DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2011/13

Notes on established structural profiles related to the 1:100 000 digital geological map of southern West and South-West Greenland, 61°30′ - 64°N

Nynke Keulen, John C. Schumacher & Thomas F. Kokfelt

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MINISTRY OF CLIMATE AND ENERGY

G E U S

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Abstract

This report presents geological details with emphasis on structural geology and structural profiles of three areas in southern West Greenland and in South-West Greenland (64-61.5°N): the area north of Buksefjorden, the area east of Bjørnesund, and the Atarngup area south-east of Paamiut. Work between Buksefjorden and Ameralik shows that no structural discontinuity exists between the Tre Brødre terrane and the Tasiusarsuaq terrane. Shearing along the alleged Qarliit Nunaat fault is associated with folding rather than evidence for a large scale structure. We propose that the Tre Brødre terrane is the outermost edge of the Tasiusarsuaq terrane. The Bjørnesund area is one of the few areas where the Fiskenæsset Complex and metavolcanic rocks are found into contact with each other. We show that the outcrops in the Bjørnesund area are chemically and structurally linked to the Ravn Storø metavolcanic belt. The Atarngup area has been interpreted to incorporate two blocks of different age and metamorphic history or as a nappe overlying younger gneisses. We have shown that the proposed block or nappe boundary does not exist, the metamorphic grade is constant over the area, and the ages of the gneisses scatter over the entire area and cannot simply be explained as two blocks with different ages. Instead we propose a single, long-lived subduction system that introduces gneisses to the area and causes shortening and a consistent metamorphic overprint.

We combined these detailed investigations with more reconnaissance-style observations in the whole area and with literature data. Based on these observations an overview over the folding events in the whole region was established. These observations have been combined with zircon age data into a table with 8 different events involving folding. A relative timing cannot be constrained for the earliest deformation between individual areas. The first main-foliation forming deformation occurred in the southern part of the area (Atarngup) between 2.92 and 2.85 Ga. A subsequent deformation event created the main foliation between Sermiligaarsuk and Grædefjord between 2.85 and 2.83 Ga. The event is tentatively correlated with the collision of blocks south of Frederikshåb Isblink and those in the Fiskenæsset-Bjørnesund area. The last deformation event took place at *c.* 2.71 Ga and is associated with the collision of the Færingehavn — Akia terranes and the Tasiusarsuaq terrane/Sermilik block. Deformation is observed from north of the studied area to Kvanefjord. A mild later overprint associated with the collision with the Kapisilit terrane at *c.* 2.67 Ga is observed in the northernmost part of the area.

Introduction

This report gives the results of the structural investigations that were produced in relation to fieldwork in southern West Greenland and South-West Greenland between 64° and 61°30′ N in the period 2008-2010. The report is part of the so-called ‘Homogenisation project’, which is a joint project between the Greenland Bureau of Minerals and Petroleum (BMP) and the Geological Survey of Denmark and Greenland (GEUS). The main results of this project are presented as a seamless digital web-based 1:100 000 scale geological map. Apart from the geology (lithology) and field data, the map has a number of theme layers; one of those is dedicated to structural profiles. This report gives further information on these profiles and provides some general remarks on the geology in the area.

This report is structured as follows: after a general introduction, details are given for three selected areas: 1) the area between Ameralik and Buksefjorden, 2) Bjørnesund-Ravn Storø, Nigerlikasik, and 3) Atarngup (SE of Paamiut). Together with some of the observations of Kolb et al. (2009, 2010, pers. comm. 2011), who studied the areas intermediately north of the Ilivertalik granite, Sermilik-Grædefjord, west of Bjørnesund, in the Tartoq Group and east of Paamiut, and of Klausen et al. (2011), who studied the area around Frederikshåb Isblink, some general structural trends of the area will be discussed. See Figure 1 for an overview of the locality of these areas.

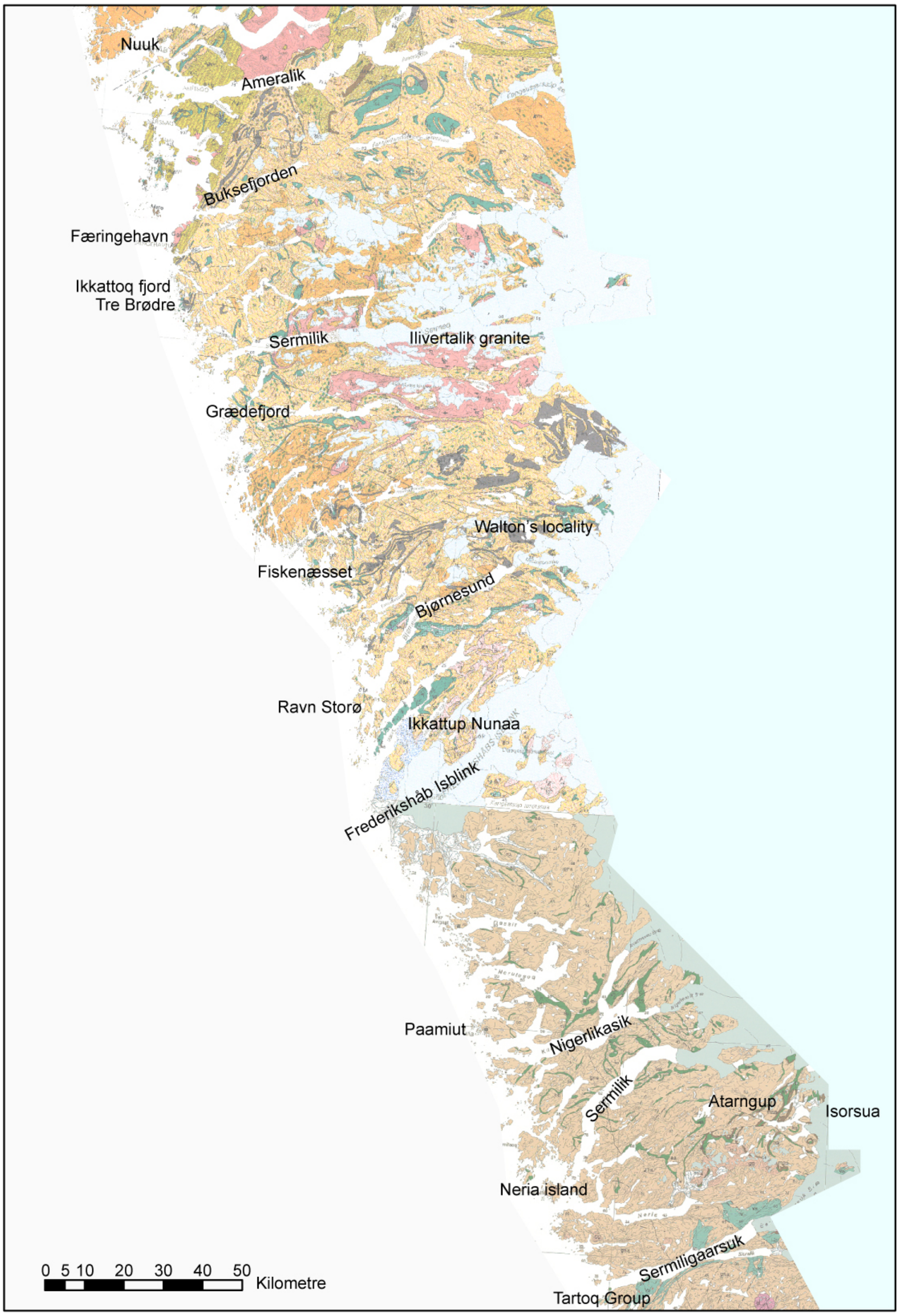


Figure 1: Overview of the place names for areas and fjords indicated in this report. Included are the more geology-based names Ilivertalik granite and the Tartoq Group.

General overview of the structures in the area 64° – 61°30′ N on Greenlands western coast

Terrane model

Based on fieldwork and laboratory measurements in a period of circa thirty years, C.R.L. Friend, A.P. Nutman, V.M. McGregor and co-workers developed a terrane model for the area between the Gothåbsfjord and Sermiligaarsuk (e.g. Nutman et al. 1993, 2004, Nutman & Kalsbeek 1994, Friend et al. 1996, McGregor & Friend 1997, Friend & Nutman 2001, 2005, Nutman & Friend 2007). This model divides the area between Ameralik and Frederikshåb Isblink into three terranes (Færingehavn terrane, Tre Brødre terrane and Tasiusarsuaq terrane). The fault zone between the Tre Brødre and Tasiusarsuaq terranes is called Qarliit Nunaat fault (e.g. Crowley 2002). Five additional blocks were described for the area south of Frederikshåb Isblink, from north to south Sioraq block, Paamiut block, Neria block, Sermiligaarsuk block and the Tartoq Group. An overview of these blocks and terranes is given in Figure 2. The terrane model is strongly dependent on geochronological measurements (SHRIMP Zircon U/Pb measurements), combined with field observations. Terrane boundaries are described as usually narrow shear zones with acclaimed differences in metamorphic grade between some of the blocks and a different thermal-chronological history. The Færingehavn terrane consists of mainly Eoarchaean gneisses, while the other two terranes are noted for mainly Mesoarchaean gneisses.

Block model

Windley and Garde (2009) published a counter model that divides the area in three blocks (Sermilik block, Bjørnesund block and Kvanefjord block), while the northernmost part of the area is defined as the Godthåbsfjord-Ameralik belt (see Figure 2 for details). The latter roughly overlaps with the Færingehavn terrane within the area south of 64°N. Each block is described with an upper zone consisting of prograde amphibolite-facies mineralogy and a partly retrogressed granulite-facies lower zone. In the Bjørnesund and Kvanefjord blocks these granulite-facies rocks are found along the northern part of block, caused by a south-facing tilting of the block, while Sermilik block is curved and has the highest grade rocks in the central part of the block. The blocks developed as several different micro-continents that were largely generated by growth of island arcs, followed by growth of active continental margin arcs and tectonic accretion in the Archaean or Palaeoproterozoic. As opposed to the terrane model, Windley and Garde (2009) point out that these micro-continents or blocks can go through the same development stages simultaneously and possibly even at short distances from each other, thus yielding similar kinds of rocks, while a classical terrane model rather suggests an accretion of unique, atypical entities (Sengör & Dewey 1990).

Figure 2: Terrane model after Friend, Nutman and co-workers (left). Boundaries are drawn after Nutman & Friend (2007) and Friend & Nutman (2001). The Tartoq Group is considered as a separate unit. The boundary under Frederikshåb Isblink is projected. Question marks indicate uncertainties in the exact locality of the boundaries.

Block model after Windley & Garde (2009, right). Tartoq Group rocks form the top of the Kvanefjord Block.

Similarities between both models exist: the authors agree on the special position of the Eoarchaean rocks in the Gothåbsfjord, on a structural boundary under Frederikshåb Isblink, while the boundaries of the Kvanefjord block and Neria nappe of Windley and Garde (2009) are based on a reinterpretation of the work of Friend & Nutman (2001) and McGregor &

Friend (1997). However, Windley and Garde include the Tre Brødre terrane in the Sermilik block, divide the Tasiusarsuaq terrane in two separate blocks: the Sermilik and Bjørnesund blocks. And they combine the Paamiut block, Sioraq block and Tartoq Group into the Kvanefjord block. In the discussion we will discuss some of these controversial areas.

Terranes in the area north of Buksefjorden

This chapter is an extension to the abstract published as Keulen et al. (2009b). Our co-workers in this abstract are gratefully thanked for their help.

Introduction

A folded terrane boundary, the Qarliit Nunaat fault, between the Tre Brødre Terrane (outer part of fold on the Buksefjorden map sheet) and the Tasiusarsuaq Terrane (inner part of fold) in the area north of the Buksefjorden has been proposed (e.g. Friend et al. 1996, Crowley 2002, Nutman & Friend 2007, see Figure 2). This terrane boundary is mainly based on geochronological work, although a terrane by definition (Sengör & Dewey 1990) is based on a structural and metamorphic discontinuity. The terrane boundary was revisited in 2008 in order to find metamorphic petrological (different PTt-history or break in metamorphic grade) and structural (significant tectonic structure between the two areas) evidence for the proposed terrane boundary.

Figure 3: West-vergent thrust zone with mylonites on the northern side of the Ikkattoq fjord. The thrust zone is c. 4 km wide and emplaces gneiss of the Tasiusarsuaq terrane on top of the much older gneiss of the Faeringehavn terrane. Hammer head point towards the North. Locality: 09NTK115 (63.64 N, 51.47 W)

South of Buksefjorden we observed intensive shearing between the Færingehavn and the Tasiusarsuaq terranes (cf. Crowley 2002; Friend et al. 1987), an example from the Ikkattoq fjord is given in Figure 3. The Tre Brødre terrane is here only a few kilometres wide. However, the tectonometamorphic styles are different at either side of the Buksefjorden. Here we will discuss the area north of Buksefjorden in more detail.

Geology

The major lithologies in the area between Buksefjorden and Ameralik are grey biotite gneiss, leucogabbroic granofels (‘anorthosite’) and two types of supracrustal rocks: mica schist and gneiss, and amphibolite. These lithologies are cut by at least two generations of mafic dykes, the early generation was folded and boudinaged by the deformation event that formed the main foliation, while the younger generation is cross-cutting these deformation structures.

Supracrustal rocks: mica schist and gneiss, and amphibolites

Within the area several units occur that originally were mapped as meta-sedimentary rocks and they are shown as mica schist’s and gneiss on the new map. Within the studied area, these rocks have a granodioritic composition (plag ±bt ±qtz ±gt ±crd ±Ksp, ±sill), are medium grained and have a uniform grain-size distribution on a meter scale. They show a well-developed 0.5-1 cm spaced foliation. These rocks are either derived from greywackes, or from volcaniclastic sediments or igneous rocks. This map unit most likely comprises a whole range of rocks, which do not necessarily all have the same protolith and were not necessarily all formed at the same time. For further details on the supracrustal rocks. see Schumacher et al. (2011).

Amphibolite (hbl ±plg ±gt ±act) occurs as layers, lenses, boudins, and map-scale units within the grey btiotite-gneiss and leucogabbroic granofels (see Fig. 4). The PT-estimate for the amphibolites suggest mid- to upper amphibolite-facies peak metamorphism with no evidence for earlier higher-grade assemblages (see Schumacher et al. 2011 for details). Associated with these amphibolites, ultramafic bodies (olv opx ±cpx ±bt ±act ±molybdenite) are found as layers or en echelon lenses in amphibolitic rock units. An example was discussed in Keulen et al. (2009a).

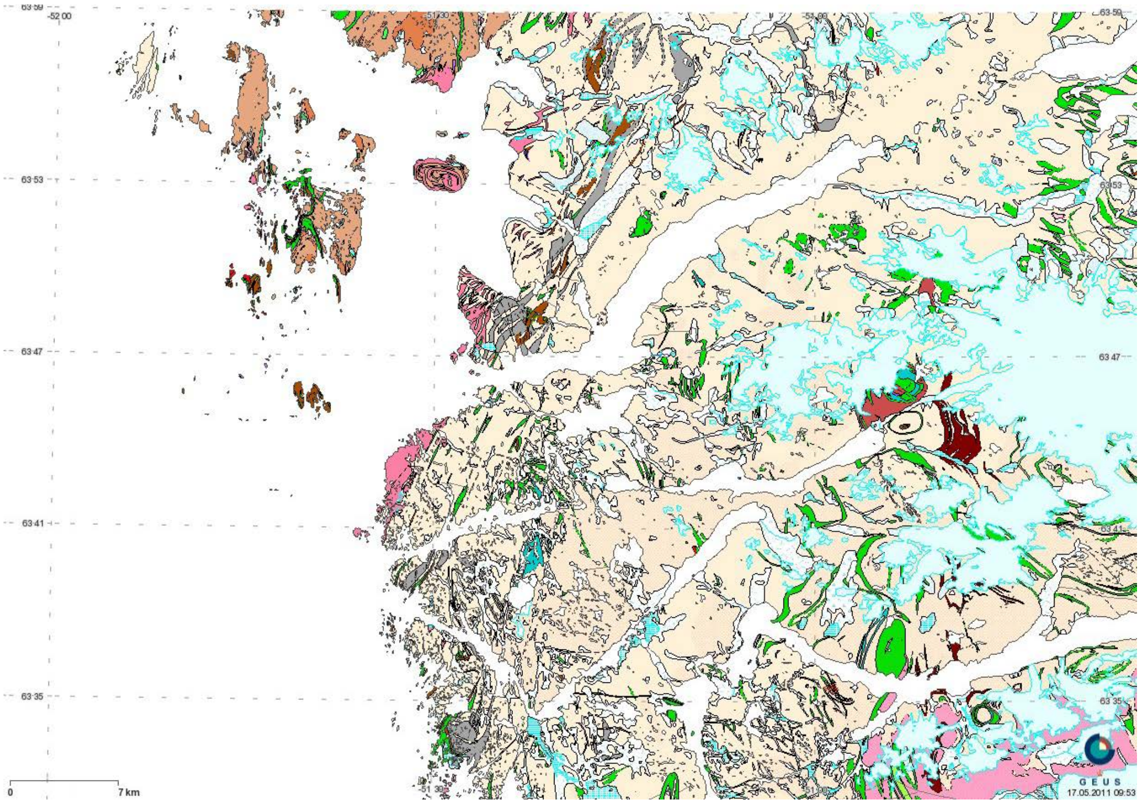


Figure 4: Map of the Buksefjorden area, extracted from the 1:100 000 web-accessible map of southern West and South-West Greenland (Keulen & Kokfelt et al. 2011). Amphibolites are indicated in green, leucogabbroic granofels in grey, gneiss in yellowish salmon, granites in pink, mica schists in brown. See http://geuskort.geus.dk/gisfarm/svgrl.jsp for details.

Leucogabbroic granofels

The leucogabbro (plg, hbl, ±qtz, ±gt, ±act, ±epi) is massive white granofels that has been mapped as anorthosite. The rocks show *c.* 60-90% plagioclase. Actinolite and epidote only occur locally. Locally, within the leucogabbroic rocks, *c.* 1-20 cm scale amphibolitic layers occur. Pegmatitic injection veins into the plagioclase-rich rocks formed spotted black-and white texture (hbl-plg) and a layered intrusion complex (Fig. 5). The leucogabbro shows a very weakly developed wide spaced foliation.

The leucogabbroic granofels shows an intrusive contact with at least part of the supracrustal rock units. Some of the mica schist and gneiss might have been deposited on top of the leucogabbroic granofels after the intrusion. Some shearing is observed at the contact of the mica schists and the leucogabbroic granofels at the west-side of the fold structure in the eastern part of the investigated area and at the eastern side of the fold structure in the western part of the fold structure (discussed below).

Figure 5: Minor shearing in leucogabbroic granofels and the adjacent gneiss. Expression of the proposed Qarliit Nunaat fault in the landscape.

Grey biotite-gneiss

In the area northwest of the Buksefjorden grey biotite-gneiss (bt, plg, qtz, ±gt, ±hbl, ?Ksp) is the major rock unit found in the outcrop. The gneiss is most probably of igneous origin in the entire areas and yields layering and gradation with mineralogical variation between tonalite, trondhjemite and granodiorite composition. These variations were described in more detail by Chadwick & Coe (1983). Its grain size ranges from fine to coarse grained, but is in general medium grained. The gneiss has a *c.* 0.5 – 3 cm spaced foliation, depending on the relative abundance of biotite and the more equidimensionally shaped minerals. The foliation is generally well developed. Mainly within the map-scale fold structure north of Buksefjorden,1 cm – 1 m scale lenses and layers of amphibolite and leucogabbro were incorporated into the gneiss. The gneisses are isoclinally folded, with fold axial traces parallel to the main foliation (Fig 6).

