Faults and fractures in central West Greenland: onshore expression of continental break-up and sea-floor spreading in the Labrador - Baffin Bay Sea

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The complex Ungava fault zone lies in the Davis Strait and separates failed spreading centres in the Labrador Sea and Baffin Bay. This study focuses on coastal exposures east of the fault-bound Sisimiut basin, where the onshore expressions of these fault systems and the influence of pre-existing basement are examined. Regional lineament studies identify five main systems: N-S, NNE-SSW, ENE-WSW, ESE-WNW and NWW-SSE. Field studies reveal that strike-slip movements predominate, and are consistent with a NNE-SSW-oriented sinistral wrench system. Extensional faults trending N-S and ENE-WSW (basement-parallel), and compressional faults trending E-W, were also identified. The relative ages of these fault systems have been interpreted using cross-cutting relationships and by correlation with previously identified structures. A two-phase model for fault development fits the development of both the onshore fault systems observed in this study and regional tectonic structures offshore. The conclusions from this study show that the fault patterns and sense of movement on faults onshore reflect the stress fields that govern the opening of the Labrador Sea – Davis Strait – Baffin Bay seaway, and that the wrench couple on the Ungava transform system played a dominant role in the development of the onshore fault patterns.

Keywords: faults and fractures, extensional tectonics, wrench systems, sedimentary basins, basement reactivation, West Greenland

Introduction

Pre-existing heterogeneities in the continental crust, such as shear zones and terrain boundaries, have long been known to influence the structure and development of later deformation events (Butler et al. 1997; Holdsworth et al. 1997, and references therein). The sedimentary basins of the Labrador Sea – Baffin Bay region are situated west of Greenland (Fig. 1) and are early Cenozoic failed spreading centres (Chalmers & Pulvertaft 2001), separated by the Davis Strait. The orientation of the Davis Strait relative to the proposed spreading centres in the Labrador Sea and Baffin Bay is consistent with the geometry of an ‘extensional transform zone’ (Taylor et al. 1994). Steep basement fabrics of the Nagssugtoqidian orogen trend highly obliquely to these offshore structures (Fig. 1) and coincide with this ‘step-over zone’ in the Davis Strait. Fault systems fundamental to the development of sedimentary basins in the Davis Strait are exposed onshore in West Greenland. In this project, the onshore fault systems of central West Greenland were studied in order to improve...
Fig. 1. Regional tectonic map of the offshore geology of the Labrador Sea – Baffin Bay area between Canada and Greenland. Modified from Chalmers & Pulvertaft (2001).

Facing page:
Fig. 2. Geological map of the Nagssugtoqidian orogen of central West Greenland (modified from Escher & Pulvertaft 1995). A: Outline map of Greenland highlighting the region covered in Fig. 2B. B: Geological map of the Nagssugtoqidian orogen showing main lithological units and basement structures. C: Topographic contour map of the central coastal area showing the field camps chosen for this study (camps 0 to 4); black dashed lines highlight major topographic escarpments. D: 3-D model view of NNE-trending coastal escarpment, constructed in ArcGIS by draping a Landsat image onto a topographic model. Abbreviations used: SNO, CNO and NNO are the southern, central and northern Nagssugtoqidian orogen, respectively. ITZ, Ikermtq thrust zone; NISZ, Nordre Isortoq shear zone; NSSZ, Nordre Strømfjord shear zone.
North America

Greenland

Iceland

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PROTEROZOIC

- Calc-alkaline intrusions
- Arfersiorfik and Sisimut suites
- Granitic intrusions
- Metasedimentary rocks
- Archaean gneisses reworked in the Palaeoproterozoic

ARCHAEOAN

- Supracrustal rocks
- Metasedimentary rocks
- Anorthosite and ultrabasic rocks
- Granitic intrusions
- Orthogneisses
- Thrusts
- Basement fabrics

Increasing height of topography

- Hilly relief
- Planated relief

Coastal escarpment

North Atlantic craton

Nagssugtoqidian orogen

Inland Ice

Disko Bugt

Aasiaat

Naternaq

Kangaatsiaq

Kaangussuaq

Søndre Strømfjord

Nordre Strømfjord

Arfersiorfik

Sisimiut

Kaangerlussuaq

Nordre Isortoq
the understanding of the role played by basement reactivation in offshore basin development.

In the summer of 2003 field work was carried out in an area along the coast stretching from Nordre Strømfjord (Nassuttooq) in the north, to Nordre Isortoq in the south (Figs 2, 3). This area was selected because it is believed that two ENE-striking Palaeoproterozoic shear zones, the N ordre Strømfjord shear zone and the Nordre Isortoq shear zone, were reactivated and played an important role in the development of the Mesozoic to Tertiary sedimentary basins. The western projection of the Nordre Isortoq shear zone appears to coincide with the southern faulted boundary of the Sisimiut basin offshore (Figs 1, 2). In addition, the offshore basins occur close to the coast in this area, and the offshore extensional faults that drop the top of the basement down to 3 km below sea level, within 10 km west of the coast, are believed to correlate with fault escarpments onshore in this area.

