DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2011/14

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Abstract

Frederikshåb Isblink has been proposed as a terrain boundary between the Tasiusarsuaq terrain to the north and the Sioraq sub-terrain (or Kvanefjord block) to the south. The lack of any apparent displacement of a *c.* 2.05 Ga NW-SE trending and cross-cutting MD3 dyke that is identified on both sides of the glacier suggests that any significant tectonic activity along the line of the glacier must have taken place before the dyke emplacement.

Archaean structures are described within four study areas, located on a N-S traverse across the proposed terrane boundary through the Frederikshåb Isblink. Most areas lie within a region of SE-dipping TTG foliation, interspersed by amphibolite bands, but differ locally. The area north of Frederikshåb Isblink is characterised by NW-verging and over-kipped folds of *c*. 1 km long wave-lengths separated by <2 m thick and foliation-parallel protomylonitic shear zones, which are all consistent with top-to-NW directed shear. Southwards, on one of Dalagers Nunatakker, there is a possible decline in the number of both protomylonitic shear zones (only one was observed) and NW-verging folds. This decline coincides with an apparent southward termination of late-kinematic, and possibly 'sheath-shaped', granites that do not differ structurally from their TTG-amphibolite hosts. South of Frederikshåb Isblink, Kangaarsuup Nunaa appears to be the structurally most complex study area, as its regionally SE-dipping foliation and protomylonitic shear zones have been locally superimposed by two conjugate sets of oblique folds with sub-horizontal, E–W and N–S orientated fold axes. Each superimposed oblique fold can readily be explained by a corresponding transpressional shear component, but it is difficult to envisage how two opposite senses of shear (suggested by the conjugate pair of folds) could have affected the same area. A more extreme superimposed deformation of the regional SE-dipping foliation is exhibited by a nearly vertical and NW–SE striking local foliation in the southernmost study area. One amphibolite boudin shear indicator, within a remarkably pale TTG (previously mapped as an anorthosite), records a SW-block-down component, possibly in combination with a right-lateral transpressional component that is consistent with the E–W striking superimposed oblique folds seen at Kangaarsuup Nunaa.

Combined, the above observations give an overall impression of a top-to-NW directed shear, with local dextral displacements along NW–SE striking transpressional shear zones including some SW-block-down component. On its own, this could be interpreted as a collision zone but it appears to be just the southernmost part of a regional system that extends as far north into the northern Tasiusarsuaq terrane as Bjørnesund. Apart from a possible southward termination of such a SE-dipping thrust and NW-verging fold system as well as late-kinematic granites that extend from one geological 1:100 000 map sheet to the next there are apparently no significant structural, metamorphic or lithological differences across Frederikshåb Isblink to support any terrane boundary.

Introduction

The North Atlantic craton of southern West Greenland and South-West Greenland is dominated by Palaeo- to Mesoarchaean orthogneisses of trondhjemite-tonalite-granodiorite (TTG) compositions that often contain conformable layers of supracrustal rock sequences, mainly comprised of metavolcanic rocks and anorthosite intrusive complexes (Windley, 1969), and rare occurrences of ultramafic rocks and metasediments (Fig. 1). These rock associations occur in what has been described as alternating amphibolite and granulite facies metamorphic belts (e.g. Bridgwater *et al.* 1976; Kalsbeek 1976).

The tectonothermal evolution of the Nuuk region has been debated for many years (e.g. Bridgwater *et al.* 1974; Friend *et al.* 1987, 1988, 1996; Friend & Nutman 2005; Nutman *et al.* 1989, 2004; Nutman & Friend 2007; Windley & Garde 2009). The earliest work in the region envisaged a regional continuity in metamorphic history and rock ages throughout the entire Archaean of south-western Greenland (e.g. Bridgwater *et al.* 1974; Wells 1976). After the introduction of the 'terrane' concept by Coney *et al.* (1980) (initially developed for the Cordilleran region), a terrane model was adapted for the Nuuk region by Friend *et al.* (1987, 1988) in which several unrelated orthogneiss complexes were identified and assigned to different tectono-stratigraphic terranes. The tectonothermal evolution of the whole Nuuk region was initially based on detailed field work and zircon U/Pb geochronology with the first terranes identified in the west and south by Friend *et al.* (1987, 1988, 1996) – the Færingehavn, Tasiusarsuaq, Tre Brødre and Akia terranes. Each tectono-stratigraphic terrane is separated by folded mylonitic zones interpreted as ductile shear zones, and is characterised by distinct early histories (i.e. ages of orthogneisses and intra-terrane metamorphism). Subsequently, additional terranes were identified in the eastern part – the Isukasia and Kapisilik terranes – as a result of remapping and more zircon dating (Friend & Nutman 2005). The different terranes were assembled into a stabilising craton through progressive amalgamation along mylonitic shear zones (Friend *et al.* 1987, 1988; Nutman *et al.* 1989). Friend *et al.* (1996) proposed that extensive *c*. 2720–2700 Ma high-grade metamorphism occurred in response to crustal thickening caused by this terrane amalgamation.

The Tasiusarsuaq terrane represents the largest terrane of the entire Archaean in south-western Greenland as it extends from the southern part of the Nuuk region at the fjord of Amaralik south to Frederikshåb Isblink. The Tasiusarsuaq terrane is characterised by TTG gneisses with intrusion ages of 2880–2860 Ma (Friend & Nutman 2001; Crowley 2002), but new geochronological data suggest that a significant crust-forming event also took place at around 2920 Ma (Kokfelt unpublished data).