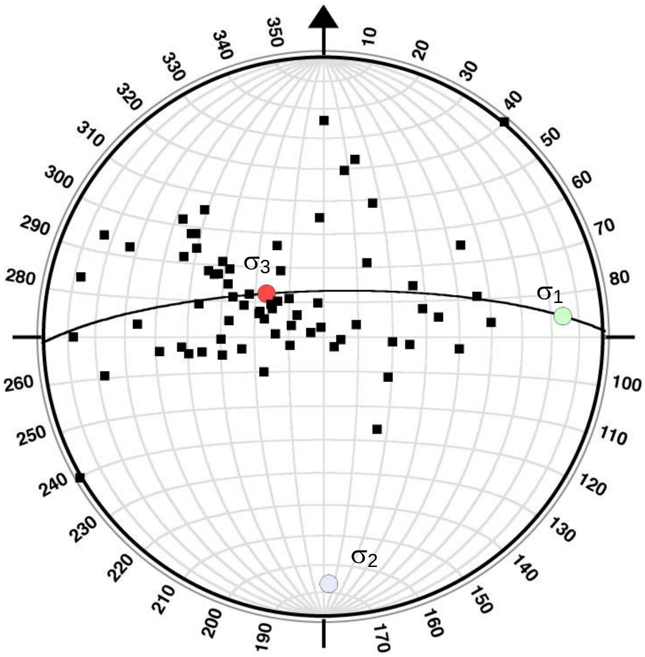
Figure 6: Grey biotite gneiss with amphibolite lenses and layer (indicated in black). The amphibolite occurs within a refolded nearly-isoclinal fold within the gneiss.

The grey biotite gneiss and the leucogabbroic rocks show two types of contacts. The leucogabbros-gneiss contact at the inner side of fold structure is mainly non-tectonic. A gradual transition from leucogabbroic granofels to gneiss is observed, however some evidence for minor shearing was observed. More intensive shearing was observed at the leucogabbro-gneiss contact at the outer side of the fold, especially where mica schist is sandwiched between the two more competent lithologies.

Structures north of Buksefjorden

Folding

At least four folding-events are recorded in the area north of Buksefjorden. The leucogabbroic granofels is formed by a tightly folded sheet with a flat-lying axial plane, or possibly by two parallel layers of leucogabbric material (see section on the structural profile; Fig. 10). This folding might be related to the intrusion of the leucogabbroic granofels into the crustal rocks. Isoclinal folding is observed in the gneiss and might related to the intrusion of its protolith. Related or unrelated to this, the leucogabbroic granofels was positioned with its fold axial plane in a roughly horizontal position.



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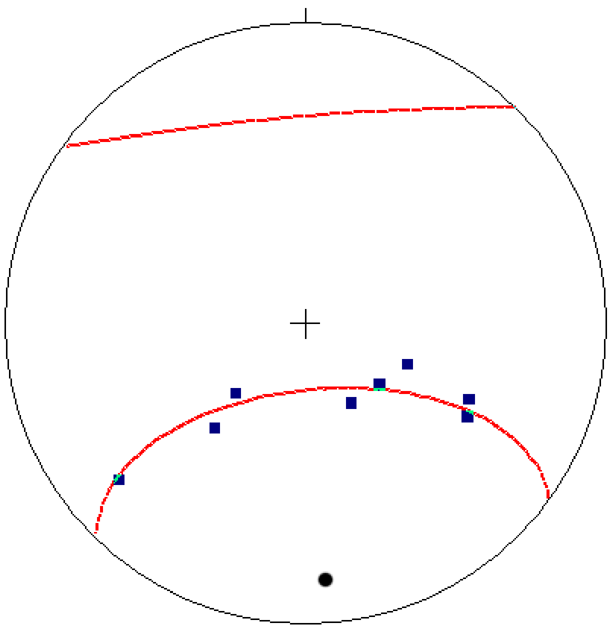

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Figure 7: a) Poles to planes of main foliation in area NW of Buksefjorden. N-S striking fold axial plane and shallow S- dipping fold-axis. The green, white and red dots indicate the directions of the principal stresses σ_1, σ_2, and σ_3, respectively. The fold axis lies at the position of the white dot. b) Mineral stretching lineations for the shear rocks of the alleged Qarliit Nunaat fault (blue squares). The data lie on a small circle of 52 degrees centred around 175/20. The black dot indicates the fold axis discussed in a).

The main foliation in the gneiss, the supracrustal rocks and even in the leucogabbroic granofels is defined by a large scale folding. This fold zone is visible on the 1:500 000 and 1:100 000 maps, on which the leucogabbroic granofels occurs as a marker horizon. The large-scale structure in the area is defined by a relatively open fold-structure with a steep dipping axial plane and a shallow SSE-SSW dipping fold axes (Figs 7 & 8). The fold has a wavelength of several kilometres.

After the folding that caused the main foliation a mild north-south compression caused a long-waved buckling of the fold structure.

Figure 8: Example of folding in the leucogabbroic granofels.

Shearing

Some shearing was observed in the gneiss near the proposed Qarliit Nunaat fault, with both dextral and sinistral directions. Shearing occurs at the contact between different lithological units (mica schist - leucogabbro; leucogabbro - gneiss), but also within specific rock units (e.g. in the leucogabbro 08NTK047; 63.95432182N, -51.17073349E). As noted by Friend et al. (1996), these shear zones are no wider than 100 m and often only tens of meters or less. In many places only a mild shearing was observed, without the complete development of a mylonitic foliation.

However, a similar amount of shearing is observed away from the alleged Qarliit Nunaat fault (see e.g. Fig 9), in shear zones that are tens to hundreds of metres wide. Thus a valid conclusion seems to be that either the position of the Qarliit Nunaat fault is poorly defined, or that another mechanism is responsible for the shearing. Here we propose the second solution.

The orientation and movement directions of these small-scale shear zones fits with flexural slip during folding (Fig 7b), rather than shearing before folding. Ramsay (1967) indicated that deformed lineations that are associated with flexural slip during folding plot on a small circle, while those associated with shearing plot on a great circle. Thus, no structural discontinuity was observed between the Tasiusarsuaq and the Tre Brødre Terrane.

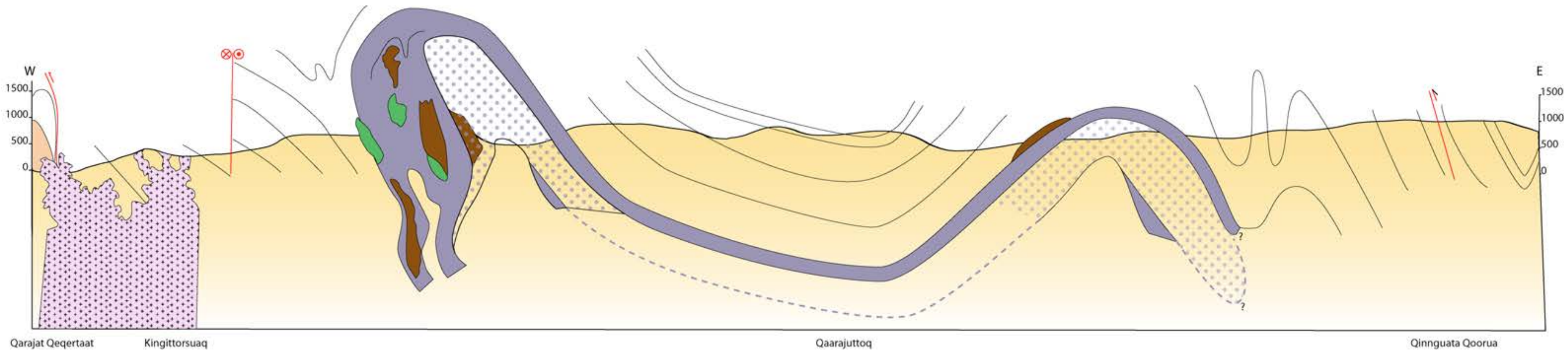
Within the area, no significant (i.e. wide and high strained) shear zones were observed, except on the peninsula at the mouth of the Buksefjorden (08NTK077;63.81712453 N, -51.34502366E). This shear zone is at least 400 m wide, and nearly completely mylonitic. Pegmatites and gneiss within the shear zone are partially sheared and saussuritised (Fig. 9). This steep-dipping sinistral shear zone strikes roughly SSE-NNW, with a dominant lineation dipping 30-60° SE and locally down-dip. It is likely that this shear zone is the northward continuity of the large shear zone south of the Buksefjorden. However, this shear zone cuts through the fold structure in the Buksefjorden area. The relative age of this shear-zone is therefore younger than the folding event unrelated to the formation of the Qarliit Nunat fault. On the detailed geological maps (Sharp 1975) can be seen that the mylonite cuts off Palaeoproterozoic dolerite dykes. The saussuritisation suggests that deformation occurred at greenschist-facies conditions. This shear zone is thus unrelated to the folding events and the possible occurrence of folded terrane boundaries in the area.

Figure 9: Saussuritised sheared gneiss. plag + qtz + bt → epi + qtz + chl.

Structural profile

Figure 10 shows the large-scale structure in the area north of the Buksefjorden. The profile strikes roughly west-east between 511200E/7094513N and 477357E/7088144N (WGS84 – UTM 22N).The fold axes dip with a shallow to intermediate angle towards the SSE-SSW, while the axial planes are near-vertical. This means that feature outcropping north of the profile are shown below the topography line, while features observed south of the profile line are indicated “in the air”.

Figure 10 (next page): West-east profile north of Buksefjorden between 511200E/7094513N and 477357E/7088144N (WGS84 – UTM 22)*. Gneiss in yellow (Færingehavn terrane gneiss in a more orange shade), leucogabbroic granofels in greyish purple, indications of occurrences of mica schist and gneiss in brown, and of amphibolites in green. Includes extrapolation from short distances above and below the profile line. Continuation perpendicular to the profile line is indicated in Figure 11.*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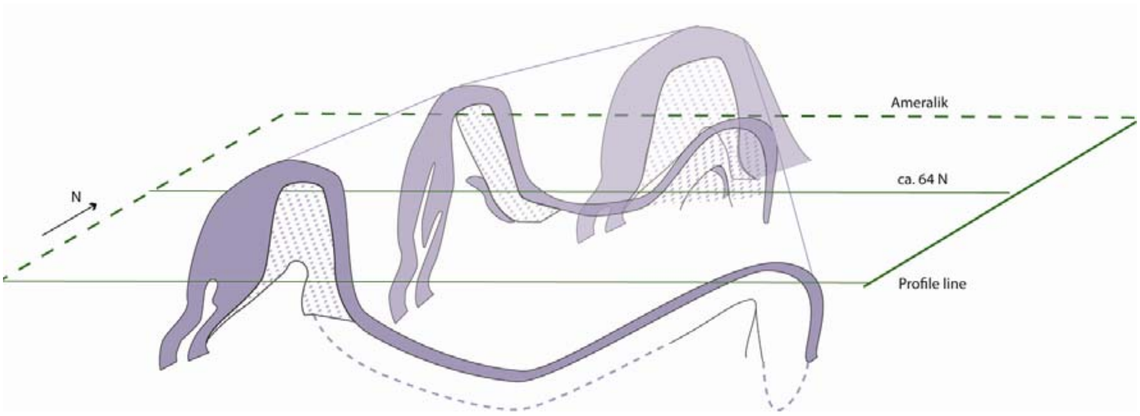


Figure 11: Schematic overview of the foldzone in the Buksefjorden in three parallel profiles at Ameralik, at c. 64°N and at the profile line. The shape of the profile is indicated by the leucogabbroic granofels. Green lines indicate the approximate position of the current day surface.

The leucogabbroic granofels is the most dominant features in the profile, defining the outline of the fold. This rock unit consists of a tightly folded flatlying fold or of two parallel sheets of leucogabbroic rock. Since gneiss intruded the leucogabbro before folding, the original shape is somewhat obscured. In the profile, the option of a fold closure at the eastern end of the fold has been chosen and is displayed. The gneiss between the two limbs, or two sheets, is full of small bodies, lenses and boudins of leucogabbroic rock.

The Færingehavn terrane is indicated in the far west end of the profile in a darker shade of orange. A larger portion of Færingehavn terrane than indicated on the profile might exist in the lower part of the profile. The contact between the gneiss in the east (Tasiusarsuaq terrane and proposed Tre Brødre terrane) is a steep thrust plane with later sinistral slip. Some smaller thrusts that are included on the Buksefjorden 1:100 000 map sheet indicate a west-vergent movement. These thrusts help to accommodate the folding, they do not yield a large displacement, based on their off-set of marker horizons.

The proposed Tre Brødre terrane can be found in the profile as the gneiss between the two sheets of leucogabbro, the gneiss between the Færinghavn terrane and the leucogabbroic granofels in west of the folded leucogabbro, and the gneiss underneath the lowermost leucogabbroic layer.

Figure 11 shows that the wavelength of the folds narrow towards the north. Northwards, the amplitude of the folded layers increases, the wavelength decreases and the synform between the leucogabbroic granofels antiforms indicated in the profile merge into one larger antiform. This feature can also be observed in orientation of the fold axes on the geological map, which are fanning out from Ameralik towards the south.

Late deformation events

Late deformation features include 1) two conjugate sets of quartz veins, locally (e.g. 08NTK040; 63.92788167N, -51.25008E) filled with sulfide minerals, indicating a roughly north-south directed extension. 2) Cataclastic fault zones (e.g. at 08NTK009;

63.94782607N, -50.95728863E) and a pseudotachylyte/ultracataclasites (e.g. 08NTK0032; 63.93215167N, -51.21977667E) both indicating south dipping lineation, were observed within the area north of the Buksefjorden. 3) Epidote veins and open fractures striking E-W. 4) Late (i.e. unaffected by the folding) dolerite dykes striking E-W. These four features are not necessarily all related or contemporaneous, but indicate a change in the orientation of the major stresses in the earth's crust (σ_3 shallow N-S oriented).

Tectonometamorphic development

The area between Buksefjorden and Ameralik

The map-scale fold structure NW of the Buksefjorden appears as a complicated refolded fold on the map. This structure can be explained with a single folding episode of a double sheet of leucogabbroic rocks and a dipping fold axis. See Figure 10.

We find no evidence for a metamorphic discontinuity across the proposed Tasiusarsuaq - Tre Brøde terrane boundary. Both sides of the proposed structure had their peak metamorphic assemblage at middle-upper amphibolite facies conditions.

Folding, rather than shearing, is the dominant mode of shortening within the area north of Buksefjorden, as hardly any large shear zones were observed. Small scale shearing occurs within and between several of the units in the fold-structure. These small scale shear zones do not fit, neither in size nor in movement direction, with the notion of a single folded thrust contact along the Qarliit Nunaat thrust for the following reasons: 1) Thrusting would be expected to occur pre-dominantly in the mica schists and biotite-rich parts of the gneiss, since these rocks consist of abundant mica and quartz, which are the two minerals that are most susceptible to plastic deformation at amphibolite facies conditions. However, shearing occurs just as commonly in plagioclase- and hornblende-rich rocks. 2) For a folded thrusted contact, one shear sense direction all along the fold should be expected. In fact, the shear sense orientation flips between dextral and sinistral along the alleged contact. 3) The Qarliit Nunaat thrust is indicated along the gneiss-leucogabbroic granofels contact. The most intensive shearing, especially in the western part of the structure, does not occur along the contact between those two units, but on contacts of other units within the fold structure.

Therefore, we propose that shearing occured related to flexural slip on layers and stretching within layers resulting from folding, rather than as a result of a significant thrusting event. A terrane boundary between the Tre Brødre terrane and the Tasiusarsuaq terrane is thus not constrained.

Crowley (2002) and Friend & Nutman (1996) describe and age of 2.82 Ga for the Ikkattoq gneiss in the Tre Brødre terrane and ages of 2.84- 2.92 Ga for the Tasiusarsuaq terrane. Additional samples were dated in relation to the current project (Kokfelt et al. 2011). Zircons from a mylonitic gneiss in the proposed Tre Brødre terrane were dated at 2.82 Ga and represent zircons from the gneiss in the wall rock of a shear zone. A tonalitic gneiss from within the Tasiusarsuaq terrane north of the Buksefjorden yield an unconstrained age of c. 2.83 Ga, or possibly two age components at 2.85 and 2.82 Ga. Næraa (2010) dated a few samples from the northernmost part of the Tasiusarsuaq terrane to

2.83-2.84 Ga, the same ages were observed in sediment samples from streams dewatering gneiss south of Ameralik (Thrane et al. 2010, confidential GEUS report).

These data suggest that either the Tasiusarsuaq terrane and the Tre Brødre terrane overlap in age, or there are rocks of broadly the same age in the Tre Brødre terrane and the Tasiusarsuaq terrane. The ages of the Tasiusarsuaq terrane just east of the Qarliit Nunaat thrust are therefore within error of those for the Ikkattoq gneiss. A division into two terranes is thus not necessarily based on geochronological evidence.

The age of the main deformation event north of Buksefjorden was determined by dating a series of deformed and undeformed pegmatites cutting through the fold-axial plane or the longest limb of the folds. Both sets of data yield the same age, indicating that the emplacement of these sheets is a syn- to late-tectonic event. The pegmatite dykes in the core of the large-scale fold structure north of the Buksefjorden were dated at 2.72 Ga. The ages coincide with discordant granite sheets dated by Friend et al. (1996) at 2.72 Ga, and with a 2.72 Ga old tonalite intrusive sheets (Næraa & Schersten, 2008), both in the Tasiusarsuaq terrane. Additionally these ages correspond to 2.74-2.70 Ga prograde amphibolite-facies metamorphism in the Tre Brødre terrain near Skinderhvalen (Crowley, 2002).

Correlation with the structures to the south of Buksefjorden

In the area east of Skinderhvalen, north of Færingehavn, a large shear zone stretching 197° with mylonites on both sides was observed. This shear zone was wider and more intensely mylonised than any observed shear zone in the NW Buksefjorden area, except the one described above (08NTK077). Quartz in the mylonites showed long ribbons and microlithons in a habit that is more typical for feldspar. Around Tre Brødre the rocks were mildly deformed (sinistral shear along a zone stretching SSW-NNE), whereas the rocks north and slightly further inland from Tre Brødre were only slightly deformed (mild shearing in the pegmatites).

We propose that the wide mylonite zone observed near Færinghavn (Crowley 2002, Friend & Nutman 1996) is an expression of the thrusting between Færingehavn and Tasiusuarsuaq terranes, rather than the Tre Brødre and Tasiusarsuaq terranes. The five kilometre-wide Tre Brødre terrane is, north and south of the Buksefjorden, the outer edge of the Tasiusarsuaq terrane.

On the geological map no leucogabbroic granofels outcrops are indicated in the Færingehavn area, whereas these units continue further south in the Tre Brødre area. One way to explain this is by a block uplift of the NW Buksefjorden and Tre Brødre area relative to the Færingehavn area. This would expose a different crustal level near Færingehavn, such that the leucogabbroic granofels rocks do not crop out and the deformation style at the contact between Færingehavn and Tasiusarsuaq is expressed as a wide mylonite zone rather than mainly by folding. At slightly higher crustal levels (at greenschist-lower amphibolite conditions) mylonitic fault zones are a more common mechanism to accomodate crustal shortening.