Tectonic and geological setting

Offshore

The Labrador Sea and Baffin Bay formed during divergent plate motion between Greenland and North America during the early Cenozoic (Chalmers & Pulvertaft 2001, and references therein). The extensional basins of Baffin Bay and the Labrador Sea are separated by a bathymetric high in the Davis Strait (Fig. 1). This transverse ridge is interpreted as a complex sinistral-shear transform fault zone, known as the Ungava fault system (Figs 1; Chalmers et al. 1995). Extensional faulting and tectonic subsidence are thought to have commenced in the early Cretaceous, at the same time as sea-floor spreading in the North Atlantic south of the Charlie Gibbs fracture zone. Opening started during the Paleocene (Chian & Louden 1994; Chalmers & Pulvertaft 2001). The Nukik platform lies to the south of the Sisimiut basin and is separated from it by a line of ENE- and E-trending faults that coincide with the offshore extension of the Nordre Isortoq shear zone onshore (Figs 1, 2). It has therefore been proposed that the faults at the southern margin of the basin by reactivation of basement shear zone structures in the central N agssuqtoqidian orogen. These faults affect Mesozoic sediments and are overstepped by Paleocene sediments, so that the latest significant movement on them must have been prior to the end of the Paleocene.

Onshore

Onshore exposures in central West Greenland, from Sondre Strømfjord in the south to Disko Bugt in the north, comprise high-grade gneisses of the Palaeoproterozoic N agssuqtoqidian orogen (Fig. 2; Ramberg 1949; van Gool et al. 2002). The N agssuqtoqidian orogen is a 300 km wide belt of predominantly Archaean orthogneisses, Palaeoproterozoic paragneisses and intrusive rocks, that were reworked during Palaeoproterozoic orogenesis (van Gool et al. 2002). These basement rocks form ENE-trending linear belts of steeply dipping gneisses, some of which are crustal-scale shear zones (i.e. the Nordre Strømfjord and Nordre Isortoq shear zones, Fig. 2), which alternate with zones dominated by kilometre-scale fold structures (van Gool et al. 2002). The N agssuqtoqidian orogen is divided into three tectonic segments: the southern, central and northern N agssuqtoqidian orogen (Fig. 2; Marker et al. 1995). The onshore research in this study lies entirely within the granulite facies orthogneisses of the central N agssuqtoqidian orogen, which is bound to the north by the coastline. The western margin of the Sisimiut basin is the NNE–SSW-trending Ikermiut fault zone (Fig. 1), a transpressional flower structure developed along the transform fault (Ungava fault zone) between the North American and Greenland plates (Fig. 2) formed during the Palaeogene (i.e. it cuts early Eocene strata; Chalmers & Pulvertaft 2001). The Ikermiut platform lies to the south of the Sisimiut basin and is separated from it by a line of ENE- and E-trending faults that coincide with the offshore extension of the Nordre Isortoq shear zone onshore (Figs 1, 2).
Nordre Strømfjord shear zone (Marker et al. 1995; van Gool et al. 2002) and to the south by the Ikertôq thrust zone (Fig. 2).

Indirect topographic evidence from geomorphological investigations has suggested that late (Mesozoic or Cenozoic) onshore fault movements may have occurred (Bonow 2004). For example, in some of the larger inlets and valleys, characteristic recent shelly marine sands can be observed up to 30 m above sea level. These are likely to have been uplifted due to isostatic rebound following glacial retreat. However, variations in elevation of these palaeoshorelines may also result from differential vertical fault movements or differential unloading. On the larger scale, the Nordre Strømfjord shear zone marks a major change between two landscape types (Japsen et al. 2002). South of the Nordre Strømfjord shear zone topography is planated, with flat mountain tops forming a plateau that gradually increases in height southwards from 500 to 1000 m (Fig. 2C, D).

In contrast, north of the Nordre Strømfjord shear zone, the land has a hilly relief with a relatively flat and low-lying topography with isolated hills up to 300 m high. Locally, the change in landscape type occurs across a more than 500 m high, ENE–WSW-oriented escarpment that drops down to the north (Fig. 2).

There is also a pronounced NNE–SSW-oriented escarpment almost 1 km high that drops down to the west between Nordre Strømfjord and Nordre Isortoq (Fig. 2). This major escarpment separates low-lying (50–150 m high) coastal flats to the west from the much higher (500 m+) mountains to the east (Fig. 2) and can be traced for over 80 km, from Sisimiut in the south to Nordre Strømfjord in the north. Similar escarpments can be observed in the near offshore on both bathymetric and horizon maps of depth to basement, thus supporting the theory that onshore structures reflect those offshore.

Methods

The present study combines regional to outcrop-scale mapping and regional studies of remotely sensed data to determine fault-fracture geometries, distribution, relative timing and kinematics in selected key areas of central West Greenland.

Regional studies comprised satellite image and aerial photograph analysis at a variety of scales (1:500 000; 1:100 000; 1:20 000) in order to identify lineaments and other geological structures (e.g. variations in lithology, fabric intensity, faults, fractures).

Field investigations were carried out in the well-exposed Precambrian basement rocks in key areas of interest that were identified during aerial photograph analysis prior to departure. A number of field camps were used during the mapping (Fig. 2C). Camp 0 was located at Inussuk, a site visited previously in 2002 (Japsen et al. 2002). Camps 1 and 2 were located on the north and south shores of Nordre Strømfjord, while camp was on the north shore of Nordre Isortoq. Camp 3 was farther inland, and is not analysed further in this study.

During field work, fault and fracture systems were mapped, and the following structural data were collected for statistical/structural analysis:

- Fault attributes including: orientation; kinematics; fault surface characteristics; mineralisation.
- Relative age relationships.
- Structural/statistical analyses to determine kinematic patterns.