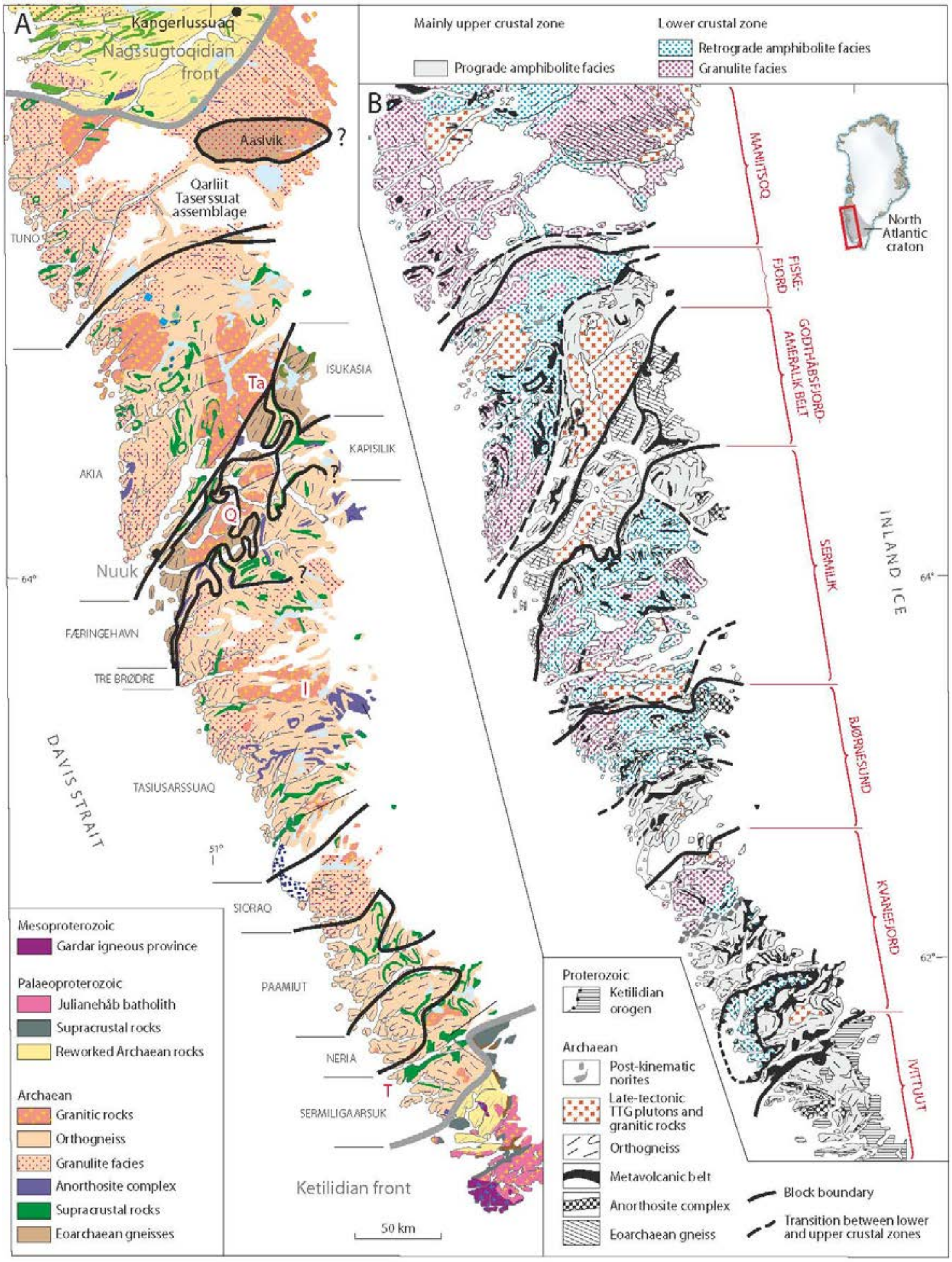

Figure 1. *Two proposed model views of the Archaean craton of SW Greenland: (A) the 'terrane' model of Friend & Nutman (2001) and, (B) the 'block' model of Windley & Garde (2009). In (A): T, Târtoq Group; I, Ilivertalik augen granite; Q, Qôrqut granite complex; Ta, Taserssuaq tonalite. See text for explanation. After Henriksen* et al. *(2009).*

South of the Tasiusarsuaq terrane four smaller terranes have been identified, from north to south these are: the Sioraq block, the Paamuit block, the Neria block and the Sermiligaarsuk block (Fig. 1a). Friend & Nutman (2001) suggested that each of these blocks contain TTG gneisses of distinct ages and as such could be ascribed to distinct tectonometamorphic terranes. According to McGregor & Friend (1997), each of these tectonically-separated blocks or terranes can be characterised as follows: (1) The Sioraq block situated just south of the Frederikshåb Isblink, contains granulite facies TTG rocks (2870–2830 Ma) that were partly retrogressed to amphibolite facies. (2) The Paamiut block contains younger TTGs (2870–2850 Ma) that show no evidence for metamorphism above amphibolite facies. (3) The TTGs within the Neria block (2940–2920 Ma) were metamorphosed to granulite facies, but totally retrogressed to amphibolite facies. (4) The Sermiligaarsuk block hosting the Tartôq Group supracrustal rocks and gneisses, were metamorphosed up to greenschist and lowermost amphibolite facies (< 3000 Ma).

An alternative to the terrane concept was described by Windley & Garde (2009) who envisaged the SW Greenland Archaean craton to consist of crustal blocks rather than petrogenetically unrelated terranes, *sensu stricto* (Fig. 1b). Based on a regional reinterpretation of available data on regional structures and metamorphism Windley & Garde (2009) explained the apparent N–S bands of differing metamorphic grade as reflecting a series of generally southward tilted blocks (i.e., in a regional scale domino-block fashion). Within each tilted block the northernmost part should therefore expose deeper erosional levels, reflected in a higher metamorphic grade of the rocks compared to the neighbouring block’s southern part.

A possible tectonic boundary in the Frederikshåb Isblink area?

The Frederikshåb Isblink area marks the proposed boundary between the Tasiusarsuaq terrane, or Bjørnesund block, to the north and the Sioraq sub-terrane or Kvanefjord block to the south (Fig. 1), and is thus inferred by both Friend & Nutman (2001) and Windley & Garde (2009) to represent a major tectonic break between areas with rocks of different metamorphic grade and age. The southern part of the Tasiusarsuaq terrane/Bjørnesund block contains TTG gneisses of amphibolite facies grade with intrusion ages of 2880-2860 Ma, whereas the Sioraq block/Kvanefjord block south of the Isblink has been described as granulite facies TTG rocks that partly retrogressed to amphibolite facies and have intrusion ages of 2870-2830 Ma (McGregor & Friend 1997; Friend and Nutman 2001). In greater detail than Fig. 1, the inferred boundaries shown in Fig. 2 pass through an area with many late-kinematic granites, either north (Friend & Nutman, 2001) or south (Windley & Garde, 2009) of Dalagers Nunatakker. Younger granites are common far north of these boundaries but only extend slightly farther south of them, as indicated in Fig. 2.

The Sioraq sub-terrane includes the area from the fjord of Nerutusoq northwards to the Frederikshåb Isblink and has been described by McGregor & Friend (1997) as comprising rocks that were metamorphosed under granulite facies conditions and only partly retrogressed to amphibolite facies. The field evidence for this retrogression is a so-called 'blebby texture', which they ascribe to a clustered metamorphic growth of mafic minerals upon rehydration. However, based on the most recent work in the SW Greenland Archaean craton (from 64 to 61.5º N), a revision of the metamorphic grades throughout the region has been proposed by Schumacher *et al.* (2011) that differs from those originally indicated on the printed 1:100 000 geological maps of the area. A new metamorphic facies map (see www.geus.dk/swgrmap/) indicates, in contrast to prior assumptions, that the Sioraq block south of the Frederikshåb Isblink only reached amphibolite grade and strongly questions the possibility of retrogression of rocks from granulite to amphibolites facies on a regional scale (Schumacher *et al.* 2011). It is also important to note that no apparent offset along an interpolated ESE-trending and 50 m thick dolerite dyke ridge (MD3 in Fig. 2) – exposed on both sides of Frederikshåb Isblink – indicates that little to no lateral displacement occurred along these tectonic boundaries since the emplacement of the dyke at around 2.03–2.05 Ga (age range of similar trending MD3 dykes within this region by Nilsson *et al.* 2010).