A structural link between the amphibolites in the Bjørnesund and Ravn Storø areas

This chapter is an extension to the abstracts published as Keulen et al. (2010b) and Keulen et al. (2011a). Our co-workers in those two abstracts are gratefully thanked for their help.

Introduction

The Bjørnesund anorthosite-greenstone belt is located on both sides of Bjørnesund (fjord) just south of 63ºN in southern West Greenland (Fig. 12). This belt consists of amphibolite and anorthosite, ultramafic lenses, a quartz-dioritic gneiss, and is intruded by granites and granodiorites, and surrounded by granodioritic to tonalitic grey orthogneisses (Fig. 12). The Bjørnesund belt is an amphibolite-leucogabbro-diorite association interpreted as an amphibolite-facies grade equivalent of a greenstone belt.

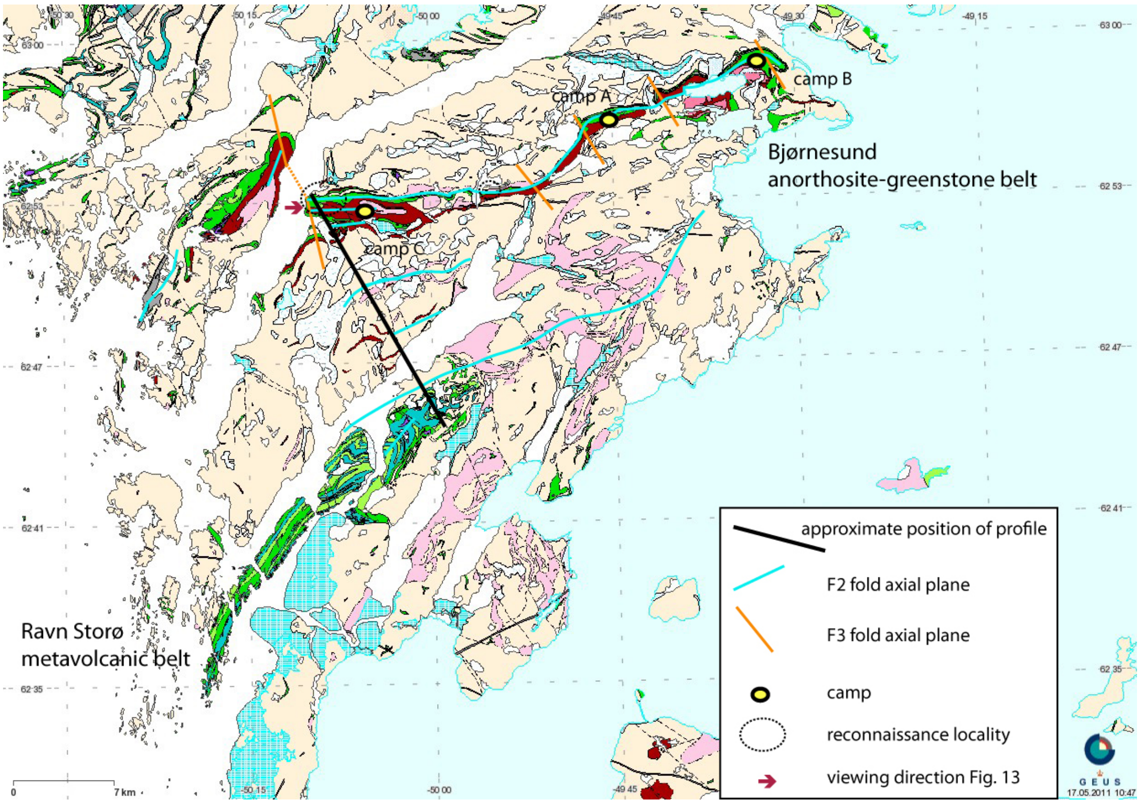


Figure 12: Part of the 100K Bjørnesund map sheet (Escher 1985) extracted from the 1:100,000 web-accessible digital map of southern West and South-West Greenland (Keulen, Kokfelt et al. 2011), showing the amphibolite (green)-diorite (dark red)-anorthosite (grey)-complex, the location of the camps A-C and the ReCo stops. camp B = camp by Vincent van Hinsberg, Brian Windley, and Kristoffer Szilas; camp C = camp by Denis Schlatter and Yong Chen. Axial plane traces of F3 and locally F2 folds (FAP) are shown. The arrow indicates the view direction of Figure 13.

Non-tectonic contact relationships between the Fiskenæsset complex (FC; southern West Greenland, *c.* 62.5-63°N) and adjacent meta-volcanic amphibolites are rare. Undisturbed contact relations between the intrusive Fiskenæsset complex and the amphibolites in the Fiskenæsset area can only be studied in a few places (e.g. Walton 1973; Escher & Myers 1975, Van Hinsberg & Windley, field observations 2009). However, the Bjørnesund anorthosite-greenstone belt is considered to be part of the FC (e.g. Myers 1985), and here the best-preserved amphibolites preserve primary volcanic structures such as lithic tuffs. These volcanic rocks are similar to those in the Ravn Storø metavolcanic belt (also known as Ikkattoq Nunaa belt). Therefore, the Bjørnesund anorthosite-greenstone belt provides an ideal opportunity to explore a possible genetic relationship between the Ravn Storø metavolcanic belt and the Fiskenæsset complex and to investigate the structural relationships between the two units. Furthermore, the Bjørnesund anorthosite-greenstone belt is the only area in southern West Greenland where amphibolites occur in contact with diorite.

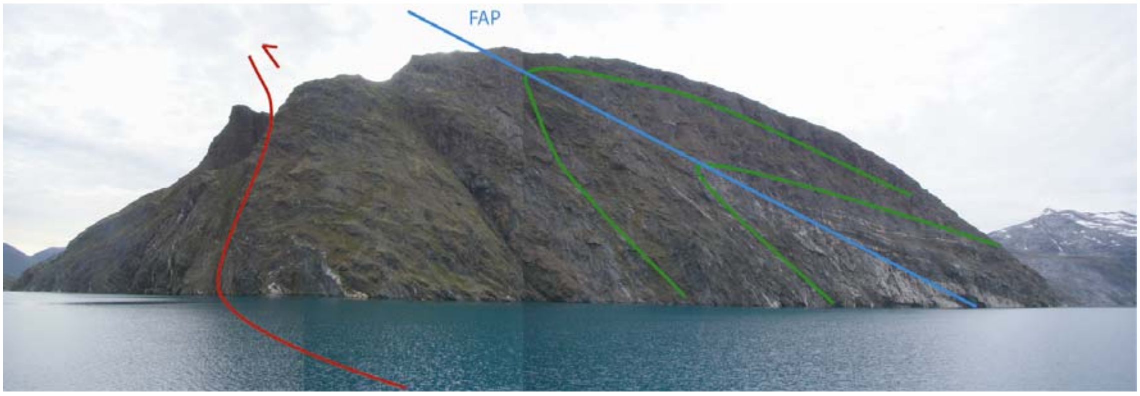


Figure 13: An overturned fold of the Bjørnesund anorthosite-greenstone belt as observed from Bjørnesund looking to the east. FAP indicates the F2 fold axial plane. See Figure 12 for locality.

Geology

The amphibolite layers are locally (e.g. near camp A at 62.95º N, 49.76º W; see Fig. 12) very intensely deformed. However, further east (at camp B at 62.99ºN, 49.54ºW; see Fig. 12) the amphibolites are almost undeformed. The amphibolites contain similar lithostratigraphy, volcanic structures and rocks as in the Ravn Storø metavolcanic belt. For example, layered leuco-amphibolites, coarse homogeneous mela-amphibolites, lithic tuff fragments in leuco-amphibolite, and very diagnostic aplite dykes containing garnets with leucocratic haloes. In the Ravn Storø metavolcanic belt the undeformed and little deformed equivalents of the upper part of the Bjørnesund layered amphibolites contain pillow lavas, interlayered leuco-amphibolites and mela-amphibolites, distinctive lithic tuffs, and aplitic layers and dykes containing garnets with leucocratic haloes (K. Szilas, V.J. van Hinsberg & B.F. Windley, pers. comm. 2009 and our own observations 2008, 2009). All these features are observed in the Bjørnesund anorthosite-greenstone belt east of the Bjørnesund as well.

The amphibolites on Ikkattup Nunaa are intruded by the gneiss. The contact is not very intensively deformed, but the amphibolites are internally deformed along faults and by folding. Andersen & Friend (1973) suggested that the rocks form a major synform, but observation from the fjords and interpretation of the structures from the geological map point to an antiform structure on the mainland north of Qeqertarssuaq Nunaa. The thrusting occurs in slatey (hence very fine grained) material on Qeqertarssuaq Nunaa, therefore the movement direction of the faulting is unknown on this island.

In the Bjørnesund area the assemblage hornblende, plagioclase, ± quartz, ± minor biotite is dominant for the amphibolites, but locally these rocks may contain garnet, cummingtonite or orthoamphibole. The presence of garnet is indicative of a bulk composition slightly enriched in FeO and lower in CaO, while the presence of cummingtonite and orthoamphibole suggests bulk compositions that are either richer in MgO or lower in CaO. Amphibolites that contain cummingtonite or anthophyllite are also typical of amphibolite- to upper amphibolite-facies conditions. Amphibolites in the Ravn Storø belt have slightly lower metamorphic grades (see Schumacher et al. 2011).

The protoliths of the amphibolites were intruded by a sheet, which mainly consists of leucogabbro (locally cumulate), gabbro and anorthosite locally with chromitite layers. Way-up criteria (anorthite-hornblende graded layers) indicate right-way-up in the south of the sheet but an inverted orientation in the north. The stratigraphy of the anorthosite is distinctly similar to that reported for the FC (e.g. Windley et al. 1973; Myers 1985). The anorthosite was folded into an isoclinal synform (F1/F2) that has also affected the diorite and amphibolites.

This leucogabbroic sheet will here be referred to by its name on the original 1:100 000 map: anorthosite (Escher 1985). The anorthosite was folded into an isoclinal synform (F1/F2) that has also affected the diorite and amphibolites (Fig. 14).

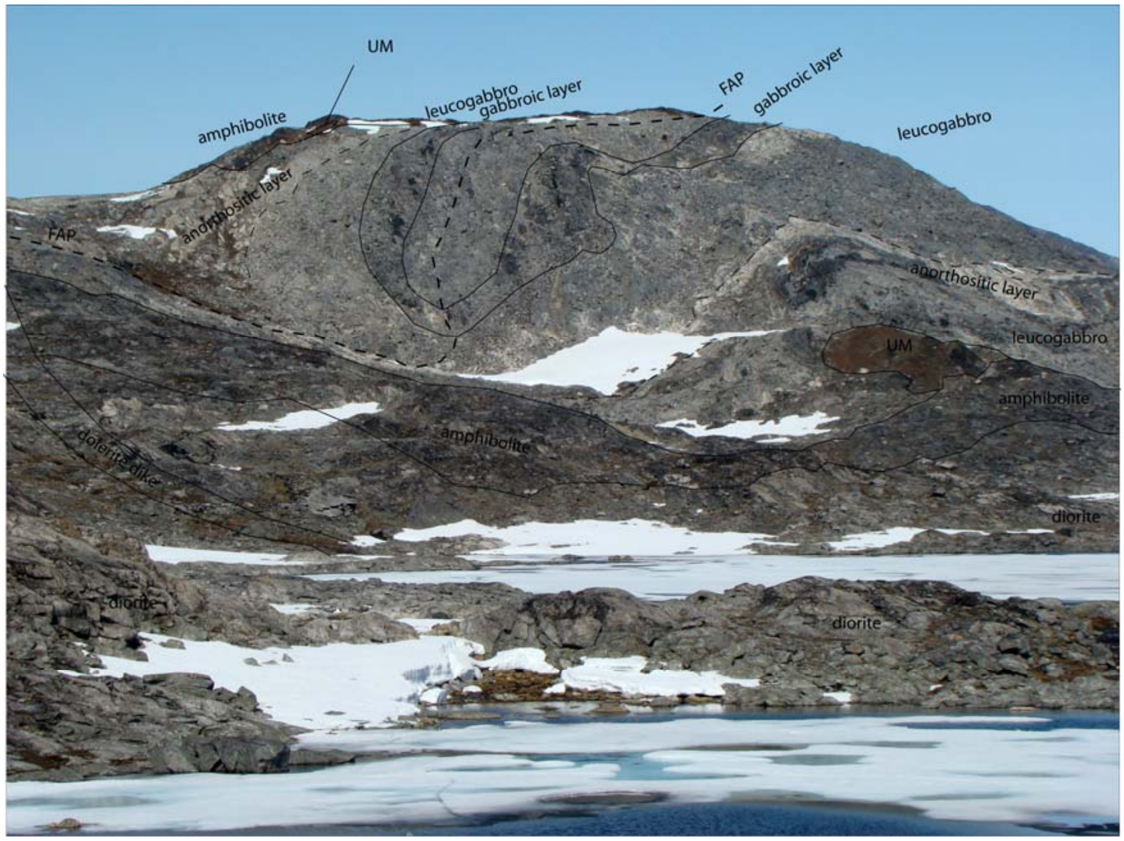


Figure 14. Isoclinally folded (FAP = F1/F2) leucogabbro, gabbro, anorthosite and amphibolite as seen near camp A.

Large lenses of ultramafic rocks occur locally along the contact of the amphibolites and the anorthosites. The central part of the ultramafic lenses consist of a nearly pure clinopyroxene body. The ultramafic rocks show variable degrees of post-emplacement (?) hydration and commonly contain anthophyllite along with relict diopside and possible orthopyroxene and olivine. Locally, *c*. 1 metre-thick metasomatic reaction zones (anthophyllite ± green pargasite ± green spinel ± sapphirine ± phlogopite) have formed at the contacts particularly in the presence of quartzo-feldspathic pegmatite. In these metasomatic zones pale-brown anthophyllite typically forms rosettes. At one locality, a pegmatite associated with the metasomatism contains iridescent orthoamphibole (up to 10 cm long) and subhedral cordierite up to 12 by >> 30 cm. At one location along the margin of this pegmatite, there is pink corundum in plagioclase (see Schumacher et al. 2011) for details. Chromite occurs on both sides of the UM body, not only in the anorthosites, where it is commonly reported in the Fiskenæsset complex, but also in the amphibolites. Chrome under most conditions is immobile. The presence of chromite commonly indicates the vicinity of a UM-body rather than a specific level in the anorthosite complex stratigraphy. Thus, it cannot be used as a stratigraphic marker in the Fiskenæsset complex.

The ultramafic bodies form σ-clasts in intensively sheared anorthosite. The anorthosites are mostly sheared to finely banded anorthosite mylonite. The shearing was facilitated by the presence of minor biotite (probably derived from intruding gneiss or pegmatites) in the anorthosite is associated with F2 folds, the axial planes of these folds strike N-S, as seen east of camp B.

The diorite is a medium- to fine-grained, homogeneous gneiss that consists of predominantly feldspar, minor quartz and biotite, and rare hornblende. Amphibolitic dykes transect the foliation at a low angle. A quartz diorite sample collected by Denis Schlatter in the western part of the Bjørnesund belt (Fig. 12) yielded a zircon U-Pb age of 2.919 ± 2 Ga (MSWD = 0.97, n/N = 61/64; Kokfelt et al. 2011).

The amphibolites and anorthosites discussed above were intruded by the protoliths of granodioritic to tonalitic gneisses. The tonalitic gneiss contains a variety of felsic layers and locally grade to Bt-granite composition. The gneisses show relatively complex zircon age patterns with a generally small ~2.89 Ga protolith age peak and a larger ~2.70 Ga metamorphic age peak. The gneisses, anorthosite, amphibolite, and diorite were affected by the F2 folding (Fig. 15). Late granites intruded the amphibolite-anorthosite belt; the largest is the Nukagpiarssuaq Granite that intruded an F2 fold core; it has a poorly constrained intrusion peak age of ~2.84 Ga and a large 2.74-2.70 Ga metamorphic age component. Two further granite samples with the same age bracket and the same structural setting were collected by Denis Schlatter in the western part of the Bjørnesund anorthosite-greenstone belt. Similar (~2.85-2.83 Ga) ages were also recorded for the granites in and around Frederikshåb Isblink (Kokfelt et al. 2011), many of those also have a similar setting, they occur in F2 fold cores.

Shearing is related and probably simultaneous to the second folding event, which has a fold axial plane that is nearly parallel to F1. The shearing does not have the same intensity along strike. Away from the ultramafic bodies, the foliation becomes almost slaty and the leucogabbro is locally enriched in biotite. Shearing seems to be enhanced in the limbs of the F2 fold.

The granites from the western part of the belt show very limited evidence for a ~2.70 Ga metamorphic overprinting in their zircon age distribution. A mild overprint of a later folding phase, F3, trending NNW-SSE has slightly bent the regional foliation, causing the staircase-like appearance of the Bjørnesund anorthosite-greenstone belt on the geological map (see Fig. 12).

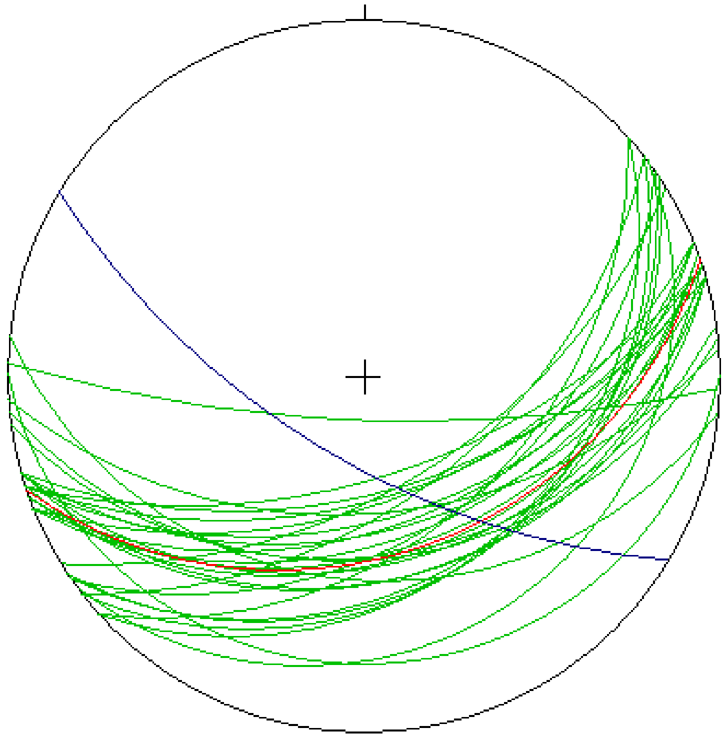


Figure 15: Foliations (green) in the area around camp A, with the F1/F2 fold axial plane (red) nearly parallel to the foliation and the F3 fold axial plane (dark blue, trending NW-SS) causing a light scatter in the orientation of the foliation.

On Ikkattup Nunaa pseudotachylytes and brecciation point to a late extensional stage of the deformation. They are probably unrelated to the tectonic movement that brought the areas south and north of Frederikshåb Isblink together, as was proposed by Windley & Garde (2009). Along the rock unit indicated as metasediments in the Bjørnesund anorthosite-greenstone belt on the original geological map sheet (Bjørnesund, Escher 1985) cataclasites and pseudotachylytes, but no mica schists, were observed. These brittle deformation features indicate a late reactivation of an earlier (D2) thrust movement (top to north). Other parts of the above mentioned metasedimentary unit are weathering horizons of amphibolite.

