238 | 0 | 08-aug | pj | Kangerlluarssuk Ungalleq | Sisimiut | *Fjord traverse, -8 km |
| 451916 | 382264 | 7442721 | 0 | 08-aug | pj | Kangerlluarssuk Ungalleq | Sisimiut | *Fjord traverse, -6 km |
| 451917 | 379861 | 7477084 | 1 | 09-aug | kesk | Ikkattut | Nordre Strømfjord | Pseudotachylyte |
| 451918 | 379716 | 7476991 | 0 | 09-aug | pj | Ikkattut | Nordre Strømfjord | *Crt. Boundary fault? |
| 451919 | 628227 | 7436401 | 0 | 09-aug | pj | Avannarlersuaq | Sisimiut offshore | *Skerries, +6 km |
| 451920 | - | - | 0 | 10-aug | pj | Kangsaarsuk camp | Sisimiut | 'Kimberlite' |

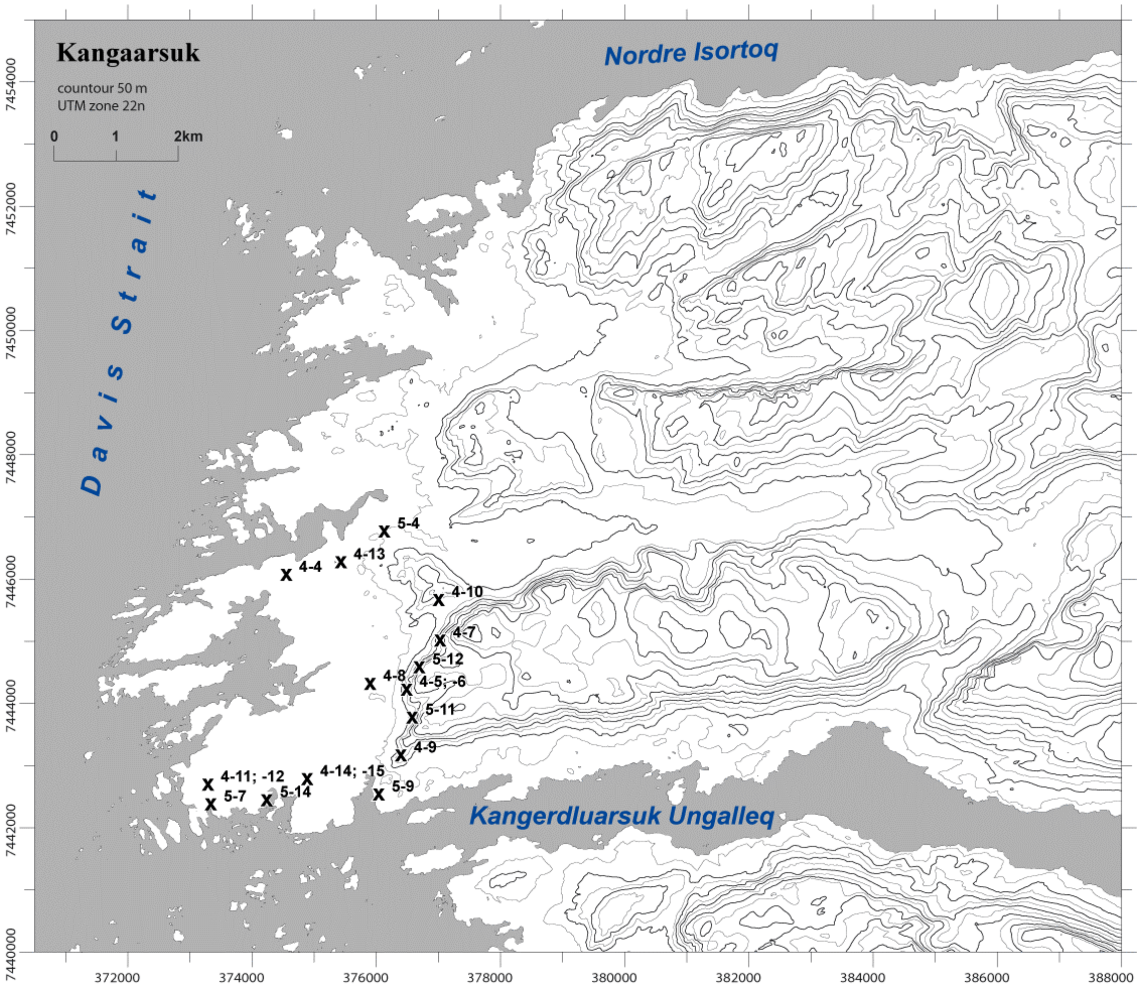

Fig. A-1. Photolocation map.