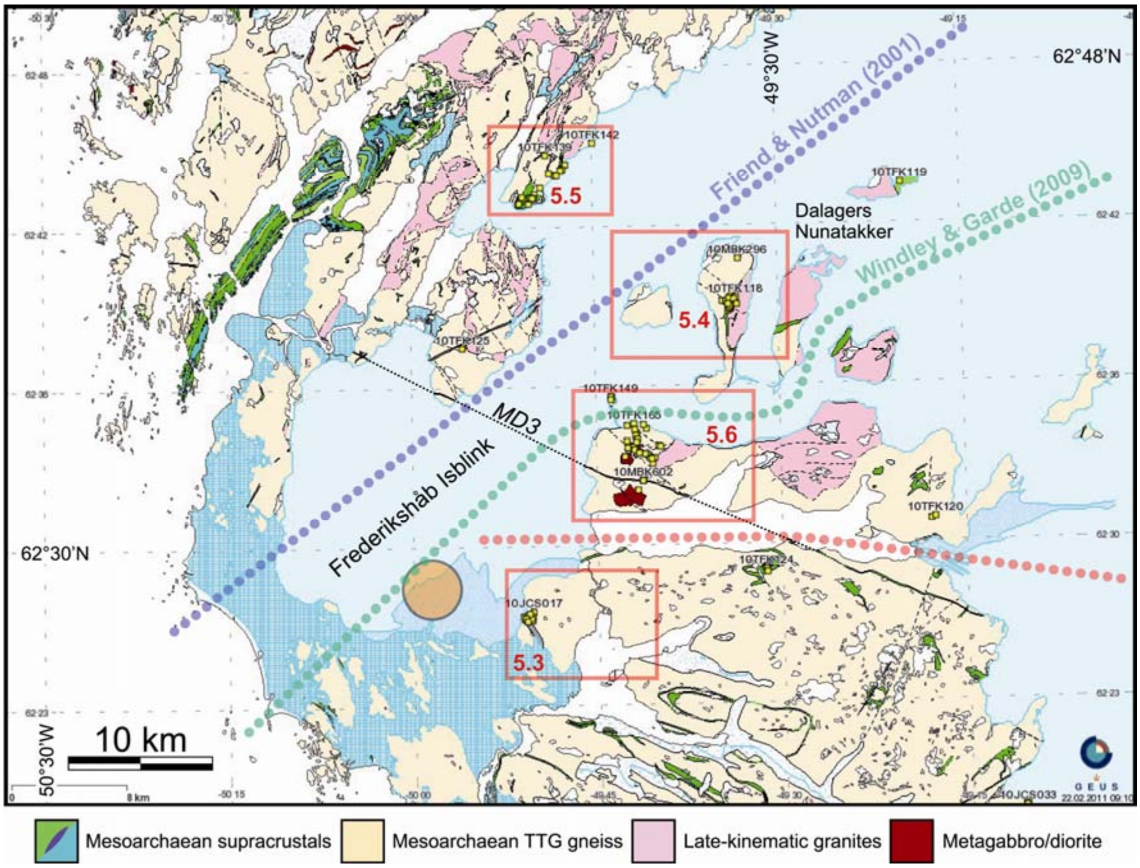

Figure 2. *Web-based geological map (www.geus.dk/swgrmap/) of the Frederikshåb Isblink area, showing the localities visited during the GEUS 2010 field work in the area (yellow squares) mainly concentrated around four fly camps 5.3 to 5.6 (orange frames outline map sections in Figs 3, 8, 10 & 12). Thick dotted lines trace possible terrane boundaries (blue and green) as indicated in Fig. 1, as well as the southern extent of late-kinematic granites (dotted red line). Several dykes and associated fault zones cut the area, including a WNW–ESE trending presumed MD3 dyke that can be traced right across any tectonic boundary. Many lamprophyre sheets and dykes appear to converge onto a geophysical anomaly that may represent an intrusive hypothetical carbonatite centre (orange circle).*

In this report we present field observations and structural measurements made during the 2010 field work in the Frederikshåb Isblink area that address the likelihood of a major tectonic boundary in the area. As the proposed boundary is covered by the Frederikshåb Isblink glacier ice tongue that extends westwards from the Inland Ice, the terrane model can only be tested indirectly by comparing the rocks north and south of the proposed boundary. The main evidence that we focus on here is the structures in these different areas, but the recent metamorphic and geochronological data from the area will also be discussed. Field investigations across the boundary between two neighbouring 1:100 000 map sheets, also, contribute towards the project's overall homogenisation of GEUS' geological map legend in scale 1:100 000.

Field observations and structural measurements

The geology around the Frederikshåb Isblink was investigated in 2010 by 2 to 3 geologists for 3 to 4 days within each of the four camp areas in Fig. 2, and during one reconnaissance helicopter trip. One camp (5.5) was located north of the terrane boundary proposed by Friend & Nutman (2001), whereas camp 5.4 was located between it and (north of) the block boundary proposed by Windley & Garde (2009). Although located south of both proposed tectonic boundaries, the camp 5.6 area resembles the northern areas, including one of the southernmost mapped late-kinematic granite intrusions (Fig. 2). Camp 5.3 lies south of these younger granites and within the variably garnet-bearing TTGs of the Sioraq block. Three camp areas (5.4–5.6) lie within the southern part of Bjørnesund 62 V.1 Nord 1:100 000 map sheet, whereas Camp 5.3 is located within the northern part of the Nerutussoq 62 V.1 Syd 1:100 000 map sheet. The two camps (5.4 and 5.6) that lie closest to the proposed tectonic boundary beneath Frederikshåb Isblink (Fig. 2) both lie within an area that is mapped and described in great detail by Dawes (1970). Field observations from each of the four camps (5.3-5.6) are presented below, from north to south. The investigated camp areas provide isolated structural and lithological clues to the possible presence and nature of a tectonic boundary, and overall they comprise a composite N–S cross section through the area.

Camp 5.5

The geological map (Fig. 3a) indicates a moderately ESE-dipping TTG/amphibolite terrain around camp 5.5, with ultramafic inclusions inside what appears to be a relatively large, migmatised amphibolite unit. We observed the amphibolite unit to be intruded by syn-kinematic pegmatites, which in places exhibit small leucosome veins of feldspar and quartz. The amphibolite units includes a large number of up to 50 m ultramafic lenses, most of which consist of either (1) hornblendite, (2) more massive, pale green and anthophyllite-bearing peridotite that is variably cross-cut by <5 cm wide chrysotile veins (Fig. 4a), or (3) rhythmically layered pyroxenites or peridotite rocks (Fig. 4c). The foliated TTG gneisses include concordant and late-kinematic granites (*senso lato*) that outcrop NNE of camp 5.5 (cf. Fig. 3a) and are similar to those around camp 5.4.