A large NNE-SSW striking vertical dipping fault zone cuts through all deformation features named above, possibly with the exception of some extensional features. It is probably acting as a minor-age-indicator for the series of events. This large fault zone runs through the outer Bjørnesund and can be traced up north towards the point where the Ilivertalik granite meets the inland ice. This fault zone is cut by two cross-cutting series of dolerite dykes. Their equivalents south of Frederikshåb Isblink were dated by Kalsbeek & Taylor (1985) at *c.* 2.1 Ga. It is therefore likely that the fault was active in the Palaeoproterozoic.

Summary

The observed stratigraphy of the anorthosite in the Bjørnesund Anorthosite-Greenstone belt is distinctly similar to that reported from the Fiskenæsset complex (e.g. Windley et al. 1973; Myers 1985). Compared with the stratigraphy of the Fiskenæsset Complex (Myers 1985), the gabbro-leucogabbro-anorthosite units occur with ultramafic lenses and their sapphirine-bearing metasomatic zones, and with the bordering metavolcanic amphibolites, but the Upper Gabbroic Unit (Myers 1985, p. 14) is absent. The observed distribution of rocks outlines a synclinal structure in the Bjørnesund area, which is comparable with that of the Fiskenæsset complex farther north. The orientations of F2 and F3 fold axial planes are concordant with those of the Fiskenæsset complex (Myers 1985).

In addition to the connection of the Ravn Storø metavolcanic belt and the amphibolites of the Bjørnesund anorthosite-greenstone belt suggested by the stratigraphy, there is also a structural connection, which is demonstrated by a cross-section between the two areas (Fig. 16). The amphibolites in the two areas are parts of the same sheet of extrusive rocks that were folded and thrusted (probably with only minor displacement) during the regional D2 deformation event. New information on the stratigraphy, geochronology, geochemistry, structural geology, and metamorphic petrology further unraveled the history of the Bjørnesund anorthosite-greenstone belt and showed that the FC and the Ravn Storø metavolcanic belt have an intrusive contact that was tectonically overprinted.

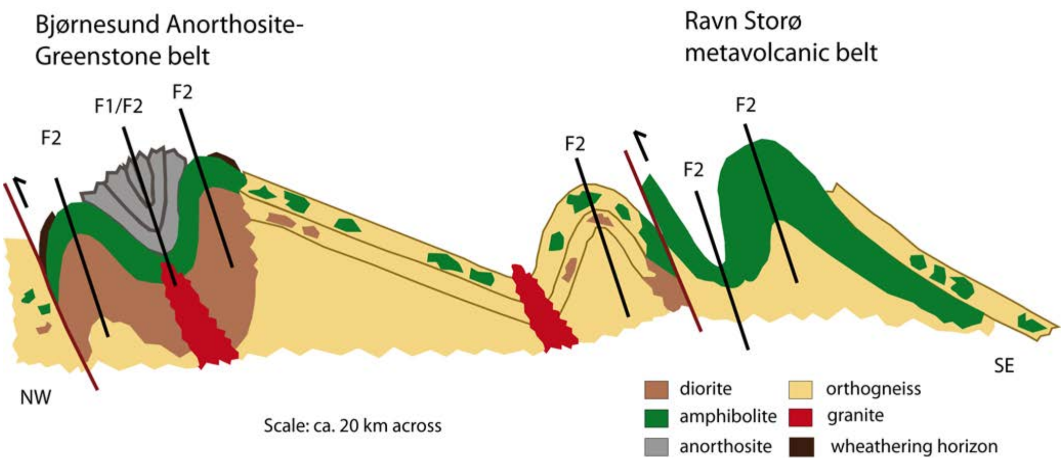


Figure 16: Schematic cross-section through the Bjørnesund Anorthosite-Greenstone Belt and the Ravn Storø metavolcanic belt. Not to scale. See Figure 12 for the trace of the profile. The profile is also available on the geological map on the internet.

Structural observations related to the Nigerlikasik geochemical profile

A series of undifferentiated supracrustal rocks are found in the 2870-2850 Ma gneisses of the Paamiut block (Friend & Nutman 2001). Windley and Garde (2009) regard them as being part of the Kvanefjord block. The supracrustal rocks were studied in large detail on the peninsula between the fjords Akulleq and Nigerlikasik (Fig. 17) in the innermost Kvanefjord area. The rocks are reported as metamorphosed at amphibolite facies conditions (McGregor & Nutman 1997, Schumacher et al. 2011).

The series consists from bottom to top of ultramafic rocks, amphibolites and felsic volcanic rocks. The series was intruded by TTG-type orthogneiss and a number of felsic aplitic sheets, especially in the lower part of the sequence, and is cut by early generation of quartz veins throughout the section. More details on the petrology and geochemistry of the supracrustal rock sequence are found in a separate report (Klausen et al. 2011).

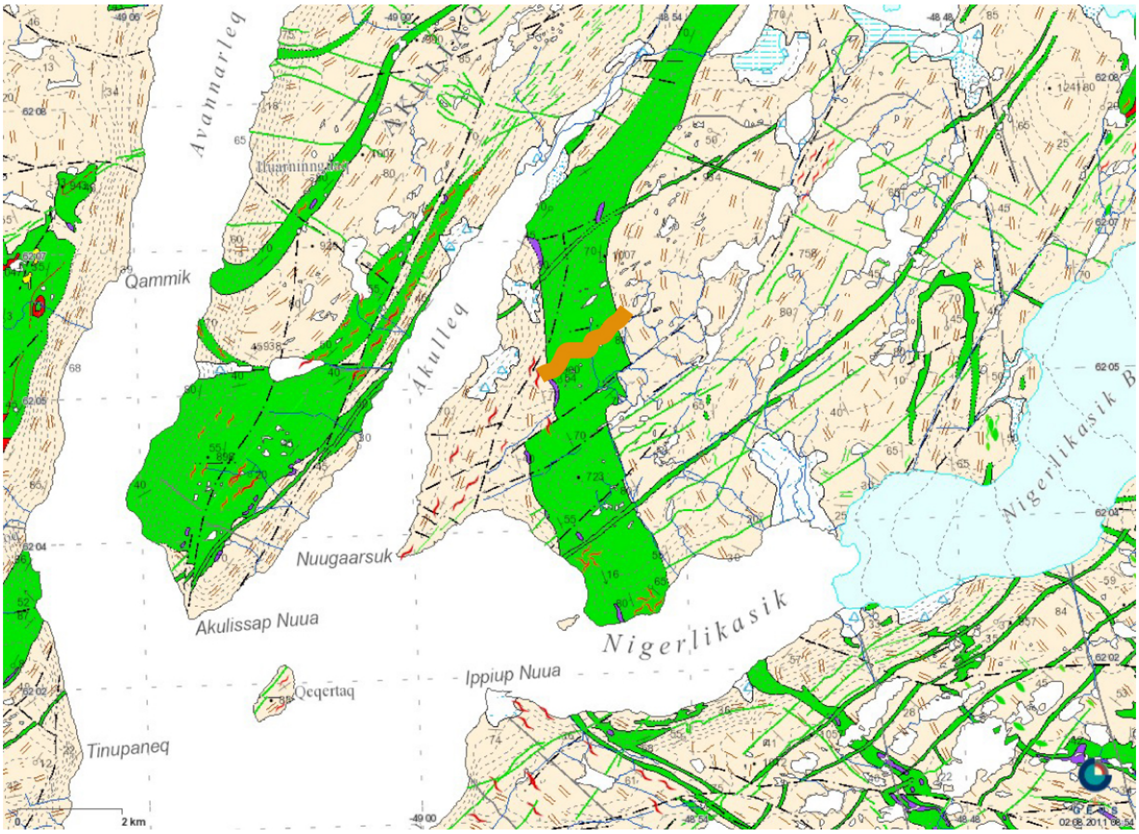


Figure 17: Map showing the inner part of the Kvanefjord. The studied section is indicated by an orange line, the geochemical profile was sampled in the eastern limb of the rocks indicated as amphibolites (green). Map after Keulen, Kokfelt, et al. (2011).

Folding:

At least two large scale regional folding events affected the rocks north of Nigerlikasik after emplacement of the TTG-gneisses (which is associated with local tectonic events that formed isoclinal and intrafolial folds), the intrusion of aplitic sheets into the supracrustal and ultramafic rocks and at least one early generation of (?associated) quartz veins.

The first generation is a tight to isoclinal folding with a steep, roughly north-south trending axial plane (Fig. 18). All sampled rock types (UM, amphibolites, felsic schists and UM rocks) are affected by this folding, but react differently on this folding event, as an effect of different rheological behaviour based on their mineralogy. This folding results in the formation of boudinaged lenses of more competent layers in the folding flanks, shearing folds in the amphibolites, parasitic folding of the quartz veins in the section. Since both the TTG-gneiss and the aplitic sheets are involved in the folding, the maximum age of the folding is 2.913±5 Ga. This folding episode occurred at amphibolite facies conditions.

Figure 18: Steep-dipping foliation in felsic schists near the synformal core of the fold. Orientation of the layering is c. 105/70 (dip direction-dip), the geologists are facing north.

The ultramafic rocks consist mainly of serpentine or talc-rich rocks (?metasomatised). Olivine-rich rocks are very strong, brittle and competent at mid-crustal conditions (Evans et al 1990, Kohlstedt et al 1995), while talc and serpentine-bearing rocks are weak and deform by crystal plastic deformation mechanisms (see e.g. Escartín et al 2001, 2008). Aplitic sheets that intruded into the serpentinised ultramafic rock before the folding were more competent than the ultramafic rocks (Figure 19), which proofs that the ultramafic rocks were hydrated before the folding. Due to their higher competence, the sheets are boundinaged. In case the ultramafic rocks would not have been hydrated, the aplitic sheets would have formed the rheologically weaker unit that would have accommodated the deformation.

Figure 19: Tightly-folded serpentinised ultramafic rock with boudinaged folded aplitic sheets and quartz veins. Both images facing north.

Folding in the amphibolites occurs as a nearly-ductile deformation. The major part of the shortening is accommodated as folding, while some movements along small scale fault or shear zones occur (shearing-folds; see Figure 20). This is a typical modus for crustal shortening in more mafic (i.e. quartz and mica-poor) rock types under amphibolite-facies conditions. Either the temperature is just too low for completely ductile shearing of mafic rocks, or the strain rate of the crustal shortening is rather high, which causes faulting along the axial plane of the fold. The shearing is often associated with grain-size reduction. Resulting from this deformation-induced recrystallisation the same minerals are formed, indicating that this deformation happened under amphibolite-facies condition (Figure 21).

The felsic schists deform in a different manner than the more mafic rocks do. In these rocks biotite and quartz occur abundantly, and these minerals are weak at mid-crustal conditions. They deform by crystal plastic deformation mechanisms. The felsic schists align their foliation to the fold axial plane orientation of the fold as a result of the isoclinal folding. Due to the weakness of the felsic schist, this isoclinal folding in the core of the synform is difficult to recognise. In some cases, the only remaining evidence of the folding is the occurrence of ptygmatically folded quartz veins in the schists (Fig. 22).

Figure 20: Shearing-fold in amphibolites. Semi-brittle folding under amphibolite-facies conditions causes faulting semi-parallel to the axial plane of the fold. A minor offset of the foliation along fold can be observed. Quartz veins outline the fault plane. Facing north.

To form ptygmatic folds, the quartz veins need to be more competent than the matrix (here the felsic schists) in which they occur and the deformation must occur under conditions where quartz-veins behave completely ductile. Compressional shortening in the limbs of the fold cause flattening of the schist, where biotite induces a strong foliation of in the schists. The more competent quartz veins that occurred at a high angle to the stretching orientation of the foliation deform by buckling. The ptygmatic folding indicates that the matrix was much weaker than the quartz-vein. Quartz deformes ductilely at temperatures above (middle-) greenschist facies conditions. Under such conditions, biotite-rich quartz-bearing felsic schists are very weak (e.g. Tullis & Yund 1977). It is therefore likely that this deformation occurred at amphibolite facies conditions.

Figure 21: Deformation induced grain size reduction of amphibolite rock reproduced the same minerals as the regional metamorphism. Both occurred at amphibolite-facies conditions. The pencil points towards the south.

Figure 22: Ptygmatic folding of the quartz veins in the felsic schist dominated part of the section. The quartz-vein was orientated at a high angle to the current foliation. Due to compressional deformation the quartz-vein shows hundreds of cm-scale folds, while the felsic schist is flattened in the same deformation event. Facing north.

The overall structure of the fold is a synform, with felsic schists in the core of the fold, and ultramafic rock in various sizes and orthogneiss on the outside (Figure 23). The overall wavelength of the first-order folds is *c.* 2-3 kilometres; parasitic folding however, occurs abundantly in all rock types (gneisses, ultramafic rocks (Fig. 20), amphibolites (Fig. 21), and felsic schists (Fig. 22, 23). Thus the original thickness of the sequence is hard to establish.

Figure 23: Parasitic isoclinal folding in the core of the synform facing south. Light coloured felsic schists form the core of the fold, surrounded by dark amphibolites. Overview towards the south.

A later stage folding overprints the main folding event. This folding has a nearly east-west trending, steep-dipping fold axial plane. It causes a buckling of the structures of the earlier deformation phase. The folding has a large wavelength (tens of kilometres). On the geological map, the effect of the folding can be observed as a variation in the dip of the mapped fold axes within the amphibolite map unit and a bending of the unit on the geological map. Within the studied profile, this folding stage has hardly any effect, since all observations are made in one limb of this fold roughly parallel to the fold axis.

Faulting and shearing

The first shearing event is associated with the main folding phase, as discussed under the folding of the amphibolites. Apart from the amphibolites, such shearing is also observed in the metasomatised ultramafic rocks.

Later shearing occurred in the metasomatised ultramafic rocks. Shearing seems to have occurred roughly parallel to the foliation (which is north-south trending and steep dipping), moving its eastern block towards the north, thus indicating a sinistral movement on a strike slip fault. The exact timing of this shearing event is unknown. It could represent a late stage of the main folding and shearing event, or be a later, separate event. Deformation seem to have occurred at intermediate to high temperature (? amphibolite-facies) conditions. The shearing movement is associated with flattening of pre-existing features. The relation and relative timing of this shearing event in relation to the later stage folding is unknown. Lineations related to this folding yield *c.* 180/30, thus a minor thrusting aspect is also present, which makes a connection to the later stage folding likely.

At least two faulting episodes occurred after the main folding phase that established the main foliation. The first generation of faults are steep dipping E-W striking strike slip faults. Deformation happened most probably at (?upper) green schist-facies conditions. The main movement along these faults is dextral. The central part of the studied geochemical profile north of Nigerlikasik was sampled along the northern side of one of these dextral faults striking 064°. The western part of the profile was sampled along one of its Riedel faults striking 078°. The amount of dextral offset for the felsic schist-amphibolite contact and the amphibolite-ultramafic rock contact varies along the profile from the northern side of the dextral fault to the southern side of the dextral fault. Either some differential internal compression occurred during faulting (accommodated in the orthogneisses), or some vertical offset (uplifting the southern block with respect to the northern block) during mainly strike-slip movement occurred.

The dextral fault zones are characterised by epidote, quartz and serpentine in the ultramafic rocks (Fig. 24). The foliation is sheared into the fault zone, but associated brittle fracturing (especially in the amphibolites) occurred.

Figure 24: Epidote veins and recrystallization in amphibolites. The epidote overprint is limited to a narrow zone of a few to c. ten cm away from the fault zone. Image facing south.

A dolerite dyke cuts through the sampled section and the dextral fault zone. Its strike is 084, which roughly fits with the orientation of the MD2 dykes. Their age is estimated to *c.* 2130±65 Ma (Kalsbeek & Taylor 1985). The dyke is not visible within in the fault zone, but can be traced on both side walls of the fault. The dolerite dyke is sinistrally offset by the fault by 16 meters. Apparently a small sinistral offset occurred after the major dextral movement. The dyke therefore provides a maximum age constraint for this greenschist-facies deformation episode.

A second series of strike-slip faults strikes N-S in the studied area and runs roughly parallel to the fault axis of the main foliation. This deformation episode seems to offset the east-west oriented strike-slip faults sinistrally by *c.* 30 m.

Structures in the Atarngup area: on the existence of a Neria nappe or a Neria block

This chapter is an extension to the abstract published as Keulen et al. (2011b). Our co-worker Alfons Berger is gratefully thanked for his help.

Introduction

In the summer of 2010 the inland area southeast of Paamiut, South-West Greenland was visited for the first time by mapping geologists (see Figure 25), since the 1960's. Several areas near the fjords have been visited in the intermediate time by mining companies, by V. McGregor and C. Friend (see McGregor & Friend 1997), and by a GEUS reconnaissance team in 2009. The area has not received as much attention as the Fiskenæsset area, or the Nuuk area.

The area contains deformed Meso-Archaean TTG-gneisses and dispersed supracrustal rocks over a distance of more than 100 km along the Inland ice. The visited outcrops are of exceptional quality and offer a rare opportunity to understand the formation of Archaean supracrustal rocks, their alteration and interaction with the intruding magmas.

Figure 25: Overview of the geology in area SW of Paamiut. Colours as on the digital map of SW Greenland (http://geuskort.geus.dk/gisfarm/gis_svgreenland.jsp; Keulen, Kokfelt et al. 2011): yellow = orthogneiss, green = amphibolite, brown = mica schist, pink = granite). Visited localities are indicated in yellow, the boundary of the proposed Neria nappe/block (Windley & Garde 2009; Friend & Nutman 2001) is indicated with a red line.

So far, two points of view exist on the structural boundaries in the area (see Figure 2): The area consists of one block (Kvanefjord block/Paamiut block) with debated boundaries to the north and the south that underlies or surrounds the Neria nappe/Neria block (Fig 2; Windley

& Garde 2009; Friend & Nutman 2001). The boundaries of these blocks (and the nappe) in the inland of the area were drawn based on a reinterpretation of the GGU fieldwork maps of the 1960s (Higgins 1974, Jensen 1975). To follow up on these interpretations field investigations were carried out in this region.

Geology

Supracrustal rocks

The supracrustral rocks in the Paamiut area include unusually well-preserved metavolcanic sequences that comprise former lavas and volcano-clastic protoliths with recognisable primary volcanic features. A *c.* 560 m thick profile was studied in detail at Nigerlikasik showing a compositional transition from ultramafic rocks at the base, to felsic metavolcanics in the upper part of the section (see Klausen et al. 2011). The occurrence of felsic volcanic rocks as Archaean supracrustal rocks is rare worldwide, and their presence may further constrain processes that actually played a key role in the formation of the Earth crust during the Mesoarchaean.

Similar supracrustal rocks situated south-east of the Paamiut area, near the inland ice, form dispersed fragments in the TTG-type basement and contain metamorphic rocks commonly interpreted as metamorphosed clastic sediments. The second, more abundant supracrustal rock-type is amphibolite that is observed in the area (Figure 26).