Over 200 pseudotachylite and mica-bearing fault-rock samples were also collected from different fault sets at various localities in order to date the fault movements using 40Ar/39Ar geochronology (results to be discussed elsewhere). All field data were geospatially located (to 5 m resolution) using Global Positioning System (GPS) waypoint collection, and were subsequently stored in a computer database with links to Geographic Information System (GIS) based maps.

Fault and fracture characterisation

Fractures include all brittle structures such as joints, fissures, cracks, veins, etc. that are not faults, bedding or cleavage surfaces, and are larger than the grain size of the rock. In general, fractures are defined as dominantly tensile (mode I) cracks, 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. Faults are mapped where distinct offsets have been identified, often with a development of slip striae on the surface (slickenlines). Criteria for determining the sense of movement were based on methods outlined in McClay (1987) and Petit (1987).

In the present study faults were classified as:

- Normal (extensional dip / oblique-slip fault).
- Reverse (compressional dip / oblique-slip fault).
- Strike-slip faults (dextral or sinistral).

The classification of faults and fractures into systems was primarily based on the orientation of the structures (i.e.
trend of lineament or strike of plane). Structures with different orientations can reflect different deformation phases, but in complex fault zones developed in three-dimensional (3-D) strain fields, multiple fault and fracture orientations may develop during a single event (see e.g. De Paola et al. 2005). Therefore further classification needs to be applied, either through systematic fracture properties (such as surface type or mineralisation), or through kinematic studies, in order to determine if only one or several phases of deformation are apparent.

Fault and fracture measurement technique
In order to accurately classify the fault and fracture systems, populations of at least 50 fractures/faults were measured at most localities. Faults were classified according to type (normal/reverse dip-slip faults or dextral/sinistral strike-slip faults). Fault orientations and the directions of slickenlines (when observed) were measured, and the following characteristics recorded:

- Surface shape: The overall fracture shape (metre-scale) was described as listric, planar, undulating or irregular.
- Surface roughness character: The surface roughness character (millimetre scale) was described as smooth, rough or slickenside (striae).
- Other features: Some fractures/faults have a filling of iron oxide precipitates, quartz crystals, epidote, or preferential growth of other crystals on the surface showing the slip direction. Special types of fractures such as conjugate shear fractures, en échelon fractures, plumose jointing etc. were noted if present.
Lineament mapping

Lineament maps for the central Nagsuqtoqidian orogen (Fig. 3) were plotted from Landsat TM images and aerial photographs at a variety of scales (1:500 000 and 1:100 000 for Landsat images and 1:20 000 for aerial photographs). Images were georeferenced and displayed in a GIS environment and the lineaments picked by hand. After interpretation, lineaments were then refined using digital terrain model (DTM) analysis and compared to pre-existing geological maps of the region (e.g. H. Enriksen et al. 2000). As the data are stored in a GIS, attribute data for each lineament (i.e. trend; length; offset; other features) were also measured or calculated and stored. Spatial analysis and rose plotting tools in ArcView GIS were used to analyse the orientation (Fig. 3) and spatial distribution of these structures.

A more detailed analysis of selected areas was then carried out at 1:20 000 scale using aerial photographs. As image resolutions are much higher in aerial photographs (2 m pixel size), particular attention was paid to how the lineaments interact with topography (e.g. V-ing into valleys, etc.) to gain a better understanding of their overall geometry. Generally all lineaments picked appear to have a steep dip as only minor interactions with topography were observed. Attention was also paid to cross-cutting relationships between lineaments in an attempt to determine the relative timing of structures (Fig. 4).

Lineament systems

In total 1284 lineaments have been identified from Landsat TM images (pixel size 30 m) at 1:100 000 scale (Fig. 3). Lineaments derived from both Landsat and aerial photographs have been grouped into systems based on their orientation. Five main lineament systems (N–S, NNE–SSW, ENE–WSW, ESE–WNW, and NNW–SSE) have been identified (Fig. 3; Table 1).

System 1 structures (green; Figs 3, 4) are oriented ENE–WSW (~060–090°), and are pervasively distributed across the region. This system has a trend similar to the Nordre Strømfjord and Nordre Isortoq fjords, and lies parallel to the regional basement fabric (foliation, gneissic banding, and shear zones; van Gool et al. 2002). Note that as these lineaments may represent either faults or basement fabrics, care must be taken when analysing these quantitatively. In an attempt to minimise the amount of oversampling, only the most pronounced lineaments (e.g. most weathered out) that mark a distinct change in structure were mapped, while those that are clearly basement fabrics (i.e. those showing ductile features such as folds) were not.

System 2 lineaments (blue; Figs 3, 4) are N–S oriented (trend ~350–010°), and often show sinistral offsets of pre-existing structures (basement fabrics). This system can be traced from Nordre Isortoq to the northernmost part of the investigated area (Fig. 3), and previous investigations indicated that they may continue as far north as Aasiaat, Disko and Nuussuaq (Japsen et al. 2002). The fault zones are closely spaced (100–500 m), and strike-slip separations of up to 30 m have been observed.

System 3 lineaments (red; Figs 3, 4) are NNW–SSE oriented (trend ~140–170°). They are closely spaced (50–100 m), and offsets of marble beds show net dextral separations in the order of 20–40 m (Fig. 4). This system is most pronounced in the Nordre Strømfjord shear zone, and less dominant in the Nordre Isortoq shear zone (see rose diagrams in Fig. 3).