The apparent large areal extent of the amphibolite units around camp 5.5 is a sectional effect through an overturned fold with a relatively flat fold axial plane, where the true thickness of such a shallow inclined amphibolite band is estimated to be less than approximately hundred metres. A single anomalously 25°NW-dipping foliation in Fig 3(a) suggests that amphibolite units are part of a superimposed SW-plunging open synform, which is in fact part of a parasitically folded limb of a tight, overturned, and WNW-verging fold. This is evidenced by a composite set of cross sections through the upper limb of the fold and hinge zone, which crop out along a series of orthogonal (trending between N104°E to N146°E) and vertical joint surfaces (Fig. 5 I-VI) along the western margin of the amphibolite unit (see Fig. 3a).

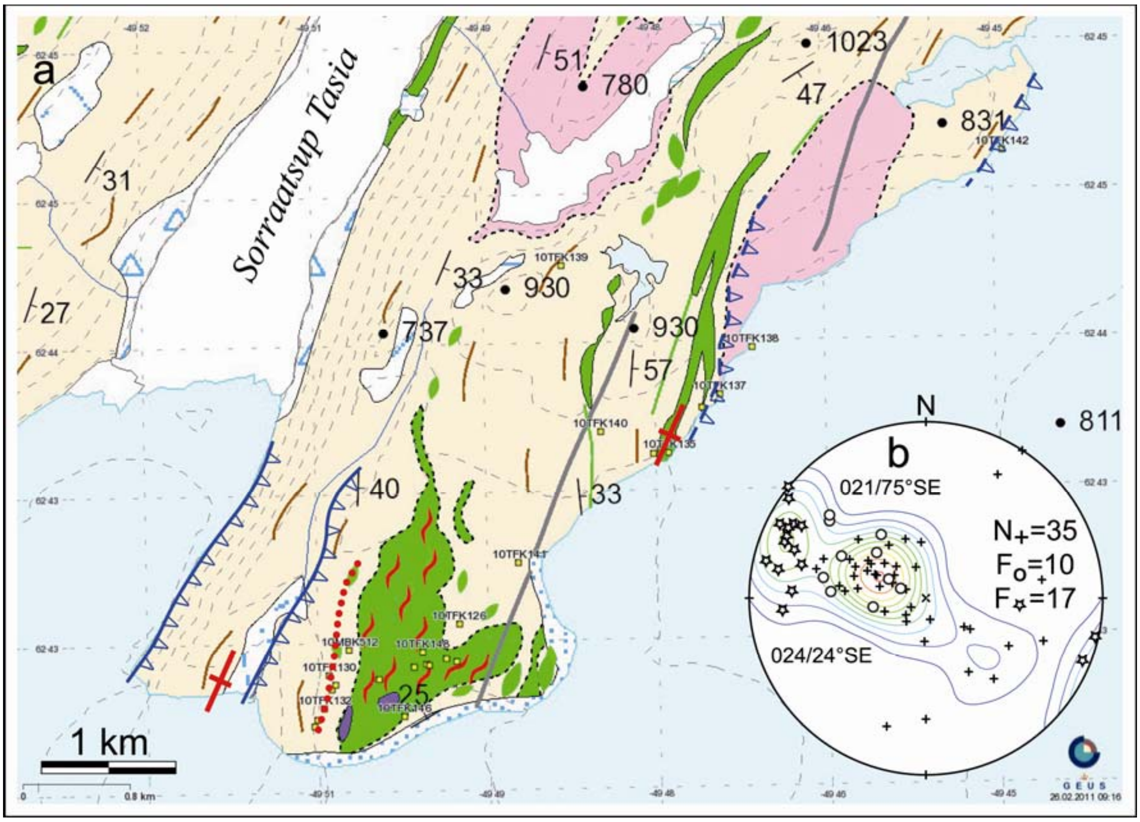

Figure 3. *Structures around camp 5.5. (a) Geological map with added locations of thrusts (blue shark toothed lines), fold axial trace of NW-verging over-kipped fold (red dotted line), and steeply dipping foliations (red vertical strike-dip symbols).Sigmoidal red 'fish' symbols indicate a migmatized amphibolite. b) Lower hemisphere and equal area stereographic projection of Kamb contoured poles to planes of regional gneissic foliation (crosses), locally steep foliations (stars), and <2 m thick, protomyolinitc shear zones (circles). Yellow squares indicate field localities visited during field work in 2010. Legend as Fig. 2.*

Outcrops in Fig. 3a expose different levels through what is assumed to be upper, finely laminated amphibolite/meta-sedimentary units (cf. inserted top photograph in Fig. 5), above some rusty beds and more massive underlying amphibolite units that most likely represent basaltic protolith. The supracrustal rock sequence is intruded by discordant to partly concordant and small-scale folded aplite or pegmatite veins. On a larger scale this assemblage is folded around a coarse-grained TTG gneissic core (Fig. 5 V–VI) with a gently ESE-dipping fold axial plane and consistent parasitic folds along its limbs (Fig. 5). A late-kinematic pegmatite dyke cross-cuts this fold structure at (V). No ultramafic units crop out within the hinge zone of the fold, in contrast to their aforementioned greater abundance along its exposed upper limb.