In most areas the amphibolites are finely banded (Fig. 26a, 26b), with slight compositional differences (amphibole-plagioclase ratio variations, and probably changing Ca, Mg and Fe-ratios). In most of the visited areas garnet are rare or even absent in the amphibolites; where they occur, they only occur in specific layers. Locally ortho-amphiboles (probably anthophyllite and/or cummingtonite), epidote and diopsite (Fig. 26c) are observed in the amphibolites.

Especially in the area between Nigerlikasik and Sermilik, but also in the area west of Sermilik large ultramafic bodies occur that were intruded by the protoliths of the orthogneiss. At the contact between the orthogneiss and ultramafic bodies, hornblende commonly forms as a reaction product, in the form of tens to hundreds of meters-sized bodies of near-pure hornblendite (Fig. 26d). Locally, biotite and layers of anthophyllite are observed. These rocks are commonly mapped as amphibolite, even in areas where no amphibolite is associated with the ultramafic rocks. Since the hornblende is a reaction product only, these “amphibolites” are actually ultramafic rocks (see Schumacher et al. 2011 for further details).

A preliminary estimation of the peak metamorphic conditions yields middle to upper amphibolite facies (see Schumacher et al. 2011 for details; Alfons Berger pers. comm. 2011).

Figure 26: Rocks mapped as amphibolites. a,b) Finely banded amphibolite, compositional differences on a centimetre scale. c) Partial melting vein with diopside in an amphibolite, overprinted by epidote. d) Ultramafic rock intruded by orthogneiss, reacted to hornblendite.

The mica schists consist of quartz, feldspar (plagioclase), biotite, garnet, in varying quantities (Fig 27a). Garnet is locally very abundant and has in many places grown over the foliation (Fig. 27b). Locally sillimanite, pseudomorphs of andalusite and/or cordierite (Fig. 27c), ilmenite, graphite, tourmanline, and pyrite were observed. The schists have a very typical brownish weathering colour.

The mica schists have been interpreted as rocks derived from pelitic to semi-pelitic sediments based on their chemistry (Rivalenti & Rossi 1972). In some outcrops, e.g. at 61.81909333N, -48.34468833E, sedimentary bedding structures can be observed as an alignment of larger clasts and variations in composition that occur at an angle with the foliation (see Figure 28).

Part of the mica schist (especially those east of Rensdyrsø) are very similar to the felsic volcanics that were studied near Nigerlikasik. They are quartz, feldspar, biotite-schists or gneisses. Locally a transition from these schists to the garnet-sillimanite-biotite can be observed. The mica schists and gneisses are interpreted as sediments or intermediate to felsic volcanoclastic rocks that were altered on the sea-floor before metamorphism (Fig 29; Schumacher & Robinson 1987; Dymek & Smith 1990).

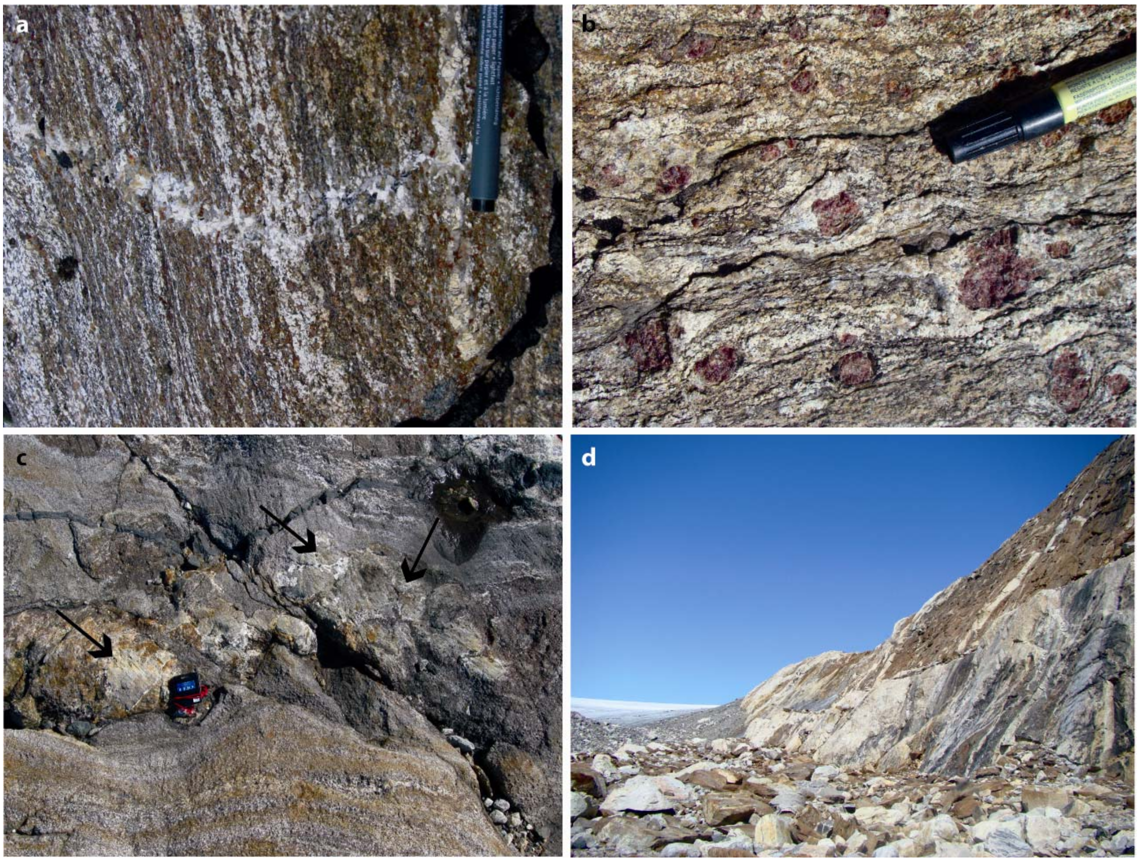


Figure 27: Rocks mapped as mica schists. a,b) Finely- to intermediately-laminated schist and gneisses, mainly rich in biotite, locally with garnet grains overgrowing the main foliation. c) Garnet-biotite-sillimanite micaschist with cordierite (arrows) associated with pegmatites. d) Orthogneiss intruded into mica schists.

Figure 28: alignment of pebbles and larger clasts and slight compositional differences occur at an angle with the main foliation. The original sedimentary bedding is indicated with a white line.

Figure 29: Felsic volcanic rocks (bottom left, with enlargement right) with alteration to garnet-mica schists (top left).

TTG gneiss

The TTG gneisses form *c.* 90% of the current outcrops of this level of the crust, thus the amount of plutonic material is significant. The orthogneisses show an intrusive contact with the amphibolites and metasedimentary rocks (see Figure 27d). The gneisses show a range of compositions from granodiorite to tonalite to trondhjemmite (based on field observations). The mafic minerals are often biotite, abundantly hornblende, and very locally both minerals occur. The gneisses are cut by several generations of felsic pegmatitic and aplitic sheets.

An intensive dating program of the gneiss yielded the following ages (Figure 30; see Kokfelt et al. (2011) for further details): a group of older gneisses of 2.935-2.929 Ga and some slightly younger gneisses of *c.* 2.88 Ga. These are intruded by 2.854-2.850 Ga gneisses and fairly young granites (2.562-2.550 Ga). Friend and Nutman (2001) used the age of the gneisses as one of the arguments for an older Neria block surrounded by younger gneiss, however our more detailed investigations show that both the older (2.93 Ga) and younger (2.85 Ga) gneiss occur within and outside their proposed Neria block.

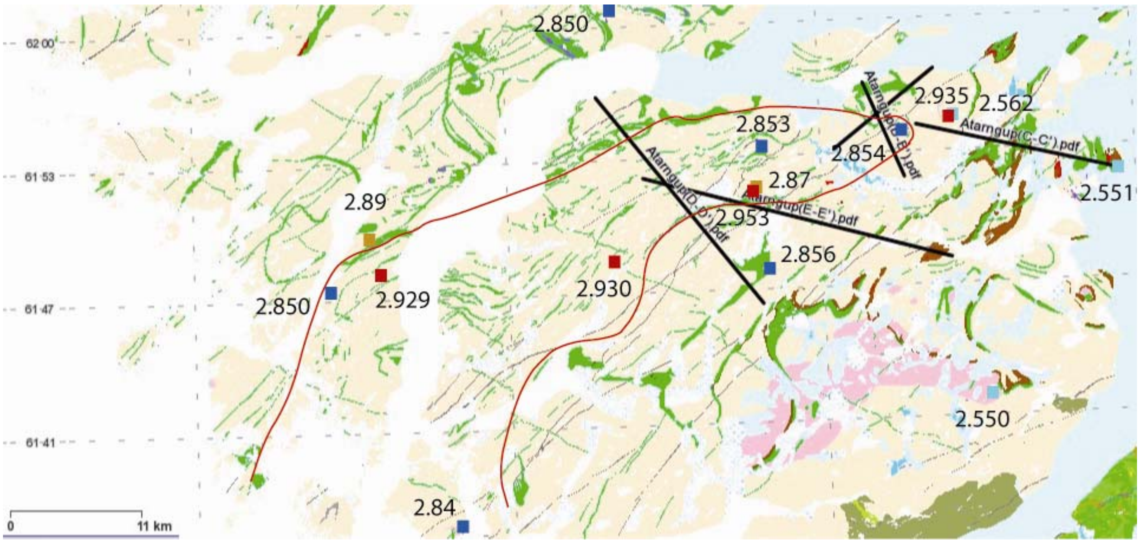


Figure 30: Zircon U/Pb ages (in Ga) for orthogneiss samples (2.935-2.84 Ga) and selected granite samples (2.562-2.550 Ga; light blue squares).Three groups of orthogneiss ages are indicated with red (c. 2.93 Ga), orange (c. 2.88 Ga) and dark blue (c. 2.85 Ga). Young (c. 2.55 Ga) granites are indicated with light blue squares. The red line indicates the boundary of the proposed Neria nappe/block (Windley & Garde 2009; Friend & Nutman 2001). The black lines indicate the profile lines of Figure 32. Colours as in Figure 24.

Structural observations

Folding

In the region SW of Paamiut, three generations of folding occur (see also Higgins 1990). The first generation is a tight isoclinal folding. The second generation has NE striking fold axial planes (Fig. 31). These folds can be seen in profiles B-B‘, C-C‘, D-D‘ and E-E‘ (Fig. 32). The folding is less intense in the north, where fold axial planes mainly strike NW, causing an interference pattern as can be observed in A-A‘ (Fig 31, 32). Thrusting only occurs to accommodate the folding. No large off-set were observed on the thrusts. The folds with a NE-striking fold axial plane are rather tightly folded in the Rensdyrsø-Isorsua area where supracrustal rocks prevail. Their fold axes are moderately dipping. Considerable shearing occurs in the limbs of the folds, especially in the area east of Atarngup

The NW striking folds have more steeply dipping fold axes, especially in the area north of Sermilik, which result in irregular outcrop patterns of amphibolites in the gneisses in this area. Late-stage structural overprint was observed in the whole area, causing a large wavelength folds, which is especially noticeable on the fold limbs of the earlier folds.

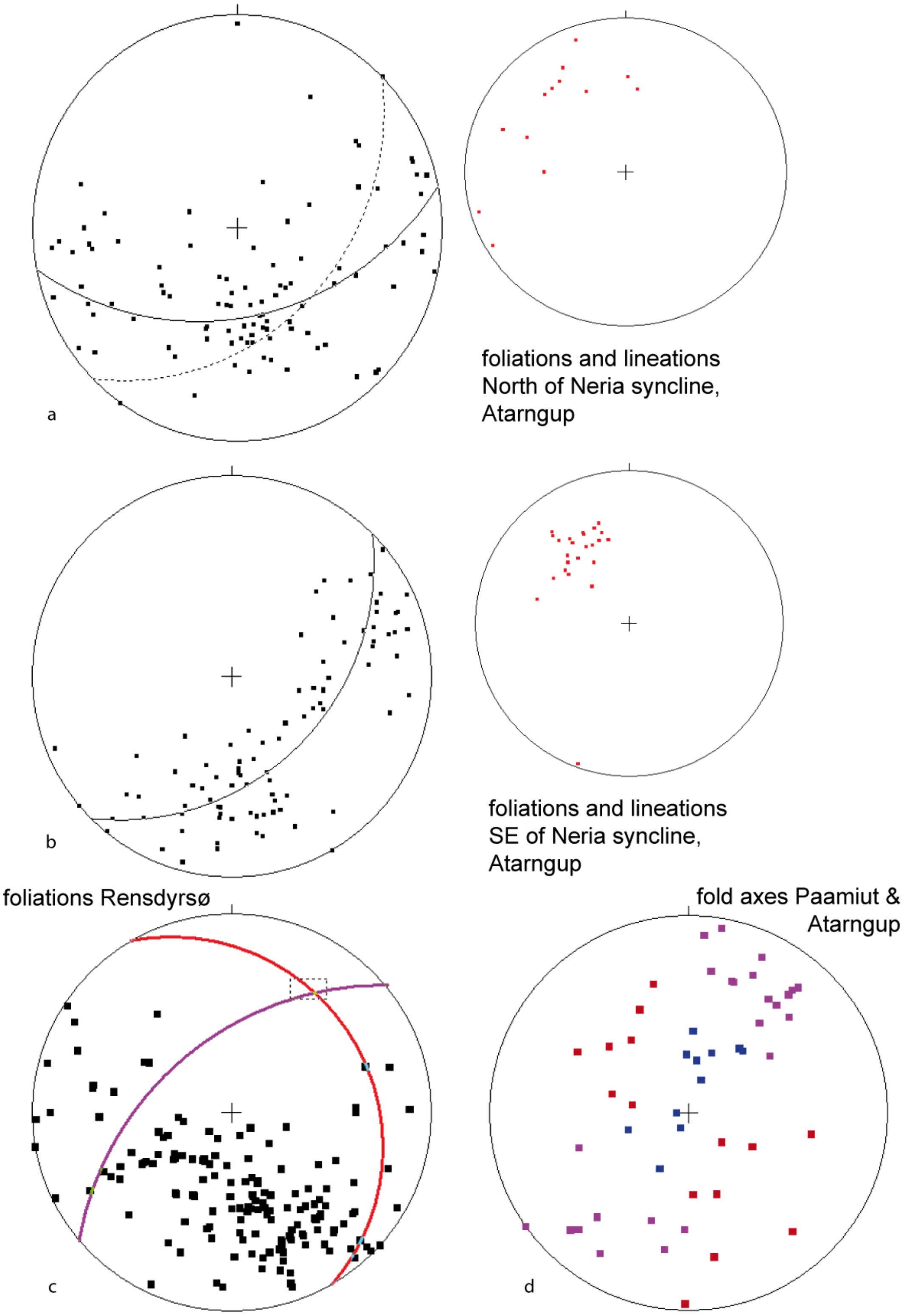


Figure 31a-b) Poles to the foliation and lineation of the area north and south-east of the Neria syncline, Atarngup. The data show a NE-striking fold axial plane. c) Poles to the foliation for the area east of Rensdyrsø. Two generations of folding are observed, an older NE striking folding generation and a younger NW striking generation. d) Fold axes from the area east of Paamiut and Atarngup-Isorsua. Fold axes in red are younger than those in purple; fold axes in blue cannot be distinguished.

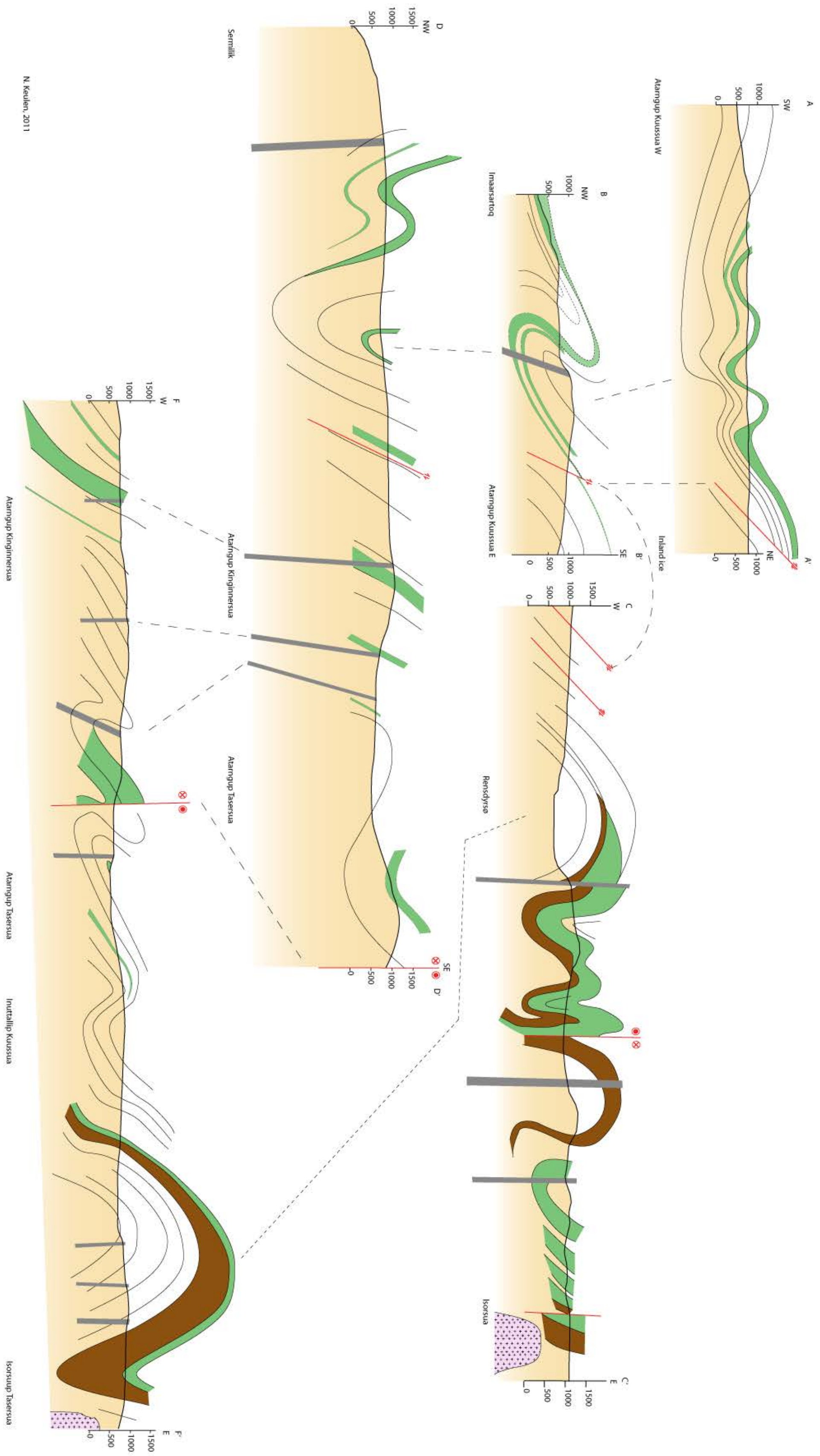


Figure 32: Simplified model to visualize the folding in the Atarngup area. See Figure 30 for the location of the profile lines.

Faulting and thrusting around the proposed Neria nappe

The boundaries of the proposed Neria nappe were visited in several places (see Figure 33).