System 4 lineaments (yellow; Figs 3, 4) are oriented NNE–SSW (trend ~010–040°) and are strongly developed in the Nordre Strømfjord shear zone region (camps 0 and 1, Fig. 3). These structures show apparent sinistral strike-slip separations of up to 400 m in the westernmost part of the study area. The spacing between them increases from approximately 500 m at the coast, to approximately 2 km farther inland. The same lineament directions were encountered at camps 2 and 4, south of Nordre Strømfjord, where these structures are shorter and more discontinuous, possibly due to differences in rock type and fabric between the two areas.

System 5 lineaments (purple; Fig. 3) consist of E–W to ESE–WNW (trend ~090–120°)-oriented structures. The valleys that distinguish this system are generally 10–30 m wide and have a curved trend. This system appears to be mostly localised into two specific areas: the first of these lies in the fold belt south of Nordre Strømfjord (Fig. 3), and the second is located south of Sisimiut (Fig. 1).

Relative timings

Figure 4 shows an aerial photograph of an area around camp 1 where an apparent order of lineament development can be deduced. The oldest structures appear to be system 1 (green), and in this area these structures appear to be basement fabrics in the form of alternating layers of semipelite and marble up to 100 m thick (H. Enriksen et al. 2000). System 2 (blue) structures show sinistral offsets of these lithological layers, while system 3 structures (red) show dextral displacements. In Fig. 4, system 3 structures appear to dominantly cross-cut system 2 structures, but this is not always the case as in some areas the reverse is true (system 2 cross-cutting displacing system 3). As there...
Field observations

Four key areas were chosen for detailed fracture and fault analysis in the field (Fig. 3), based on their structural interest (i.e. their potential to enable all systems to be analysed) and accessibility. The first objective of the field work was identification of the lineaments picked from the aerial photographs. In most cases field observations proved that the lineaments correspond to major fault structures, many of which are weathered out to leave gorges and river valleys (Fig. 5A–C). However, whilst many of the ENE–W SW-oriented system 1 structures are faults, others also correspond to basement fabric features, such as strongly foliated zones, lithological contacts and shear zones (Fig. 5D). Therefore care must be taken in any quantitative geometric or spatial analysis of this system.

After a regional reconnaissance from each field camp, detailed structural analysis was carried out. Ninety outcrop locations were investigated in the four camps, distributed along the coast between Nordre Isortoq and just north of Nordre Strømfjord (Fig. 2). In total c. 1700 faults and fractures were measured and described.

Fault geometries

A wide range of fracture orientations were observed (Fig. 6A), with dominantly N–S and N NW–SSE strikes and an overall mean fracture plane of 167/89E. Various fault orientations can be separated out in the field (dominant trends are N–S and EN E–W SW), showing a range of slip movements and shear senses (Fig. 6B–F). Dominant fault movements appear to be strike-slip (71% of faults recorded show strike-slip movements), although extensional and compressional faults were also apparent.
A set of ENE–SW-oriented faults (green planes/mean poles in Fig. 6) appear to reactivate strong basement fabrics in the Nordre Strømfjord and Nordre Isortoq shear zones. These faults correspond to system 1 lineaments and exhibit various forms of fault movement (e.g. extensional, compressional and strike-slip; Fig. 6B–F). Faults corresponding to systems 2 (N–S, blue), 3 (NW–SE, red) and 4 (NE–SSW, yellow) can also be easily distinguished from the fault data in Fig. 6. However, lineament system 5 (E–W to ESE–WNW, purple) is not apparent. As previously discussed this system appears to be a more geographically localised system (i.e. local to areas south of the Nordre Strømfjord and Nordre Isortoq shear zones), and correspond to zones dominated by reverse fault movements (Fig. 6B) and a small number of ESE-trending dextral strike-slip faults (Fig. 6E).

Fault systems corresponding to lineament systems 2, 3 and 4 appear to consist of parallel fault zones separated by non-faulted, but generally strongly fractured rock. The fault zones range typically between 1 and 50 m in width (Fig. 5B) and consist of multiple parallel faults with variable spacing. These zones are commonly located in pronounced valleys and gorges (Fig. 5A), so characterisation of fault planes was often difficult as the valley floors are generally covered by recent sediment and vegetation.
**Fault kinematics**

In addition to the characterisation of the faults and fractures in terms of their trend and distribution, they can also be described according to their movement patterns (see Table 1). The nature and timing of tectonic events that are responsible for the formation of these fault-fracture systems is quite complex. Multiple directions of slickenlines on several fault surfaces indicate that many faults were either reactivated or that individual faults exhibit curved movement trajectories consistent with complex strain histories.

**Strike-slip faulting**

Strike-slip slickenlines account for 71% of those observed and were observed on all main fault geometries or systems. Multiple orientations of strike-slip faulting are common in wrench-dominated fault systems due to the development of Riedel, P and X shears (e.g., Woodcock & Schubert 1994).

Basement parallel faults (system 1, green) show both dextral and sinistral movements (note, RM structures – Petit 1987 – associated with R-shears suggest dextral movements on basement faults in Fig. 5D). N N W-trending (system 3, red) faults appear to correspond to dextral movements. N-trending faults (system 2, blue) appear to...
Fig. 7. A: Panoramic photograph showing exposures of a series of parallel ENE-dipping extensional faults, in the vicinity of camp 1. B and C: close-up photographs showing en échelon fracturing on the footwall of normal faults and pseudotachylite fault exposure in more detail. D: Lower hemisphere, equal area stereographic projection of poles to planes, and associated slickenlines, for faults and fractures observed at the outcrop of Fig. 7A. Fault orientations and kinematics suggest ENE–W SW extension as indicated by stress arrows (red); n, number of measurements.
show both dextral and sinistral movements, while NNE-trending faults (system 4, yellow) are sinistral structures (Fig. 6D–F).