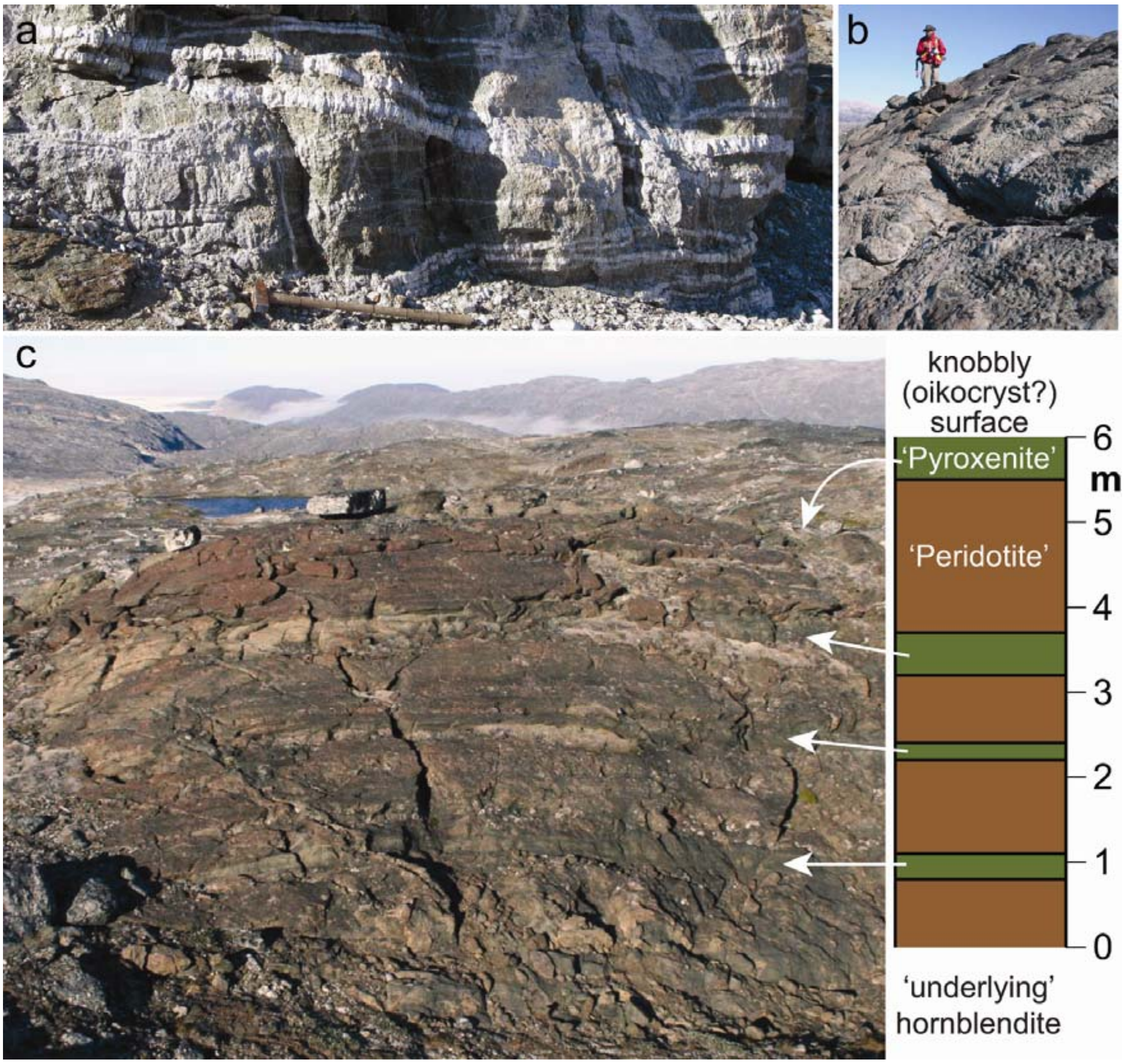

Figure 4. *Ultramafic rocks near camp 5.5. (a) Chrysotile veins through anthophyllite-rich meta-peridotite. (b) Knobbly (oikocrystic?) surface of (c) distinctly rhythmic sequence of thinner, greenish meta-pyroxenite, and thicker, reddish-brown meta-peridotite layers (looking west).*

At least one *c.* 2 m thick and moderately ESE-dipping thrust is located immediately to the WNW of the hinge zone to the overturned fold in Fig. 5. A similar thrust was observed in the westernmost edge of the area, outcropping along the eastern shore of Sorraatsup Tasia (Fig. 3a). Figure 3b shows that ten measurements on these two thrusts planes (average of *c*. 028/37°SE) are orientated roughly parallel to the tightly folded regional foliation (*c.* 024/24°SE), adding further credence to an overall, syn-kinematic and top-to-WNW directed simple shear component in the western part of the camp 5.5 area.

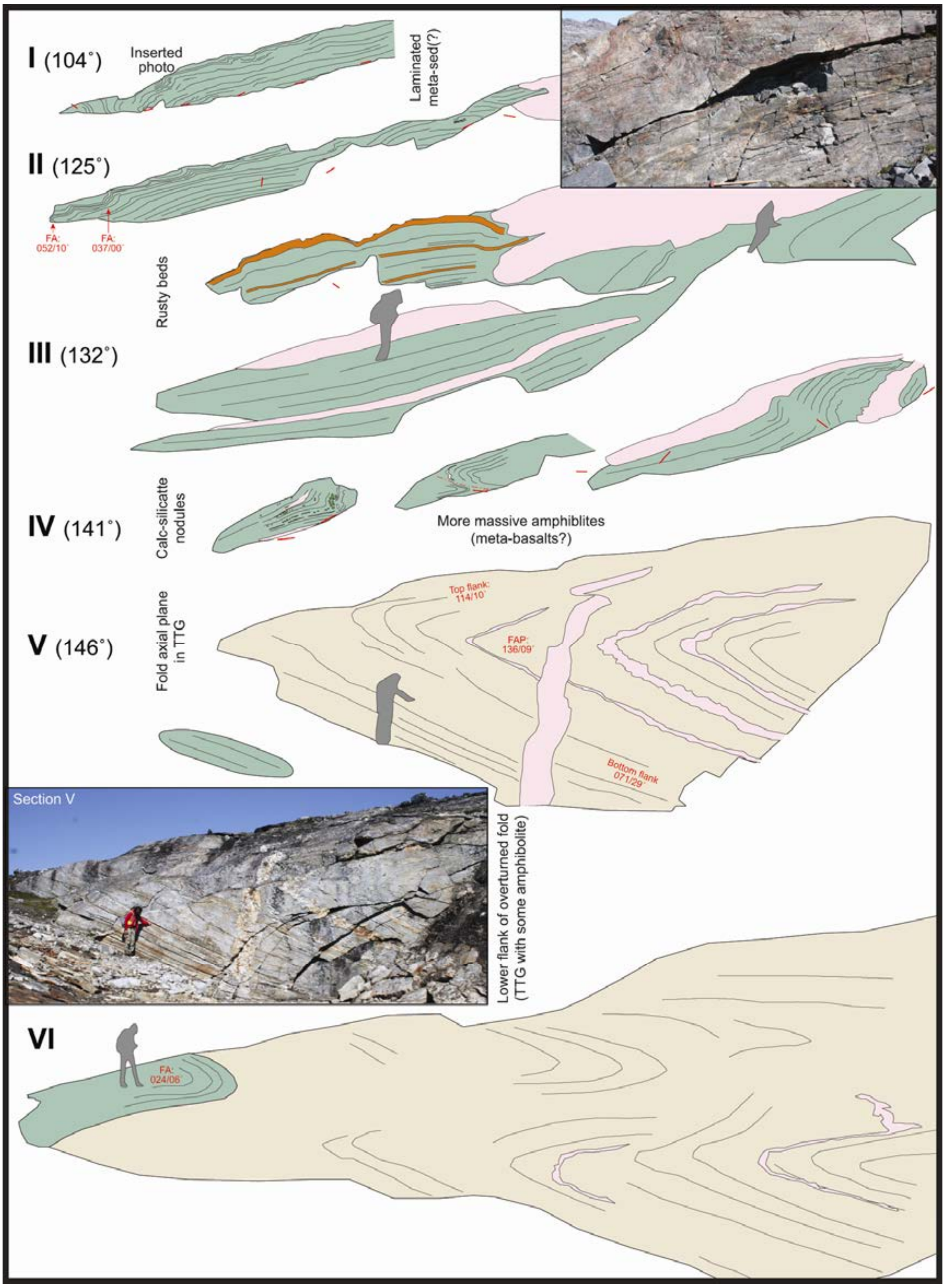

Figure 5. *Looking north-east, a compilation of a series of cross sections (trends indicated in brackets) that expose different parts of a WNW-verging (left), overturned fold. (I–II) Finely laminated amphibolite/meta-sedimentary units (cf. inserted photograph). (III) More massive amphibolitic unit with rusty beds. (IV) Minor S-folds and thrusts within amphibolite with calc-silicate nodular strands. (V) Foliated TTG, with sub-concordant (i.e. folded) and more cuspate pegmatites, with a fold axial plane that dips very gently towards SE. The fold is also cut by a regularly sub-vertical pegmatite (picture centre). Outcrop is traced from the inserted photograph. (VI) Parasitic Z-folds along lower limb of the overturned fold, with the possible 'base' of the amphibolite band. FA = fold axis. FAP = fold axial plane. Figures (in grey) and 60 cm long hammer shafts (short red lines) provide scales.*