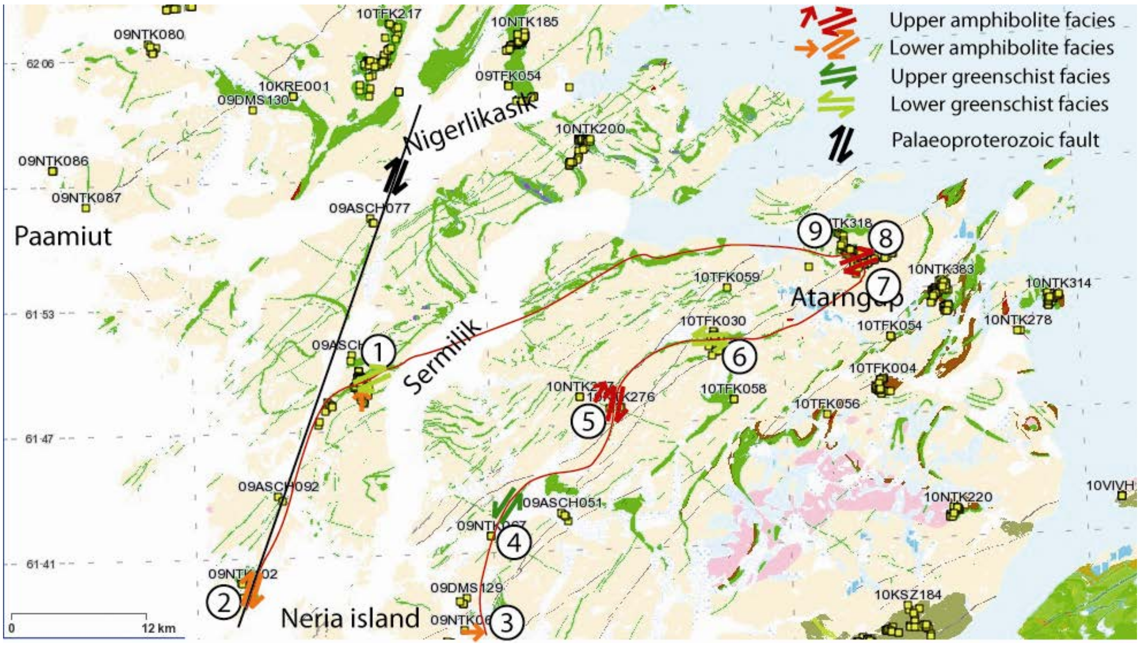


Figure 33: Shear zone and fault zone movements along the boundaries of the proposed Neria Nappe in the area SE of Paamiut. Thrust movements are indicated with single arrows, strike-slip movements with double arrows. Colours indicate the approximate temperature during deformation. Numbers correspond to numbers in the text.

1) West of southern Sermilik

A major cataclastic fault zone with a two-stage movement history has been studied west of the southern Sermilik. The zone is *c.* 500 m wide. First movement shows south-side upwards movement at conditions where bt-qtz-fsp are stable and fsp forms large clasts, while qtz is able to recrystallise in long ribbons. Deformation is semi-brittle to transitional brittle-ductile. Timing of the movement with respect to the intrusion of the dolerite dykes is uncertain. The second stage of movement happened after the intrusion of the dolerite dykes. The second movement caused a dextral offset of probably *c.* 4 km, measured from the offset of the dolerite dykes. This deformation stage involved a high activity of fluids with massive epidote, quartz and K-feldspar deposition in the fault, and the formation of chlorite. The fault seemed to be offset by the later major *c.* 020-striking Palaeoproterozoic fault in the region.

The amphibolites south of the fault contain diopside+garnet; north of the fault only garnet was found in some layers of the amphibolite. A first estimate of the temperature differences (field observations) on both sides of the fault is *c.* 50ºC higher south of the fault than north of the fault.

The grey gneisses (TTGs) on both sides of the fault seem to be different with more mafic well-foliated and locally hbl-bearing gneisses south of the fault and more felsic (granodioritic), surprisingly well-folded gneisses in the north.

Structural trends and folding phases on both sides of the fault are the same. The main foliation and the orientation of the fault are similar.

2) Akinaq island

On Akinaq island, a mylonitic shear zone has been overprinted by the later Palaeoproterozoic fault that cuts from Vesterland NNE-ward with a strike of *c.* 30º and a steep dip. This late dextral fault zone with deformation at transitional brittle-ductile conditions overprints the mylonitic earlier shear zone. East of the shear zone clinopyroxene was observed in the amphibolites, but clinopyroxene was not found west of the shear zones, which could simply indicate a shift of bulk composition in these amphibolites.

3) Neria fjord

Citation from field report of Brian Windley, October 2009:

"… I checked the presence or absence of this nappe on the southern and northern coasts of Neria fjord. The retrogressed gneisses were described by McGregor and Friend (1997, Precamb. Res., 86, 59-70) as being characterized by spots of hornblende and biotite after hypersthene. However, I found no spotty gneisses at all anywhere along the southern coast of Neria; present are only fine-grained leucocratic biotite gneisses and some coarse biotite gneisses. The thrust is correctly positioned on the northern side of the fjord in a 6 metre wide gully with highly fractured and crushed rocks with epidote staining and some 25-30 cm-wide sheets of pink K-feldspar granite, where so-called retrogressed gneisses have been thrust eastwards over prograde gneisses. The position of the thrust is spectacularly marked by the large-scale structure of the gneisses along the northern side of the fjord where shallow-dipping gneisses pass westwards to the west-dipping thrust where they bend up on its downthrown eastern side. The thrust does not pass directly to the south side of the fjord where Windley and Garde (2009) indicate it, but it crosses to the southeastern side of the fjord exactly where McGregor and Friend (1997) mark it, and where it correctly dips steeply to the west, carrying western gneisses over eastern gneisses, and in the thrust zone are 30 cm-wide sheets of pink K-feldspar granite. In conclusion, the thrust nappe appears to exist, but evidence for retrogression from granulite to amphibolite facies is lacking."

4) South of Tasiusaq

Mylonites, formed at relatively low temperature (?upper greenschist facies) with south dipping lineations and a sinistral sense of movement were observed south of Tasiusaq. Adularia, hematite and epidote in the shear zone suggest a high fluid activity associated with the deformation.

5) East of Tasiusaq

Two reconnaissance stops were used to check another part of the proposed Neria block/nappe boundary on the Neria map sheet, east of Tasiusaq. Deformation here took place at much higher temperatures (estimated to amphibolite facies), whereas the movement was dextral strike-slip or dextral transpressional.

6) Northwest of Atarngup Tassersua

The boundary of the proposed Neria nappe is here a cataclasite in TTGs in the E-W trending fault zone south of an amphibolite unit, which shows a large (1-2? kilometre-scale) sinistral displacement. The fault zone cuts through a dolerite dyke. Pseudotachylytes have been observed associated with the faulting in the grey gneiss.

7) Southeast of the Neria syncline, Atarngup

Cataclasites in migmatites and grey gneiss have dip direction-orientations between SW and NW. The zone with cataclasites is a few hundreds of metres wide, but the intensity of the deformation varies across the zone. There seems to be little or no displacement, the cataclasites might be related to an extensional movement (stress relaxation). The fault rocks have different grain sizes and behaviour, depending on whether they are part developed from migmatites or grey gneiss. Syn- to post-deformational (stress-free) ilmenite is growing in the cataclastic zone, and probably formed from biotite.

8) Eastern side of the Neria syncline, Atarngup

This locality lies at the eastern-most tip of the assumed Neria nappe, where thrusting is predicted. A mylonite was observed in the fold zone (Neria syncline). The mylonite is folded and shows a flat-lying NW dipping lineation, which is related not to thrusting, but to a dextral strike-slip movement (see Figure 34). Coarse-grained hornblende grew over the foliation, roughly aligned with the foliation; interpreted as late-kinematic growth.

Figure 34: Folded mylonite with lineations indicating strike-slip at the location of the proposed Neria thrust. Sense of shear and orientation of the shear zone do not fit with an overthrusted nappe model.

9) North of the Neria syncline, Atarngup

Cataclasites similar to the ones found southeast of the Neria syncline were also found north and north-west of the Neria syncline. Here as well, the cataclastic rocks do not indicate a large displacement, but seem to be associated with stress-relaxation after the three interacting folding phases in the area.

Discussion

The supracrustal rocks have been interpreted as metamorphosed clastic sediments. However, our field observations raise questions about the origin of these rocks. An origin as felsic volcanic rocks that were altered by circulating fluids in the ocean floor seems in some cases more likely than a sedimentary precursor.

It is commonly proposed that all TTG rocks within specific terranes formed at the same time. In the studied area the existence of three tectonic blocks (Paamiut, Neria, Sermiligaarsuk blocks) have been proposed (McGregor & Friend 1997; Friend & Nutman, 2001). However, our fieldwork has not been able to confirm the presence of major tectonic boundaries; for example the boundaries proposed for the Neria block were sought, but not located. Where a structural contact was found, it did not show a consistent movement direction, nor consistent deformation temperatures.

The combined observations at the Neria syncline and on other locations around the proposed nappe/block boundary make it hard to envisage a nappe that is emplaced during one continuous deformation event. The movements at amphibolite facies conditions do not correspond to a single eastward thrusting movement of a nappe over other basement gneiss. The lineations do not show a consistent trend with thrusting. Microstructures in the deformation zones relevant for the proposed nappe-movement actually have formed at very different temperatures, which shift inconsistently around the nappe, and possibly at different times (compared to the intrusion of the dolerite dykes).

The distinction between retrograde amphibolite facies (in the Neria block) and prograde amphibolite facies (in the Paamiut block) claimed by Friend & McGregor (1997) was not observed. In fact, all studied thin sections of amphibolite and mica schists show middle to upper amphibolite facies as peak metamorphic conditions (Schumacher et al. 2011, Alfons Berger pers.comm. 2011, Figure 35). This is also in line with the observations made by Brain Windley in the Neria fjord, which also dispute the retrograde origin.

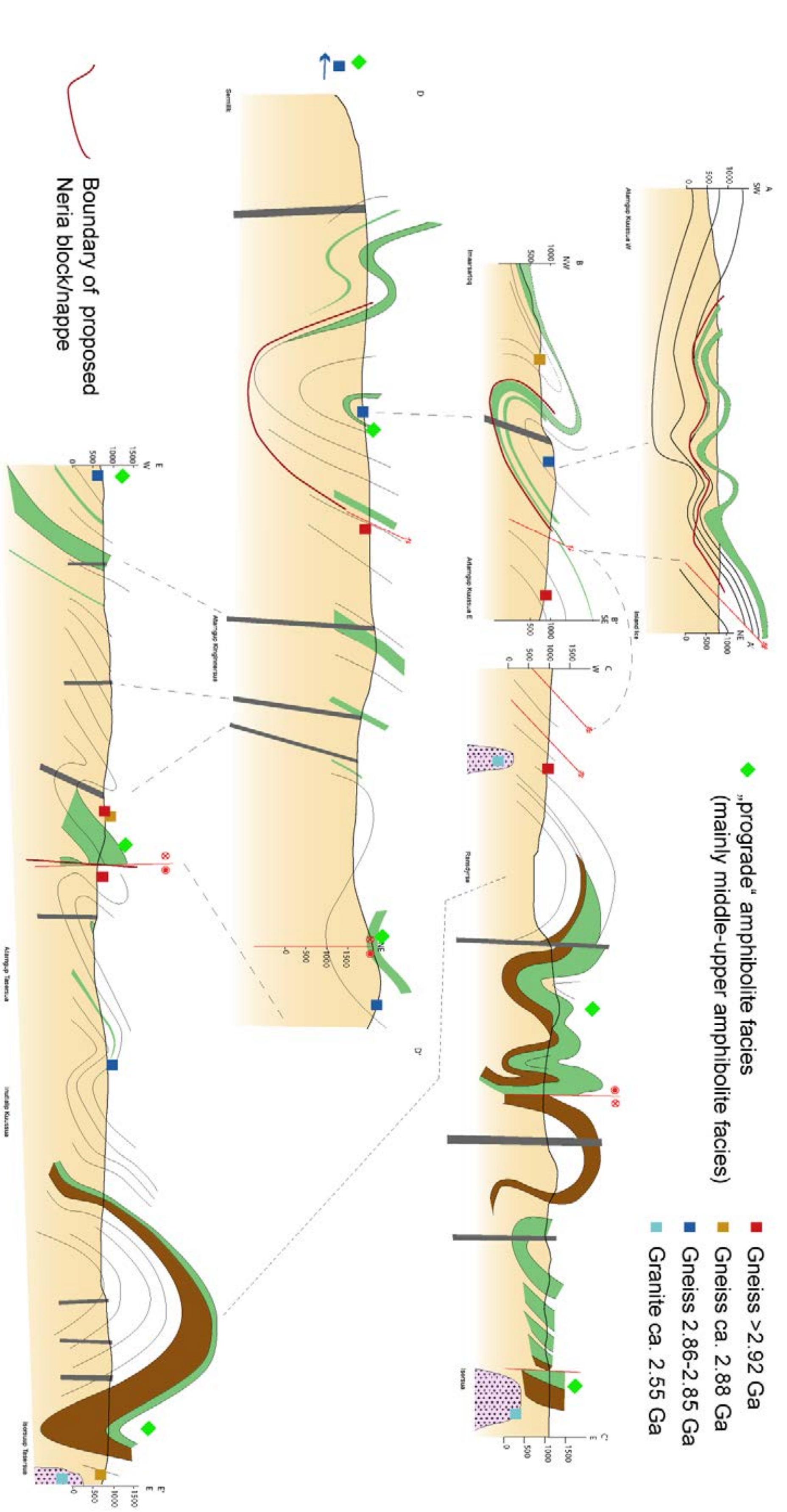


Figure 35: Structural framework for the tectonometamorphic evolution and the geochronology of the basement. See text for discussion.

Instead of the nappe model, we propose a tectono-magmatic situation characterised by repeated emplacement of magma into the upper crust of a single, long-lived subduction system (Fig. 36). Deformation and temperature evolution is related to the emplacement tectonics of the large volumes of plutonic rocks. The locus of magmatism may have shifted position relative to the leading edge over time. Such a scenario would likely result in a wider range and a more random distribution of magma emplacement ages within a restricted area, compared to the clearly differentiated events inside terranes divided by relative sharp tectonic boundaries, as predicted by a terrane model.

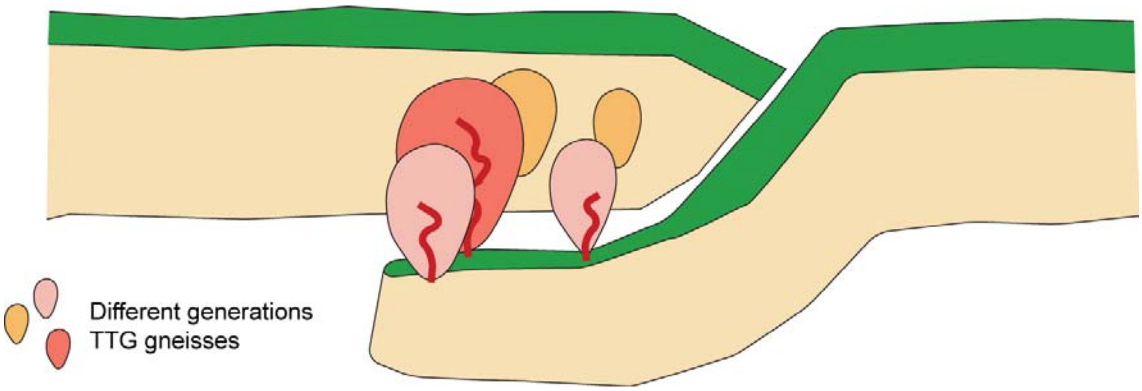


Figure 36: Simplified sketch showing a model for the generation of different ages of gneisses that is consistent with the observed structural and metamorphic data.

Regional overview of the main structures between Ameralik and Sermiligaarsuk fjord

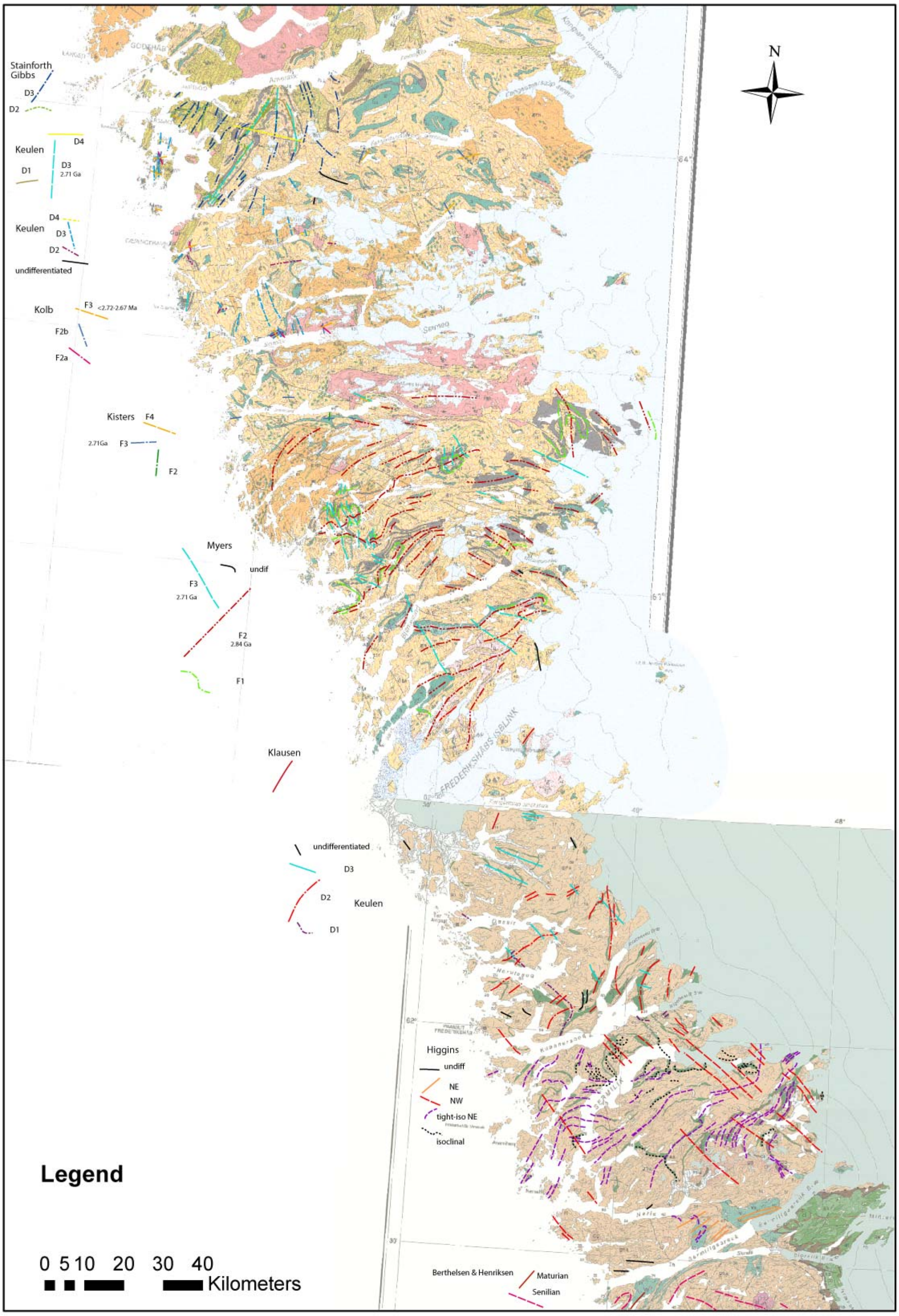
Folding and the formation of the main foliation

In the previous sections structures in local areas were discussed. Here we aim to give an overview of the structural evolution of the entire area between Ameralik and Sermiligaarsuk fjord in terms of spatial distribution of deformation events and of timing of these events. Figure 37 shows an overview of all folding events as described by authors previously working in the area, as well as own field observations made in the period 2008-2010. The map shows the folding phases with the names as they were defined by the individual authors. Table 1 shows a new possible correlation between the individual publications; this correlation is made visible by similar colours for the same event on the map in Figure 37.