Extensional faulting

Although all five fault systems show dominantly strike-slip movements, normal and oblique-slip components of displacement were also recorded on some sets. These faults appear to have two dominant orientations, N–S (system 2) and ENE–WSW (system 1; Fig. 6C). In some areas N NW–SSE (system 3) -oriented structures also appear to be normal faults (Fig. 7), but these are not the dominant orientations in bulk analyses (Fig. 6). Field observations suggest that strike-slip movements post-date dip-slip.

Compressional faulting

Reverse faults (Figs 6B, 8) appear to be confined to areas close to camps 2 and 4, and to be spatially associated with system 5 lineaments. These faults strike parallel or sub-parallel to basement structures (ENE–W SW to E–W, Fig. 6B) and exhibit dextral-oblique slickenlines, which plunge towards the ESE (Figs 6B, 8).

As these compressional or thrust faults are only found on the southern shore of Nordre Støm fjord and the northern shore of Nordre I ssortoq (i.e. abutting against major basement shear zones) it is possible that these structures are the result of local transpressional thrust faulting, which may be linked to steps in the en échelon sinistral fault system (system 4). Field observations suggest these compressional faults post-date most other fault and fractures. However, at camp 4, a N–S sinistral strike-slip fault appears to cross-cut these thrusts (Fig. 8B).
Fractures and joints
A diverse array of fracture orientations was recorded. Dominant orientations vary from NW–SE through to NNE–SSW. The orientation of the mean plane is NNW–SSE. All fractures recorded showed no evidence for shear movement (i.e. rough surfaces and with no apparent offsets) and are thus interpreted as opening mode 1 fractures and suggesting extension directions varied from c. E–W to N E–W SW extension. This extension cannot, however, explain the apparent basement-parallel (system 1) extensional faults, which suggest an apparent N NW–SSE extension. These EN E-trending normal faults have also been observed in seismic interpretations and are thus important structures regionally.

These two extensional fault sets show a quadrimodal fault distribution, i.e. four sets of fault planes (Fig. 6C). If regarded as two separate fault sets, this geometry would suggest two separate extension directions (E–W and N NW–SSE); however an alternative to this is that these faults formed contemporaneously under three-dimensional strain (Reches 1983; Nieto-Samaniego & Alaniz-Alvarez 1997). As one set of normal faults trends parallel to a pre-existing plane of weakness (e.g. basement fabric) it is likely that basement reactivation played a role in the development of these faults, and that this has lead to formation of extensional faults oblique to the regional extension. The regional tectonic setting would fit with 3-D strain as the area borders the transfer zone between two extensional basins, i.e. is a transtensional deformation zone (Dewey 2002; De Paola et al. 2005).

Interpretation and discussion
An overall summary of each of the fault systems identified through remote sensing (i.e. lineament mapping) and field studies is presented in Table 1. In this section we discuss the possible interpretations and implications of these observations.

Fault development
System 1 (EN E–W SW) faults and fractures appear to be the oldest structures, however multiple slip vectors and apparent fault movements suggest that there has been activity on this system during later tectonic episodes (note that system 1 faults are apparent in all stereoplots for all fault types, Fig. 6B–F). These lie parallel to the pre-existing Nagssugtoqidian basement fabric, which dates at c. 1.8 Ga (van Gool et al. 2002).

Cross-cutting relationships interpreted from analysis of aerial photographs suggest that the next systems to develop were systems 2 and 3 (Fig. 5). It is difficult to determine if one of these systems predates the other as mutually cross-cutting relationships can be seen; however, it does appear that system 3 is the more pervasive system and thus may be more recent.

Strike-slip movements and offsets on systems 2 (N–S) and 3 (N NW–SSE) suggest that, if active at the same time, these would represent a strike-slip conjugate system. In such cases the inferred extension vector would trend EN E–W SW, subparallel to system 1 foliation-parallel faults. This extension vector is also consistent with the dip-slip fault movements seen locally on these same fault systems.

These strike-slip movements appear to be preceded by dip-slip extensional movements. System 2 (N–S) is the dominant extensional fault orientation in the area (Fig. 6C), while some localities showed small populations where N NW–SSE-oriented extensional faults represent the preferred trend (e.g. Fig. 7). These faults are indicative of E–W to EN E–W SW extension. This extension cannot, however, explain the apparent basement-parallel (system 1) extensional faults, which suggest an apparent N NW–SSE extension. These EN E-trending normal faults have also been observed in seismic interpretations and are thus important structures regionally.

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Geoffroy et al. (1998) recorded similar fault geometries and kinematics farther north in Disko and Nuussuaq (Fig. 1). Their interpretation is that strike-slip and dip-slip faulting developed during a single tectonic episode of W SW–EN E extension, which is in agreement with a model of 3-D transtensional strain.

As the stereoplots in Fig. 6B show, strike-slip faults are the dominant fault type in the area (as mentioned above, 71% of all faults measured are strike-slip) and these appear to post-date extensional movements. All fault systems show evidence for strike-slip movements. System 1 (EN E–W SW) exhibits both dextral and sinistral senses of shear, systems 3 (N NW–SSE) and 5 (ESE–W NW) show dextral shear, while systems 2 (N–S) and 4 (N NE–SSW) are dominated by sinistral shear movements. System 4 faults (N NE–SSW) appear to cross-cut all other fault sets, and are characterised by major fault zones (Fig. 5). These major sinistral strike-slip structures lie subparallel to the sinistral Ikermiut and Ungava fault zones that dominate the Davis Strait offshore (Fig. 1). Assuming a ~NNE-trending sinistral wrench system for the study area, strike-slip fault movements on each system appear to correlate closely with synthetic (R) and antithetic (R' ) Reidel shears, and also with synthetic P and antithetic X shears typical of a plane strain wrench tectonic regime (Fig. 9; Woodcock & Schubert 1994).