Figure 6. *Steeply SE-dipping and zebra-striped amphibolite/aplite in the eastern part of the 5.5 area, cut by a 2.4 m thick, porphyritic alkaline dyke (right side of picture). Person on hill slope provides a scale.*

The moderately ESE-dipping regional TTG gneiss foliation continues farther east and north of camp 5.5, within which a <100 m thick band of foliated amphibolite exhibits much steeper to sub-vertical orientations (Fig. 6; *c*. 021/75°SE in Fig. 3b). Such anomalously steep dips within domino-type rotated blocks would be inconsistent with (i.e. opposite to) a top-to-WNW directed shear regime, and are therefore interpreted to represent the steep flank of a synform. This interpretation (Fig. 7) is supported by what appears to be a consistent stratigraphic up-towards-WNW sequence from meta-basalt to meta-sediment, across the steep amphibolite belt NE of camp 5.5 (Fig. 3a), as well as the fragments of another steeply dipping and highly contorted amphibolite belt (not previously mapped) that crops out beneath the observed thrust and its overlying, dragged and overturned antiform in Fig. 5. A fourth thrust is inferred along the easternmost edge of the area (closest to the Frederikshåb Isblink), from a few outcrops with gently SE-dipping and highly sheared augen gneiss.

The fold and thrust geometries as well as the SE-dipping regional foliations in Fig. 7 are all consistent with an apparent top-to-WNW directed simple shear. Fig. 7 sketches the overall deformation of the area around camp 5.5, where a pervasive regional compressional strain was accommodated along localised shear zones between folds.

One 2.4 m thick and SW–NE trending alkaline dyke, with a high concentration of flow-segregated olivine, pyroxene and phlogopite phenocrysts cuts Archaean structures (Fig. 6).

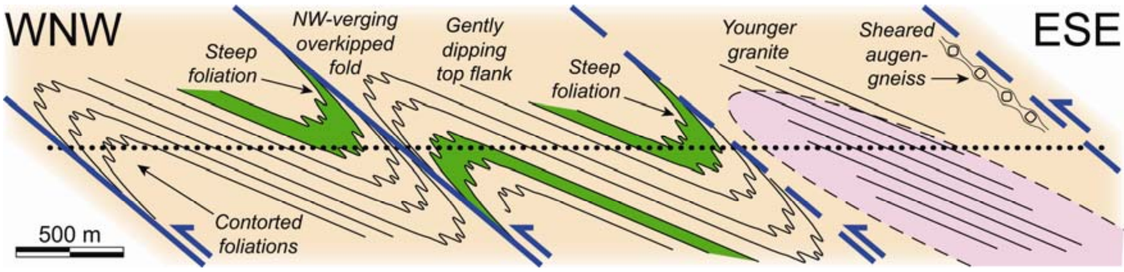

Figure 7. *Schematic structural section through the camp 5.5 area, orientated at right angles to the strike of the regional foliation. Green bands represent amphibolite bands whereas the pink unit is a younger granite within the foliated TTG gneiss (yellow-brown). Solid and dashed blue lines represent observed and inferred, respectively, protomylonitic shear zones, interpreted as thrusts. See text for more explanation.*

Camp 5.4

According to Dawes (1970) Saliaata Nunaa (Fig. 8a) is made up of an older TTG gneiss and a younger (late-kinematic) granite (*sensu lato*), separated by a <100 m wide band of amphibolite. Our field observations mainly confirm the mapping by Dawes (1970). One *c*. 2 m thick and moderately SE-dipping protomylonitic (to weakly cataclastic) thrust similar to that at camp 5.5 (Fig. 3a), is located NW of the amphibolite unit and orientated roughly parallel to a surrounding TTG and amphibolite foliation that clusters around *c*. 029/56°SE (Fig. 8b). According to Dawes (1970), this moderately SE-dipping foliation appears to drape around the younger granite intrusion and thereby closes around a fold axis (Fig. 8a) that is much more steeply E-plunging than the nearly horizontal fold axis in the camp 5.5 area. In a top-to-NW-directed shear regime, such a steeply plunging fold axis is best reconciled with the younger granite having a geometry resembling a sheath-shaped fold. The following additional observations were made in 2010:

Large parts of the TTG and the younger granite exhibit similar, regular SE-dipping foliations with local isoclinal folds (Fig. 9a–b). Only the western margin of the younger granite exhibit more diffuse foliations (e.g. Fig. 9b), whereas more strongly foliated inner (eastern) parts of the intrusion suggest that it intruded relatively early during the orogenic event. Furthermore, the young granite appears to be cross-cut by several, narrow and oblique shear zones, with minor components of apparently both right-lateral and left-lateral displacements (Fig. 9c), as well as, syn- and post-orogenic pegmatites (as in Fig. 5V). At least two, distinctly cross-cutting, post-orogenic pegmatite generations cut the younger granite (Fig. 9d).