In general terms the earliest events are found in the Eo-Archaean gneisses in the northernmost part of the area, in the Fiskenæsset area and in the southern part of the area between Nigerlikasik and Sermiligaarsuk. The events cannot be correlated with each other and probably give evidence for the early individual local evolution of the areas, which may or may not happen in the vicinity of the other areas. The main deformation formed in three steps, defined by event 2, event 4 and event 6 in Table 1, which can be found in the Nigerlikasik-Sermiligaarsuk area, the Grædefjord-Nigerlikasik area, and the Ameralik-Grædefjord area (and probably further to the north), respectively. A detailed discussion of the individual phases is given below.

Apart from folding, crustal shortening by thrusting and more general (pure shear) compression have taken place. Thrusting occurs in many areas associated with the folding, either simultaneously or shortly before or after the folding event. However, we concentrate on the folding events here, as they form the major modus of crustal shortening in the area, while thrusting usually only accommodates the folding. Where the offset of the thrusts could be investigated, only minor offsets were observed, on the scale of tens to hundreds of metres, rather than several kilometres. Peak metamorphism occurred at amphibolite facies conditions or above (Schumacher et al. 2011) and under such temperatures, folding is the expected crustal shortening mechanism, rather than thrusting. Thrusting is expected where high strain rates or cooling after peak metamorphic conditions prevail.

Figure 37 (next page): Overview of reported fold axial plane orientations by Bertelsen & Henriksen (1975), Higgins (1990), Myers (1972, 1975, 1985), references in these five publications; Klausen et al. (2011), Kolb et al. (2009, 2010; including Kisters et al.), Gibbs (1976), and Stainforth (1977), own observations (camps) north Buksefjorden, south of Grædefjord, east of Fiskenæsset, north and south of inner Bjørnesund, the Ravn Storø metavolcanic belt, Aturngup-Isorsua area, west of (southern) Sermilik and reconnaissance stops between Buksefjorden and (northern) Sermilik, outer Bjørnesund, in all fjords between Frederikshåb Isblink and Tartooq with the exception of (southern) Sermilik. The definition of the individual folding phases is applied as in the cited publications. Table 1 suggests a correlation between the individual folding phases discussed in the publications.



N
Stainforth
Gibbs
D3
D2
Keulen
D4
D3
2.71 Ga
D1
Keulen
D4
D3
D2
undifferentiated
Kolb
F3 <2.72-2.67 Ma
F2b
F2a
Kisters
F4
2.71Ga
F3
F2
Myers
undif
F3
2.71 Ga
F2
2.84 Ga
F1
Klausen
undifferentiated
D3
D2
Keulen
D1
Higgins
undiff
NE
NW
tight-iso NE
isoclinal
Legend
0 5 10 20 30 40
Kilometers
Berthelsen & Henriksen
Maturian
Senilian

Event	Berthelsen & Henriksen 1975	Higgins, 1990	Keulen*	Klausen et al. 2011	Myers 1972, 1975, 1985	Kisters (Kolb et al. 2010)	Kolb et al. 2009, 2010	Keulen**	Keulen et al. 2011	Gibbs 1976 Stainforth 1977	Timing
8						F4	F3	D4	D4		ca. 2.67 Ga
7	Maturian	NE									
6			D3		F3	F3	F2b	D3	D3	D3	ca. 2.71 Ga
5							F2a	D2			ca. 2.76 Ga
4	Senilian	NW	D2		F2						ca. 2.84 Ga
3									D1	D2	
2		tight-isoclinal NE	D1								
1					F1	F2					

Table 1: Overview of the major deformation phases with associated folding of the rocks in southern West Greenland and South-West Greenland, from south to north between c. 61.5 and 64° N. See text for discussion. Keulen and Keulen** refer to observations from the 1:100 000 maps, combined with field observations in the area, Keulen et al. 2011 refers to the chapter on Buksefjorden in this report.*

The major folding events in the area between 61.5 and 64°N on Greenland's western coast are listed in Table 1 and shown in Figure 37. The oldest folding phases (Events 1-3) are events that are only locally observed. Event 1 occurs in the Fiskenæsset Complex (Myers 1972, 1975, 1985, see also the chapter on the Bjørnesund area in this report), where it might be related to the intrusion of the Fiskenæsset Complex magmas into the supracrustal rocks of the area. If so, this folding event occurred at *c.* 2.95 Ga (Keulen et al. 2010a, Polat et al. 2010). V.J. van Hinsberg and B.F. Windley (pers. comm. 2009) indicate that the supracrustals rocks were already foliated and metamorphosed to amphibolites facies conditions, when they were intruded by the Fiskenæsset Complex magmas. This early foliation might be the same as observed by Kisters (Kolb et al., 2010) in the amphibolites. It is thus likely that more than one deformation event is included in this early event.

Event 2 is a tight isoclinal NE striking folding of orthogneiss and previously isoclinally folded supracrustal rocks (Higgins, 1990). The exact timing of this folding, or tectonometamorphic event, is unknown; however, it occurred before Event 4, which is dated to *c.* 2.83-2.85 Ga and after the formation of the protolith of the orthogneiss in the area, which happened at 2.87-2.92 Ga. The timing of the first isoclinal folding in the supracrustal rocks is unknown.

Event 3 is observed in the northernmost part of the studied area and might actually include at least two separate events both occurring north of Buksefjorden. Stainforth (1977) and Keulen et al. (this report) describe the first folding in the anorthosite unit, which might be related to its intrusion, as D2 and D1, respectively. Gibbs (1976) uses the D2 as well to describe this folding, but also applies D1 to describe an early folding phase in the Eo-Archaean gneisses of the Færingehavn terrane near Narssuaq (*c.* 64°N). It is however likely that these two folding events are unrelated, as the Færingeringehavn terrane and the units in the Buksefjorden antiform were probably not juxtaposed at that time. Earlier deformation events in the Eo-Archaean gneisses occurred (D1 in Gibbs 1976), but are not discussed here. The reader is referred to Chadwick & Nutman (1979), McGregor et al. (1991), and Gibbs (1976) for details.

Event 4 occurs over a major part of the area, between Sermiligaarssuk and Grædefjord and defines the main foliation in most of this area north of Nigerlikasik. Deformation is associated with the syntectonic intrusion of granitic to granodioritic magmas along fold planes, which were dated to *c.* 2.85 Ga south of Frederikshåb Isblink, *c.* 2.84 Ga in the Bjørnesund area, and *c.* 2.83 Ga in the Fiskenæsset area (Myers 1985 and own observations). South of Sermiligaarssuk the Senilian folding event was described by Berthelsen & Henriksen (1975). No deformation ages of this folding event are known. However, the Senilian deformation yields fold axial traces that are parallel to the NW striking folds, described by Higgins (1990). Fold-axial planes are NW striking south of Nigerlikasik and in the inner Bjørnesund area, *c.* N south of Frederikshåb Isblink and east of Sinarssuk, and NE trending in the area around Fiskenæsset.

Event 5 is only locally observed, especially in the area west and north of the Ilivertalik granite. Whether it is only locally confined or it cannot be resolved in orientation from Event 4 or not be resolved in age from Event 6 in other places is not entirely certain. Pegmatites and tectonometamorphic overprint of zircons in the orthogneisses yield ages of *c.* 2.77-2.74 Ga. Such ages do not abundantly occur in other areas. Axial planes mainly strike E-W to NW-SE.

Event 6 defines the main foliation in the area north of Grædefjord and yields a diminishing overprint of the main foliation in Fiskenæsset area towards Kvanefjord. Deformation has been dated with zircons from syntectonic pegmatites to 2.70-2.73 Ga, applying U/Pb zircon dating by LA-ICPMS. Most fold axes are dipping towards the SE to SW.

Event 7 has never been dated to our knowledge. Since it only occurs in the southernmost part of the area, its relative timing with regard to Event 5, Event 6 and Event 8 is unclear. Event 7 occurs in the rocks of the Tartoq Group and in its surrounding gneisses. This folding event has been called Maturian folding by Berthelsen & Henriksen (1975). It disturbs fold axial planes of the Senilian folding event (Event 4), thus is younger than that. Its timing is either related to the emplacement of the Tartoq group rocks, or happened after this event. Fold axial planes strike NE-SW.

Event 8 is only observed in the northern part of the area on and near the island Qilangaarssuit and in the northeastern part of the area. Deformation is observed as a mildly overprinting large wavelength folding with roughly E-W striking fold axes. Late-stage pegmatites related to this folding event were dated to *c.* 2.68 Ga (Kolb et al. 2009; Kisters et al. 2010). In some areas this event is associated with a concentration of gold in quartz veins (J. Kolb pers. comm. 2010).

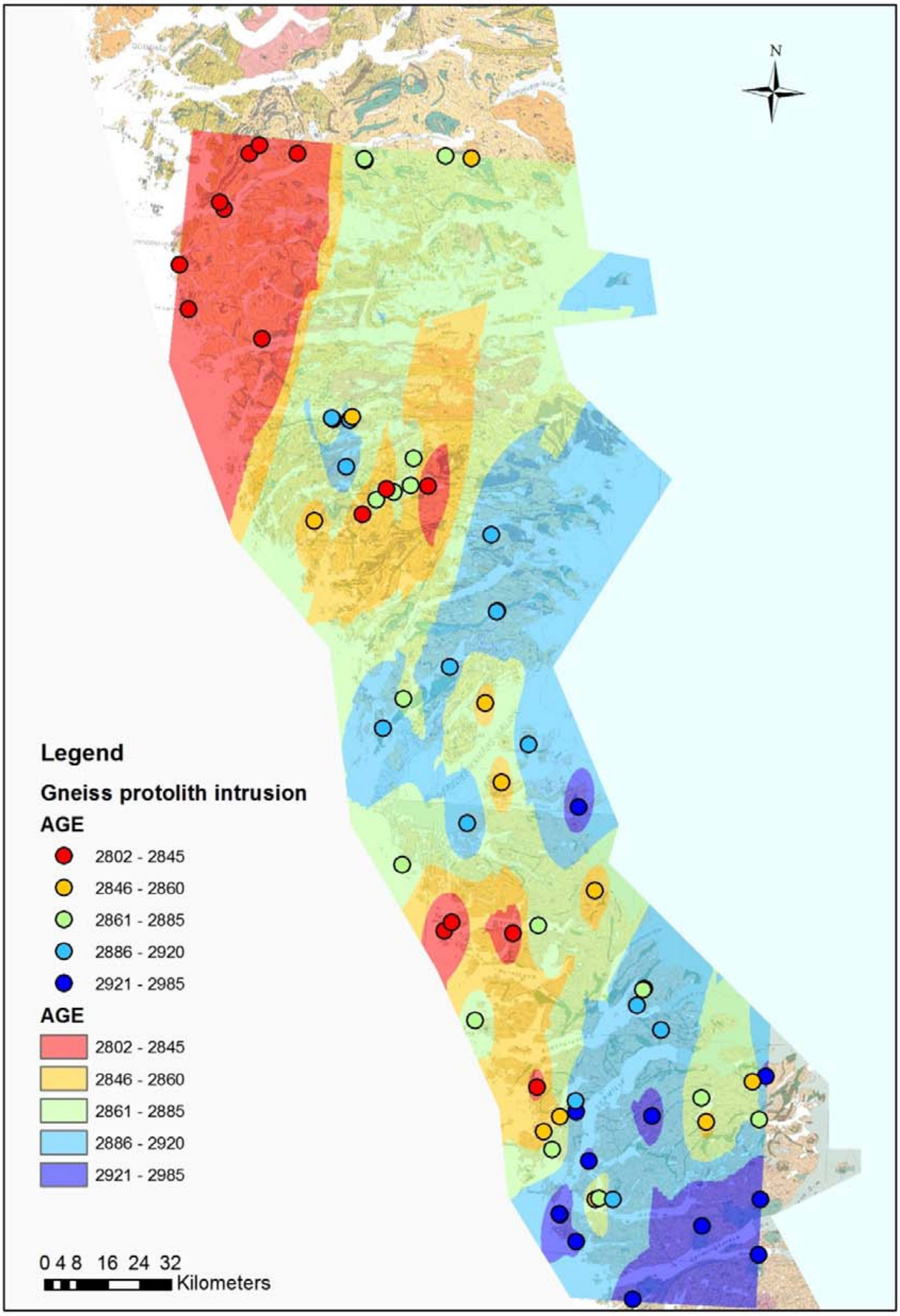


Figure 38: Zircon U/Pb ages measured with ICP-MS and their interpolation (see Kokfelt et al 2011 for details on the methods) for zircon grains that were interpreted as representing the main gneiss protolith intrusion event.

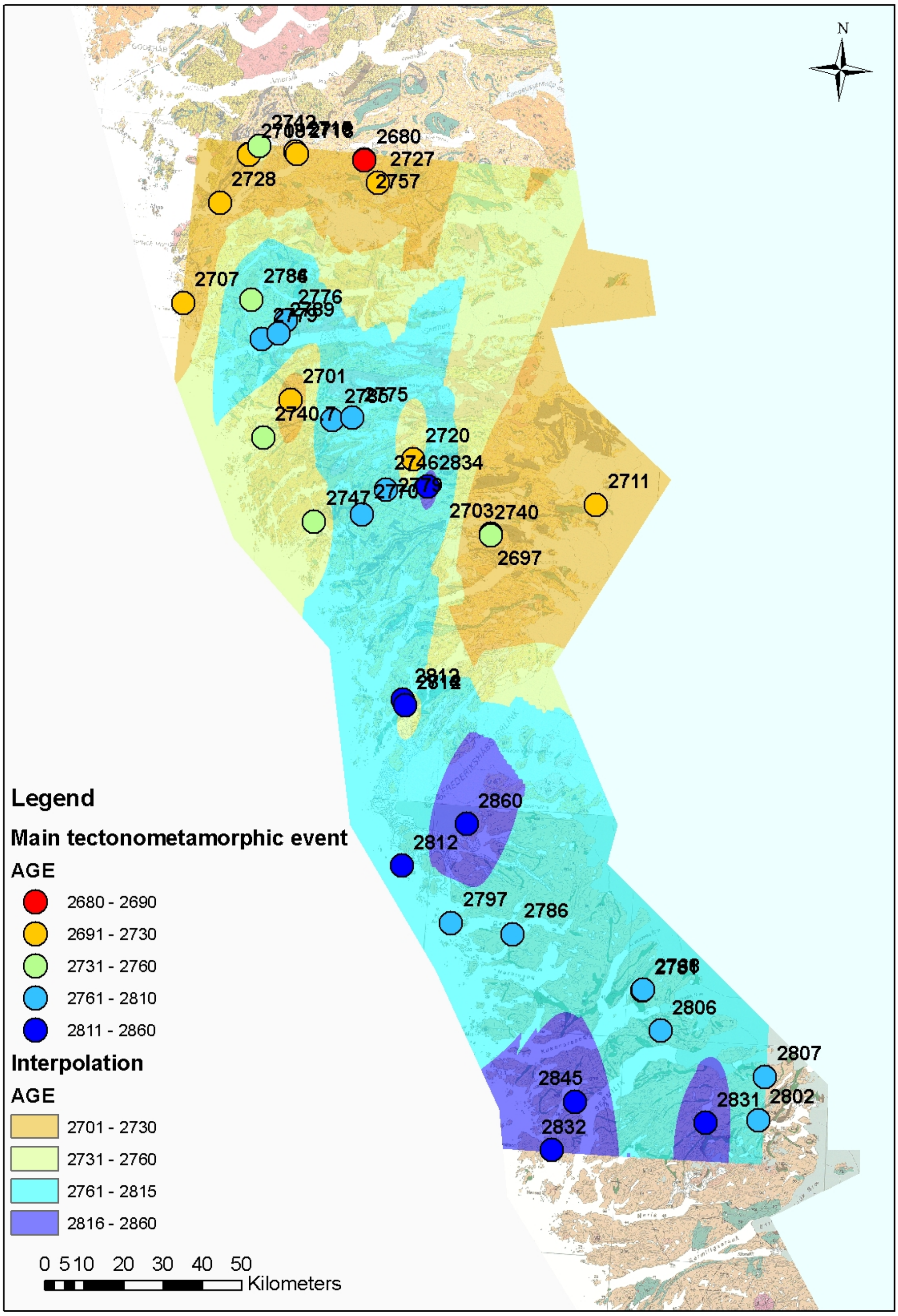


Figure 39: Zircon U/Pb ages measured with ICP-MS and their interpolation (see Kokfelt et al 2011 for details on the methods) for zircon grains that were interpreted as representing the main tectonometamorphic event. See text for discussion.

The two maps on the previous two pages show the gneiss protolith intrusion ages (Fig. 38) and the ages for the main tectonometamorphic event in the area (Fig. 39). The map indicates that the age of the gneiss protolith is decreasing from south to north, with some older ages occurring in the Fiskenæsfjorden area and some younger gneisses near Paamiut (see Kokfelt et al. (2011) for details). The map is included here to report the age of orthogneiss, which obviously must have been emplaced, before the main deformation events occurred.

The same younging northward trend is observed for the main tectonometamorphic event: Figure 39 shows a general decrease in age for the main tectonometamorphic event from south to north. Four major stages in the age of the main deformation event can be distinguished from south to north. The first stage occurs in the sourthern part of the area and near the Fiskenæsset complex, where ages older than 2.82 Ga prevail (blue colour dots). Older ages are more abundant in the area around (southern) Sermilik and around Qassit. This area covers the major part of the area affected by Event 4 (Table 1, compare to Figure 37). The earlier Event 2 cannot be recognised in the zircon ages, which might either be caused by an overprinting of Event 4, or indicate that deformation temperatures during this earlier event were too low to leave trace in the zircon record, or that the Event happened shortly after the gneiss protolith formation and cannot be resolved in time. The age of 2.815 Ga lies close to the onset of granulite-facies deformation in the Fiskenæsset area (see Kokfelt et al. 2011). In the southern area an undefined event at *c.* 2.78-2.81 Ga can be observed between Paamiut and Atarngup.

The next stage that can be observed in Figure 39 is a deformation event at *c.* 2.76-2.73 Ga, which is mainly observed around Ilivertalik granite and locally in the Fiskenæsset complex (green dots). Similar ages are also observed in the north-eastern part of the area, north of Ilivertalik (J. Kolb, pers comm. 2009). This stage is correlated here with Event 5.

The latest stage, which mainly yield ages of 2.70-2.73 Ga occurs abundantly in the northern part of the area, but has also been observed in the Fiskenæsset complex. It is indicated with yellow dots in Figure 39. This deformation stage is correlated with Event 6. Later thermal events are locally observed, but within the area covered by the zircon analyses, only one zircon U/Pb age interpreted as the main deformation event and correlating to Event 8 was observed (red dot in the area east of Buksefjorden).