Compressional faults appear to be relatively late structures (although cross-cut by ~N–S-trending sinistral faults) and are localised in areas of strong basement fabric (i.e.
shear zones). These faults strike parallel to basement fabrics and indicate an oblique compression (from the ESE or SE; Fig. 8). Offshore there is evidence for thrusting in a similar orientation along the Ikermiut fault zone (Fig. 1). Positive flower structures have been identified (Chalmers & Pulvertaft 2001) and are interpreted as inversion structures formed at a restraining bend during sinistral strike-slip along the Ungava transform fault, during the early Eocene (c. 54–49 Ma, Chalmers & Pulvertaft 2001). If trends of basement shear zones (outlined in Fig. 2) are continued along strike offshore they appear to coincide with these transpression zones within the Ikermiut fault zone. It is possible that thrusts observed onshore have formed in a similar way to those offshore with basement shear zones acting as restraining bend structures, thus leading to localised compressional zones. Furthermore, slickenlines on the reverse faults suggest a compression from the ESE or SE (Figs 6B, 8), which is consistent with the compressional axis for a sinistral wrench system (i.e. N E–SW extension and N W–SE compression; Fig. 9).

Regional onshore correlations
Farther north in the region of Disko and Nuussuaq, onshore faulting episodes can be dated relative to the deposition of basaltic lavas and the sedimentary systems during Campanian to Eocene times (Geoffroy et al. 1998; Storey et al. 1998; Chalmers et al. 1999; Dam et al. 2000). Dam & Sønderholm (1998), Dam et al. (2000) and Dam (2002) document at least three phases of faulting recorded in the sedimentary record prior to Paleocene volcanism. Cretaceous–Paleocene sediments on Nuussuaq show distinct unconformities, with incised valleys and submarine canyons, reflecting disturbances in early Campanian, Maastrichtian and early Paleocene times. These unconformities and channels are thought to have formed in response to structural movements associated with regional N E–SW rifting (and also the arrival of the North Atlantic plume in the latter two cases).

$^{40}$Ar/$^{39}$Ar dating has revealed that volcanism commenced in West Greenland between 60.9 and 61.3 Ma and that 80% of the Paleocene lava pile was erupted in less than 1 Ma (Storey et al. 1998). These lavas show a distinct coastal flexure (Geoffroy et al. 1998, 2001; Larsen & Pulvertaft 2000), presently expressed by seaward dipping basalts lavas. This flexure has an arcuate course, striking N W–SE in southern Svartenhuk Halvø and northern Ubekendt Ejland, turning through N–S in south-west Ubekendt Ejland to N E–SW in north-west N uussuaq and finally to N – S in north-west Disko (Fig. 1; Geoffroy et al. 1998, 2001; Larsen & Pulvertaft 2000). Numerous dykes cut these lavas (e.g. see figs 4 and 5 in Larsen & Pulvertaft 2000), and so do various fault sets (Geoffroy et al. 1998). The timing of the various phases of volcanic eruption, dyke emplacement, and block faulting relative to one another is still a matter of debate. Geoffroy et al. (1998) presented detailed structural evidence suggesting that fault and dyke intrusion on Disko took place during tilting of lava sys-
Table 2. Proposed event stratigraphic model and apparent correlation with offshore events

<table>
<thead>
<tr>
<th>Event #</th>
<th>Timing and event</th>
<th>Offshore tectonic structures</th>
<th>Onshore tectonic structures</th>
</tr>
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<tbody>
<tr>
<td>5</td>
<td>Pliocene to</td>
<td>• Subsidence</td>
<td>• Uplift?</td>
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<tr>
<td></td>
<td>Pleistocene</td>
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<td>• Possible reactivation of</td>
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<td></td>
<td>tilting</td>
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<td>systems 1-4 as normal faults</td>
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<td>4</td>
<td>Eocene Labrador</td>
<td>• N- to NNE-trending sinistral</td>
<td>Faults consistent with NNE-</td>
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<td></td>
<td>sea-floor</td>
<td>transverse fault system (Ungava</td>
<td>oriented sinistral wrench</td>
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<td></td>
<td>spreading</td>
<td>fault zone).</td>
<td>system: NNE-trending (system</td>
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<td>(Ungava system)</td>
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<td>4) faults and</td>
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<td>transstensional faulting (e.g.</td>
<td>basement-parallel (system</td>
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<td></td>
<td>Ikermiut fault zone)</td>
<td>1) faults active as antithetic</td>
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<tr>
<td>3</td>
<td>Late Cretaceous</td>
<td>• N-trending faults in Davis</td>
<td>• Systems 1, 2 (and 3?) faults</td>
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<tr>
<td></td>
<td>to early</td>
<td>Strait (E-W extension) leading</td>
<td>all active as extensional</td>
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<td>Paleocene</td>
<td>to formation of the</td>
<td>faults during NE-SW to EN</td>
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<td></td>
<td>extension</td>
<td>Siimsuit Basin offshore</td>
<td>E-W SW extension</td>
</tr>
<tr>
<td>2</td>
<td>Early or middle</td>
<td>• N W-trending normal faults</td>
<td>• Uncertain?</td>
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<td></td>
<td>to late</td>
<td>in the Labrador Sea (SW-N E</td>
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<td></td>
<td>Cretaceous</td>
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<td>• W SW – EN E faults bordering</td>
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<td>thermal subsidence</td>
<td>the Siimsuit basin to the</td>
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<td>during events 2 and/or 3</td>
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<tr>
<td>1</td>
<td>Proterozoic and</td>
<td>• Uncertain?</td>
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<td></td>
<td>later</td>
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<td>• Possible system 1 EN E-W SW</td>
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<td>localised</td>
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<td>foliation-parallel faulting</td>
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<td>reactivation</td>
<td></td>
<td>prior to late Mesozoic?</td>
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</table>