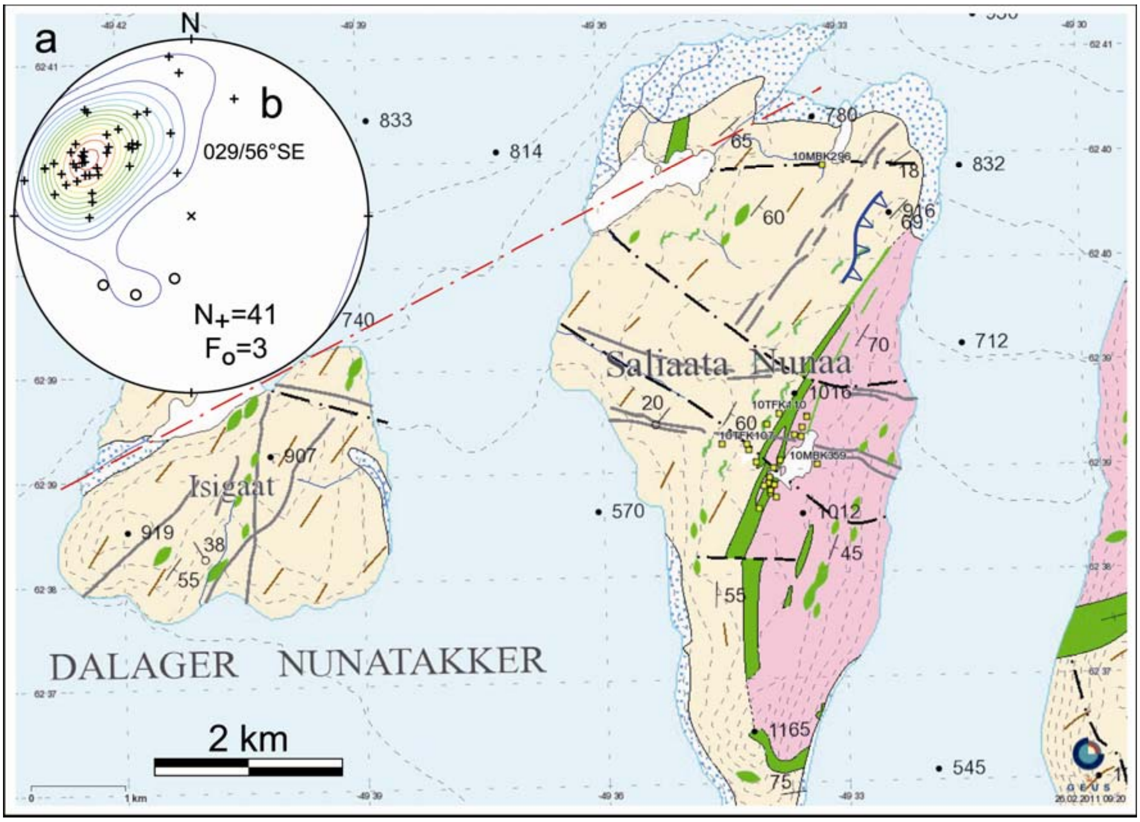

Figure 8. *Structures around camp 5.4. (a) Geological map with additional locations of thrusts (blue shark toothed lines) and a prominent SW–NE trending cataclastic fault zone (dashed red line). (b) Stereographic projection of contoured poles to planes (as in Fig. 3b) of regional gneissic foliation (crosses), cut by NE–SW trending, cataclastic and epidotised normal fault zones (circles in b) that are parallel to MD3 dykes. Yellow squares indicate field localities visited during field work in 2010. Legend as Fig. 2.*

Dismembered amphibolite lenses inside the TTG and the younger granite show subparallel foliations, indicating that substantial deformation produced these structures. A more coherent amphibolite band separates the older TTG and the younger granite. The lithological association (basal ultramafic peridotite and pyroxenite, a central amphibolite zone and an upper banded meta-sedimentary sequence; Fig. 9e–g) appears to be relics of an ophiolite suite (e.g., Szilas *et al.* 2011).

The SE-dipping regional foliations within the camp 5.4 area resemble those recorded around camp 5.5 (Fig. 3b). Together with a sheath-shaped younger granite near camp 5.4, these structures are consistent with top-to-WNW directed shear. The skewed contoured pole distribution in Fig. 8b, from more steeply, easterly dipping to more gently, southerly dipping foliations, probably conforms to the large sheath-shaped fold structure in Fig. 8a.

Saliaata Nunaa is cut by <5 m thick, E–W trending and moderately S-dipping, dolerite dykes with an abundance of large, dark phenocrysts (black feldspars by Dawes, 1970), which flow-segregated along head-wall contacts and into narrow apophyses.