Figure 40b shows all thermal events recorded with Zircon U/Pb for the age ranges 2870-2820 Ma, now not only the features that are interpreted as main tectonometamorphic event, as well as later tectonometamorphic events, intrusion ages of gneiss protoliths, intrusion ages of granites and pegmatitic sheets are included. Comparing the structural map showing the main folding events to the 2870-2820 Ma thermal events a well-defined overlap between these ages and the occurrence of Event 4 folding can be established. Apart from the ages for main deformation of the orthogneiss, many granites between Bjørnesund and Nigerlikasik have been dated to 2.85-2.83 Ga. In the Chapter on Bjørnesund and Ravn Storø, it is discussed that these granites intrude syntectonically into F2 fold axial planes (Event 4 folding). 2870-2820 Ma ages are also observed in the northern part of the area (north of northern Sermilik); here this age range corresponds to the formation ages of orthogneisses in the area (compare to the gneiss protolith age, Fig. 40; Crowley 2002, Nutman & Friend, 2001).

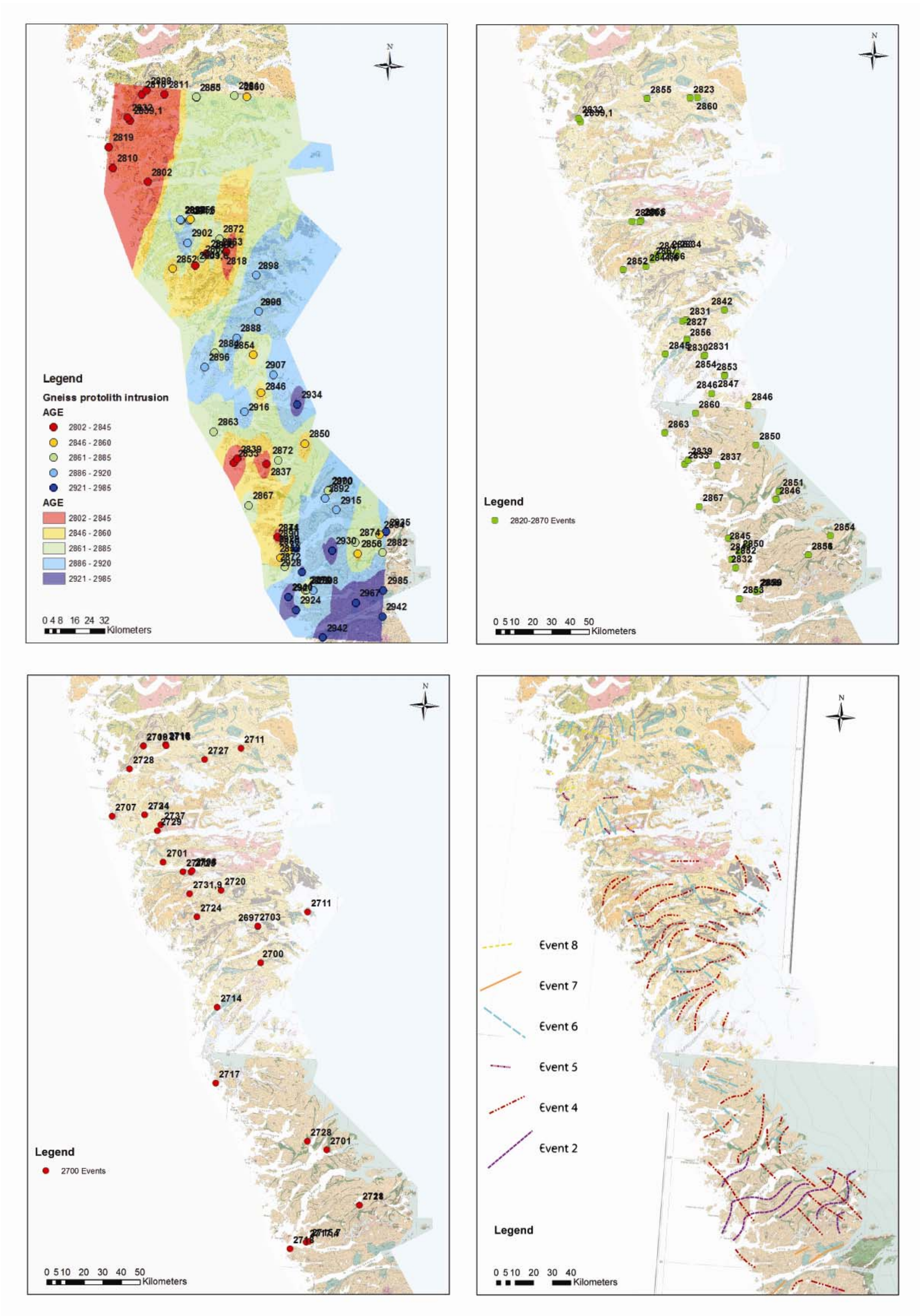


Figure 40: Main deformation events: Gneiss protolith age, as in Figure 38 for reference (upper left). Thermal events indicated by zircon U/Pb analysis within the age range 2870-2820 Ma (green dots, upper right) and 2730-2690 Ma (red dots, lower left). Summary diagram of Figure 37 with the Events discussed in Table 1 indicated (see Kokfelt et al 2011 for details on the geochronological methods).

Figure 40c shows all thermal events recorded with Zircon U/Pb for the age ranges 2730-2690 Ma, again originating from main and later tectonometamorphic events, intrusions of granites, and pegmatites. The age range 2730-2690 Ma shows a strong spatial overlap with the Event 6 folding. This age range is especially abundant in syn- to late tectonic pegmatitic veins associated with this folding, as discussed in the Chapters on Buksefjorden and on Bjørnesund and Ravn Storø.

Later deformation events

Figure 41 shows later tectonometamorphic events, mainly recorded in the orthogneiss. Again the 2730-2690 Ma age range shows up north of Frederikshåb Isblink, especially in areas where both Event 4 and Event 6 occured. A few more 2.68-2.66 Ga ages are recorded in the northeastern-most part of the area, but the 2.73-2.68 Ga age is also abundant in the south-eastern part of the area.

A late folding overprint has been observed in the Buksefjorden area and west of the Ilivertalik granite. This folding event is associated with pegmatitic sheets of 2.68-2.66 Ga in the (northern) Sermilik area (Kisters et al., 2010; J. Kolb pers. comm. 2010). However, no zircons of that age could be determined in the Buksefjorden area. Here, this weak late overprinting apparently did not mobilise as much fluids that the zircons could be reset during this amphibolite facies event.

Locally some younger events, peaking around 2.66 Ga and 2.60 Ga have been observed. The former has been associated with gold formation world-wide (J. Kolb pers. comm. 2009); see Figure 42 for localities.

Palaeoproterozoic deformation is mainly defined by faulting, which can reach offsets of up to ten kilometres in the studied area (Fig. 42). A series of major NNE-striking faults cuts through the area, the most important example is the fault between the outer Bjørnesund and the south-eastern corner of the Ilivertalik granite. This fault zone has some major conjugates off-setting the Fiskenæsset complex. The offset of this fault has been dated with baddeleyite U/Pb on ICP-MS (M. Nilsson pers. comm. 2010), the exact ages are however still confidential (to be released in the autumn 2011). A second, parallel, fault of a similar age runs from Vesterland to Avannarleq Bræ. It is worth noting that the *c.* 2.66 Ga Ivinguit fault north of the study area, along which the 2.56 Ga Qorqut granite intruded, runs nearly parallel to these faults. These large dextral faults indicate a NE-SW-oriented principal stress component in the late Archaean and early Palaeozoic.

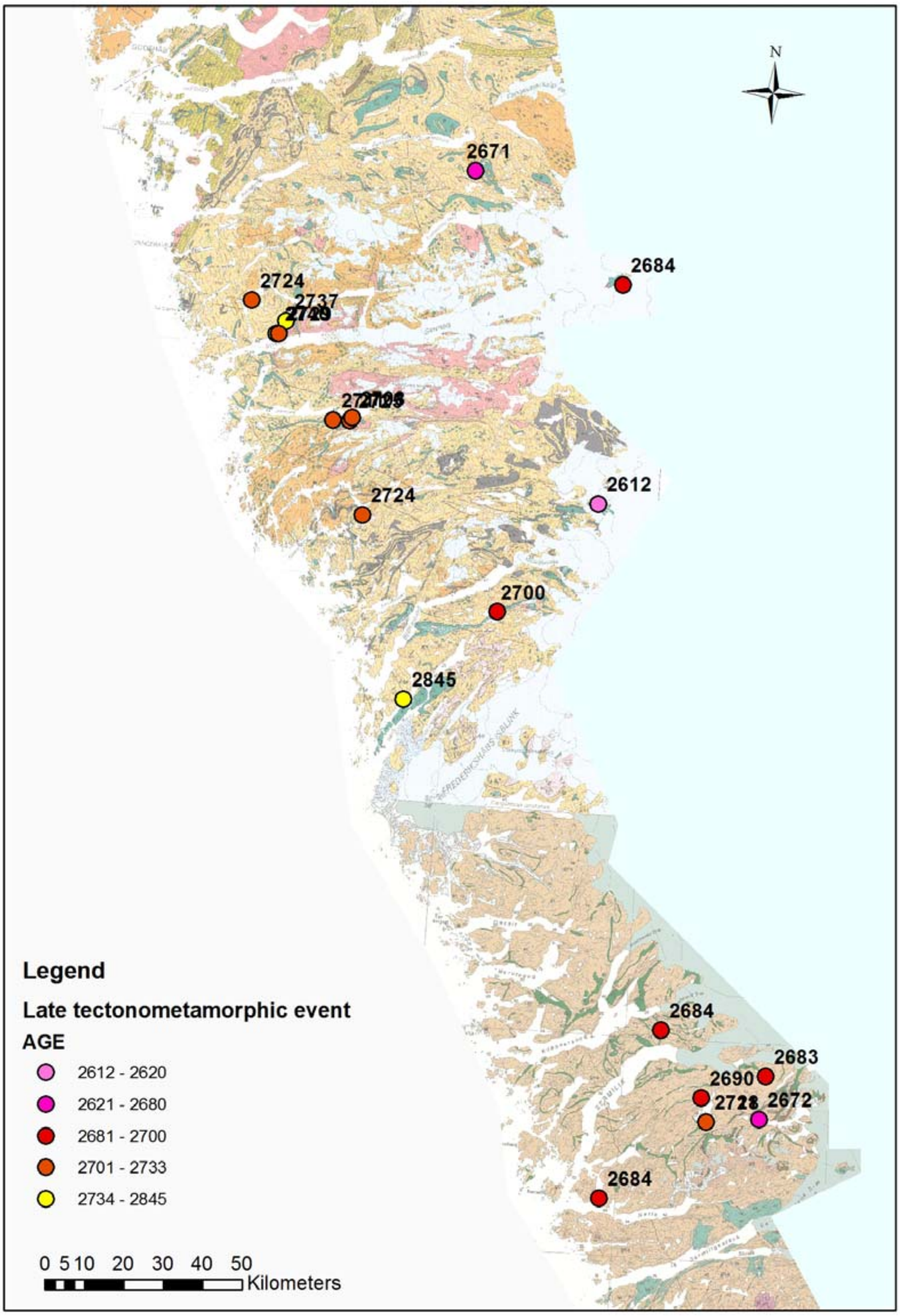


Figure 41: Zircon U/Pb ages measured with ICP-MS and their interpolation (see Kokfelt et al 2011 for details on the methods), for zircons grains that were interpreted as representing the later tectonometamorphic events. See text for discussion.

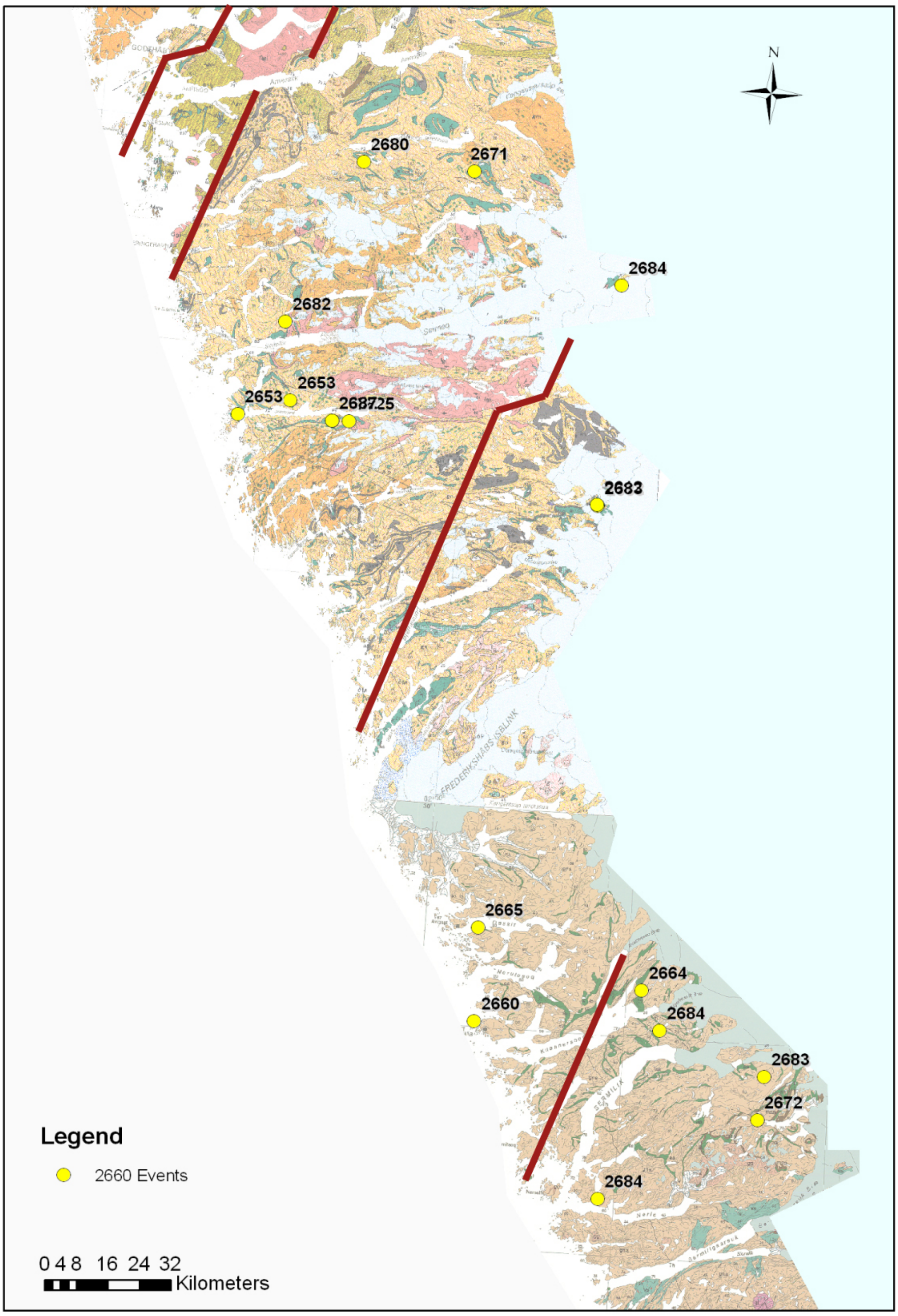


Figure 42: Major late Archaean and early Palaeoproterozoic faults (dextral) in southern West Greenland and South West Greenland and localities with zircon ages indicating thermal events between 2630 and 2690 Ma.

Interpretation of the deformation events

The first three folding events are observed locally and they are hard to interpret in terms of large scale tectonic events, mainly due to later overprint. As discussed above, their relative timing is uncertain. However, Event 2 might be associated with the event discussed in the Chapter on the Atarngup area (see Figure 36), where different generations of magma intruded between 2.87-2.92 Ga. Continued shortening in the later stages of these series of intrusions could eventually explain the tight NE striking series of fold axial planes in the Atarngup area.

Event 4 (Table 1, Figure 37) was observed between Sermiligaarsuk and Grædefjord. Syntectonic granites and pegmatites were dated to *c.* 2.85 Ga south of Frederikshåb Isblink, *c.* 2.84 Ga in the Bjørnesund area, and *c.* 2.83 Ga in the Fiskenæsset area. The largest amount of igneous activity of this age range (2.85-2.83 Ga) is found around Frederikshåb Isblink and in the Bjørnesund area. The event might tentatively be interpreted as the thrusting of a plate or block from the Bjørnesund-Fiskenæsset area on top of another plate or block south or southwest (in terms of current day's localities) of the Frederikshåb Isblink. The most intensive shortening and igneous activity appears to have moved northward between 2.85 and 2.83 Ga. Evidence of Event 4 folding has not been observed north of the Grædefjord – Ilivertalik granite area. This might be an indication for the occurrence of two different blocks, (e.g. the Bjørnesund and Sermilik blocks,) without any direct contact to each other, rather than a single (Tasiusarsuaq) terrane. However, deformation might as well be less intense towards the north and absorbed by the more competent Ilivertalik granite, in which case the two blocks could have been in contact with each other.

As discussed above, Event 5 might be an early stage of Event 6, or a separate Event in the Grædefjord – Ilivertalik area with a north-south oriented compression direction. Pegmatites associated with this event were dated to 2.76 Ga. This event might be tentatively associated to the collision of the Bjørnesund and Sermilik blocks. However, Kisters et al. (2010) place that collision to *c.* 2.71 Ga, thus as Event 6. Alternatively, Event 5 could be associated with uplift after the intrusion of the Ilivertalik granite.

Event 6 can most likely be interpreted as the collision between the Færingehavn terrane (and the associated terranes northwest of the Færingehavn terrane in the Godthåbsfjord area) in the west and the Tasiusarsuaq terrane or Sermilik block in the east. This Event is the main deformation in the northern part of the area and yields in important overprint as far south as Kvanefjord. Friend et al. (1987) and Nutman & Friend (2007) indicate that the Tre Brødre terrane and the Tasiusarsuaq terrane were placed on top of the Færingehavn terrane at *c.* 2.715 Ga. The timing fits with our own observations in the area, where syntectonic pegmatites date the event to 2.73-2.69 Ga. We however reinterpreted this collisional event as a contact between the Tasiusarsuaq terrane and the Færingehavn terrane, while the intermittent Tre Brødre terrane is seen as the edge of the the Tasiusarsuaq terrane, rather than associated with the Færingehavn terrane (e.g. McGregor et al. 1991); see the Chapter on the Buksefjorden for details.

Since deformation associated with this event has been observed so far to the south, it seems likely that the Færingehavn terrane, or associated parts of the Akia terrane, originally stretched much further to the south, causing a roughly east-west oriented compression as far south as Kvanefjord. Deformation seems more intense at the coast, but this might also result from a different observation density.

As discussed before, Event 7 is limited to the Tartoq Group and surrounding gneisses, but has also been observed south of the studied area (Berthelsen & Henriksen 1975). Deformation might speculatively be associated with the thrusting of the Tartoq Group on top of the gneisses, or with events further south in the Ivituut area.

Event 8 has an east southeastward trend and is mainly observed in the northeastern part of the area and as a mild overprint in the northwestern part of the area, where deformation is more intense in the Eoarchaean gneisses than in the adjacent Mesoarchaean ones. Its timing is set as 2.67 Ga. Nutman & Friend (2007) propose that this deformation is related to a collisional event that involves the Færingehavn-Tasiusarsuaq terrane and the Kapisilit terrane.

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