Gauts. Geoffroy et al. (2001) then stated that N W-SE-oriented, flexure-parallel dykes in southern Svarthukyield dates of around 54.6 ± 0.6 Ma. This suggests that most of the coastal flexure is of Eocene age (or later?). Further evidence for this comes from north-west N uussuaq where tilted lavas (Larsen & Pulvertaft 2000) have been dated at ~53 Ma (Storey et al. 1998).

Systems 2 (N-S) and 3 (N NW- SSE) extensional faults in this study appear comparable to faults that cross-cut these Paleocene basalt lavas (G effroy et al. 1998). Taking the dates outlined above for dyke emplacement which is believed to be associated with faulting, it would appear that our system 2 and 3 faults were active during Eocene times. Taking all these onshore tectonic timings into account it would then appear that the faults observed may have been active from late Cretaceous (Maastrichtian) through to Eocenetimes(D am & Sønderholm 1998; G effroy et al. 1998, 2001; Chalmers et al. 1999; D am et al. 2000; Larsen & Pulvertaft 2000; D am 2002).

Normal fault orientations similar to systems 2 (N-S) and 3 (N NW-SSE) occur in and around the N uussuaq basin (Fig. 1; G effroy et al. 1998; Chalmers et al. 1999) and are consistent with either EN-E WSW (G effroy et al. 1998) or E-W (Chalmers et al. 1999) extension. Chalmers et al. (1999) proposed that the N-S faults formed by E-W-oriented crustal extension, while associated ESE-W NW faults formed as a consequence of reactivation of shear zones in the underlying basement. Normal faults are dominantly N-S onshore (Fig. 6C), fitting with this model proposed by Chalmers et al. (1999). However, this implies that while Baffin Bay in the north and Labrador Sea in the south were undergoing EN-E WSW extension (deduced from dominant fault trends and earliest magnetic anomaly trends, Chalmers & Pulvertaft 2001), southern West Greenland and the N uussuaq basin were undergoing E-W extension. A better explanation is that the Davis Strait at this time (i.e. prior to the onset of sea-floor spreading) lay in a transfer/step-over zone between two extensional basins, and that it was strongly influenced by basement fabrics such that this region experienced complex 3-D strain associated with regional EN-E WSW extension (Fig. 10). Onshore normal fault sets form a quadrimodal fault distribution (four sets of fault planes, Fig. 6C) consistent with 3-D strain.

This faulting is then subsequently dissected by N-S (system 2) and N NE-SSW (system 4) -oriented faults during the Eocene (Chalmers et al. 1999). The Itilli fault zone (Fig. 1) is one such N NE-SSW-oriented structure cutting through north-west N uussuaq. This fault zone appears to be a left-lateral splay from the northern extension of the Ungava fault zone in the Davis Strait (Chalmers et al. 1999).
STAGE 1:
Late Cretaceous–Paleocene extension (N-E–SW to ENE–SSW). Pre-existing basement anisotropy (Nagssugtoqidian orogenic belt) appears to influence fault patterns in the Davis Strait. Possible strain partitioning between basement-parallel and N–S-trending normal faults.

STAGE 2:
NNE-trending Eocene sinistral wrench system (NE to ENE extension, SE to SSE compression) reactivating earlier extensional faults and basement-parallel structures (e.g. thrust faults at camp 4, and the Ikermiut fault zone).

Fig. 10. Proposed two-stage tectonic model for the tectonic evolution of upper Mesozoic–Cenozoic extension within the Nagssugtoqidian orogen. Stage 1(A): N- and ENE-trending normal faults and dextral basement reactivation due to ENE–WSW extension. Stage 2 (B): N- and NNE-trending sinistral strike-slip faulting, and associated strike-slip wrench tectonic systems, with compressional structures (reverse faults) forming in zones of basement anisotropy (e.g. shear zones). Block diagrams show schematic cartoons outlining fault patterns observed onshore, while maps show the regional context, based on correlations between onshore and offshore fault structures.
Correlation with fault structures offshore

Fault patterns offshore in the Davis Strait exhibit similar c. N–S and ENE–WSW dominant orientations. The south and east bounding faults to the Sisimiut basin strike ENE–WSW and N–S respectively (Fig. 1). Significantly, the southern margin of the Sisimiut basin is coincident both in orientation and location with a major basement shear zone (the Nordre Isortoq shear zone), and is likely to have exerted a similar structural control to that interpreted for onshore. Block faulting has been dated via drilling as having taken place between the late Campanian and late Paleocene (Christiansen et al. 2001; Dalhoff et al. 2003), indicating that these extensional faults are of similar age to those associated with valley incision on N uusuaq and north Disko (Dam & Sønderholm 1998; Dam et al. 2000; Dam 2002).

The Ungava fault zone with its associated fault systems (e.g. the Ikermiut fault zone) is the most prominent structure in the Davis Strait (Chalmers & Pulvertaft 2001). This NNE–SSW-oriented structure is interpreted as a transform fault zone showing sinistral shear, and has been linked to the Illili fault zone (Fig. 1; Chalmers et al. 1999). System 4 (NNE–SSW) faulting onshore, around Nordre Strømfjord, is consistent with late sinistral strike-slip movements, and it is reasonable to suggest that this system is of similar age. As already discussed, offshore evidence for sinistral strike-slip movements can be seen in the Ikermiut fault zone on the western margin of the Sisimiut basin (Chalmers & Pulvertaft 2001) where transpressional thrusts (similar to compressional flower structures modelled in Dooley et al. 1999) appear to have formed in the restraining bend of a strike-slip fault (see fig. 6 of Chalmers & Pulvertaft 2001). These thrusts cut early Eocene mudstones, but are overlain by late Eocene sediments, providing further evidence for timing of these movements. This sinistral shear is thus a consequence of left-lateral movement of the Canadian plate relative to the Greenland plate along the Ungava transform system during sea-floor spreading in the Labrador Sea (Fig. 1).

Evidence for neotectonic faulting?

Chalmers (2000) presented evidence for Neogene uplift in offshore areas of central West Greenland, while recent onshore topographic and apatite fission-track data analysis has identified similar Neogene activity (Japsen et al. 2002, 2005). A common observation in this field area is the presence of raised beaches and palaeoshorelines, up to elevations 30 m above present sea levels (Fig. 5A). They are probably the result of isostatic readjustment following the removal of Pleistocene ice load. Topographically, the region appears to be divided into blocks, split by ENE-trending fjords and NNE–E-trending escarpments (Fig. 2C). These must be quite recent features as they have not been eroded during glacial activity (and may in fact be a consequence of it). The trend of system 4 faults (and also locally those of system 2) is generally parallel to the pronounced NNE-trending escarpment from Nordre Isortoq to Nordre Strømfjord onshore, and also to a similarly trending scarp near offshore (identified in bathymetry maps), and it is possible that these faults have been reactivated as normal faults during a recent tectonic event. This conjecture still needs to be verified, as the main escarpments were not studied in detail during our field work.

Summary

The observed fault and fracture systems reflect a brittle tectonic history that is ultimately related to far-field plate movements, uplift and basin formation. The development of Mesozoic to Cenozoic basins offshore West Greenland appears to be strongly controlled by faults. Therefore, knowledge of the fracture systems in the exposed Precambrian basement provides a valuable insight into fault geometries and kinematics during the development of offshore basins and potential hydrocarbon reservoirs. It also provides insights into the possible influence of basement reactivation.

Several possible tectonic-event models may be constructed for this region given the lack of definite ages for structures. Table 2 shows a basic summary of the relative timings of fault systems identified in this study relative to regional offshore tectonic models, while Fig. 10 presents a model for fault development based on the observations and correlations made in this study. The absolute timing of the fault activity onshore, as deduced from correlation to other fault systems with known ages, needs to be tested by dating of fault rock samples. A simple two-stage model has been outlined to explain the complex fault patterns exhibited in onshore exposures of the central Nagssugtoqidian orogen (Fig. 10).

The brittle tectonic evolution of the region appears to be dominated by NNE–WSW extension, which is consistent with the opening of the Labrador Sea and Baffin Bay. Only slight variations in the regional stress field are required to account for the diversity of fault orientations. According to Chalmers & Pulvertaft (2001) there was a 15° counter
clockwise rotation in spreading direction between the Paleocene and the Eocene in the Labrador Sea, opening started between Greenland and Europe, which is consistent with the two-stage model outlined in Fig. 10. In the early stages of opening, faulting was dominated by extensional structures (under 3-D strain conditions), favouring an E-W to NE-WSW extension (Fig. 10A); however, as the Ungava transform fault developed, faulting became more wrench dominated (2-D plane strain), and suggests NE-SW extension (Fig. 10B). Variations in fault geometry reflect these changes in the regional stress field. However, the influence of basement structure also appears to have played an important role throughout (e.g. extensional faults not normal to the extension direction, and the apparent localised compressional zones associated with intense basement fabrics). Although most faults observed onshore trend highly obliquely to basement fabrics, fault patterns do appear to vary in areas of intense pre-existing structure (such as the Nordre Strømfjord and Nordre Isortoq shear zones) which suggest that the fabrics within the Nagssugtoqidian orogen may have had some influence on the fault complexity of the Davis Strait.

The conclusions from this study show that the fault patterns and sense of movement on faults onshore reflect the stress fields that govern the opening of the Labrador Sea – Davis Strait – Baffin Bay seaway, and that the wrench couple on the Ungava transform system played a dominant role in the development of the onshore fault patterns.

Acknowledgements

The authors would like to thank BP (Norway) and Statoil (UK) for providing additional funding for this field research, and to NERC for funding R.W.W.’s Ph.D. research (NER/S/S/2001/06740). Thorough and insightful reviews from S. Bergh and T.C.R. Pulvertaft and additional help from the latter concerning numerous details are greatly appreciated. The bulletin editors, A.A. Garde and F. Kalsbeek, are also thanked for their helpful and encouraging comments.

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Manuscript received 26 October 2004; revision accepted 1 November 2005