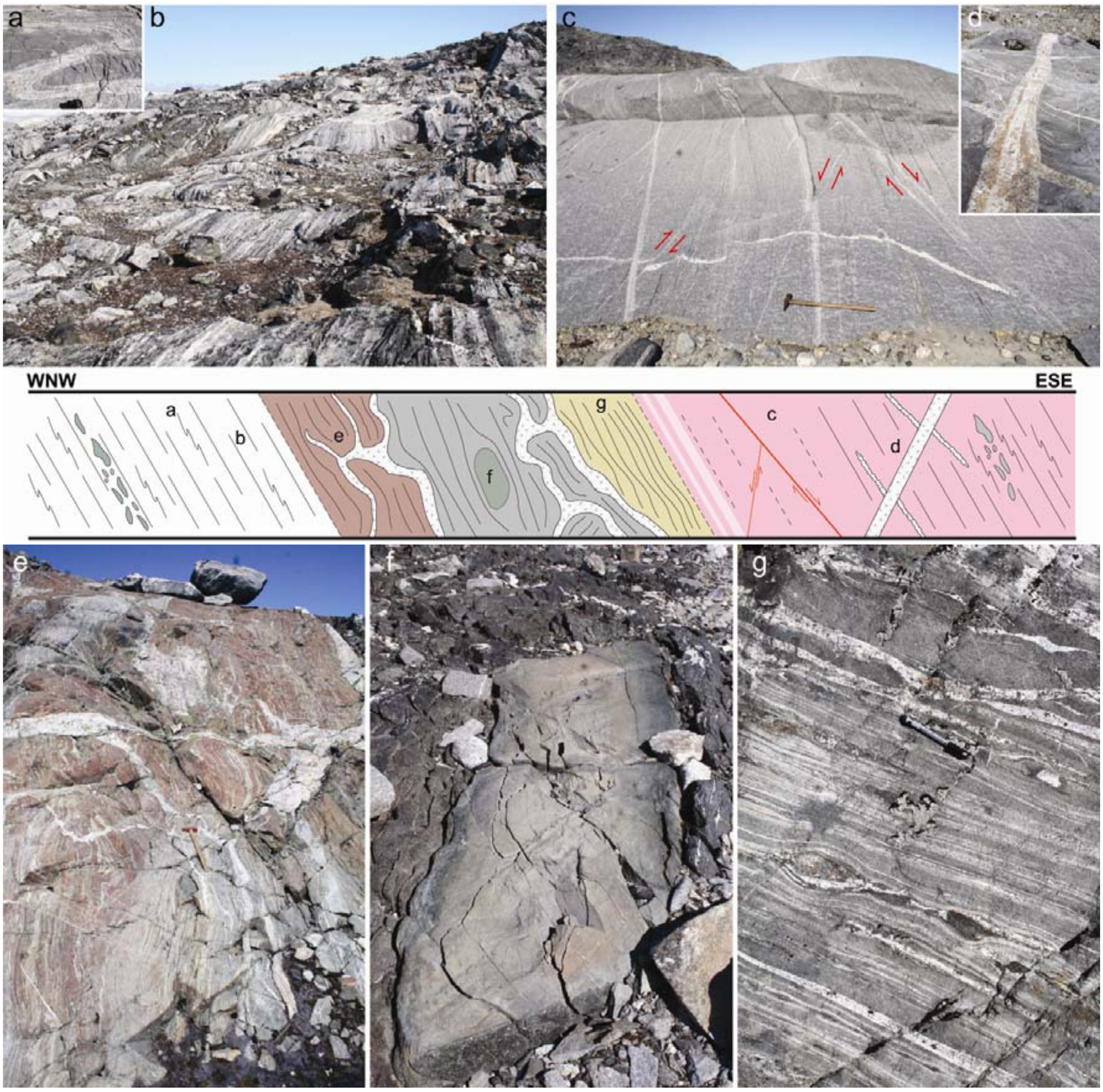

__Figure 9.__ Structural and lithological variations across the TTG-amphibolite-granite contact around Camp 5.4. Isoclinally folded (a; width of view c. 1.5 m) and moderately SE-dipping regional foliation (b) within the older TTG. Closer to the amphibolite bands, the younger 'granite' exhibits a less distinct SE-dipping foliation that is cut by narrow shear zones (red arrows in c), as well as syn- and post-tectonic pegmatites (d; large pegmatite c. 0.5 m wide). Between the old TTG and the younger granite, the amphibolite band is made up of weakly layered ultramafic units including reddish pyroxenite (e), dark amphibolite with rare ultramafic rafts (f; raft c. 1 m wide), and (calc-silicate) meta-sediments (g), indicating a stratigraphic way up towards the ESE.

Camp 5.6

According to Dawes (1970) Kangaarsuup Nunaa is made up predominantly of TTG with SE-dipping foliation, intruded by a minor late-kinematic granite (*sensu lato*), and containing scattered amphibolite rafts. This semi-Nunatak is cut by (E)SE-trending meta-doleritic dykes, an unusually brown-weathered meta-dolerite/diorite sill, and a relatively dense swarm of NE-trending lamprophyre dykes. Our field observations from the area between the most north-westerly exposed regional SE-dipping foliation and the intrusive NW-margin of the late-kinematic granite (Fig. 10a) are compiled as a composite structural and lithological cross section in Fig. 11 (green bars in Fig. 10).

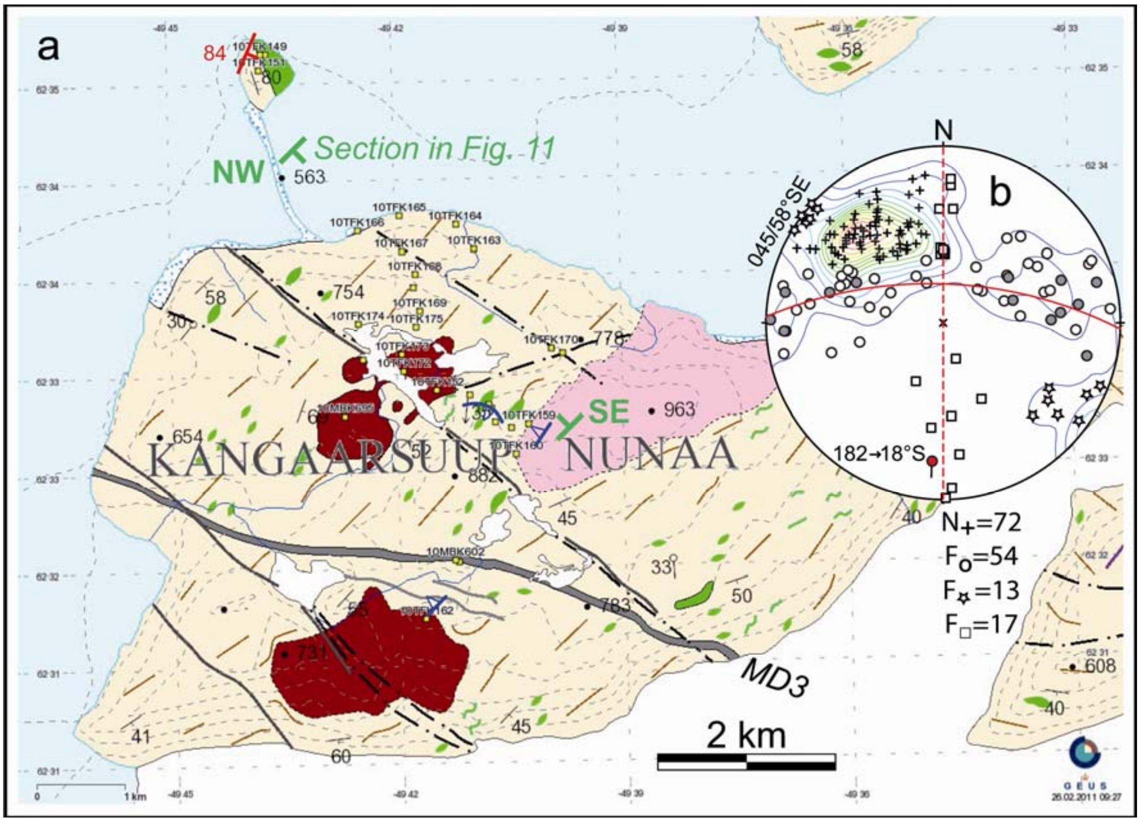

Figure 10. *Structures around camp 5.6. (a) Geological map with one edited foliation measurement on small nunatak in upper right corner. The dark red meta-gabbroic/dioritic intrusions are unique for the Frederikshåb Isblink area. (b) Stereographic projection of contoured poles to planes (as in Fig. 3b) of regional, SW-NE striking gneissic foliation (crosses), including locally steeper-striking amphibolite foliation measurements (stars), N–S striking foliation (circles), including the open synformal plane of a <2 m thick, protomylonitic shear zone (grey circles), and E–W striking foliation measurements (squares). Great circles constrain two fold systems with sub-horizontal fold axes (solid red curve through circles = 182→18°S and dashed red curve through squares = 090→00°E) that are superimposed on the regional foliation (045/58°SE). Field observations are orthogonally projected onto a composite geological section in Fig. 11 that is orientated roughly at right angles to the regional foliation (marked NW–SE in green on a). Yellow squares indicate field localities visited during field work in 2010. Legend as Fig. 2.*

Relict igneous structures in and around the most dominant meta-gabbroic intrusion of Fig. 10a include intrusions of more medium grained gabbro into a coarser grained and generally more foliated gabbroic host (Fig. 11b). Locally developed breccias include a wide range of mafic and felsic angular clasts (Fig. 11c), quartz-free and amphibole-bearing coarse grained dykes/pegmatites (Fig. 11d), and thin (< 0.1 m) mafic veins that both cross-cut and are slightly deformed by the regional foliation (Fig. 11e). These lithologies are only found within or in close proximity to the meta-gabbro bodies of the area and were formed during their emplacement into the TTG. Less foliated parts of the meta-gabbro are often cut by localised high strain shear zones (e.g., Fig. 11f–g). It is also possible that some pristine looking dolerite outcrops stem from post-tectonic injections into the Archaean meta-gabbro; in this case most likely from the nearby large Palaeoproterozoic MD3 dyke (cf., Fig 10a).

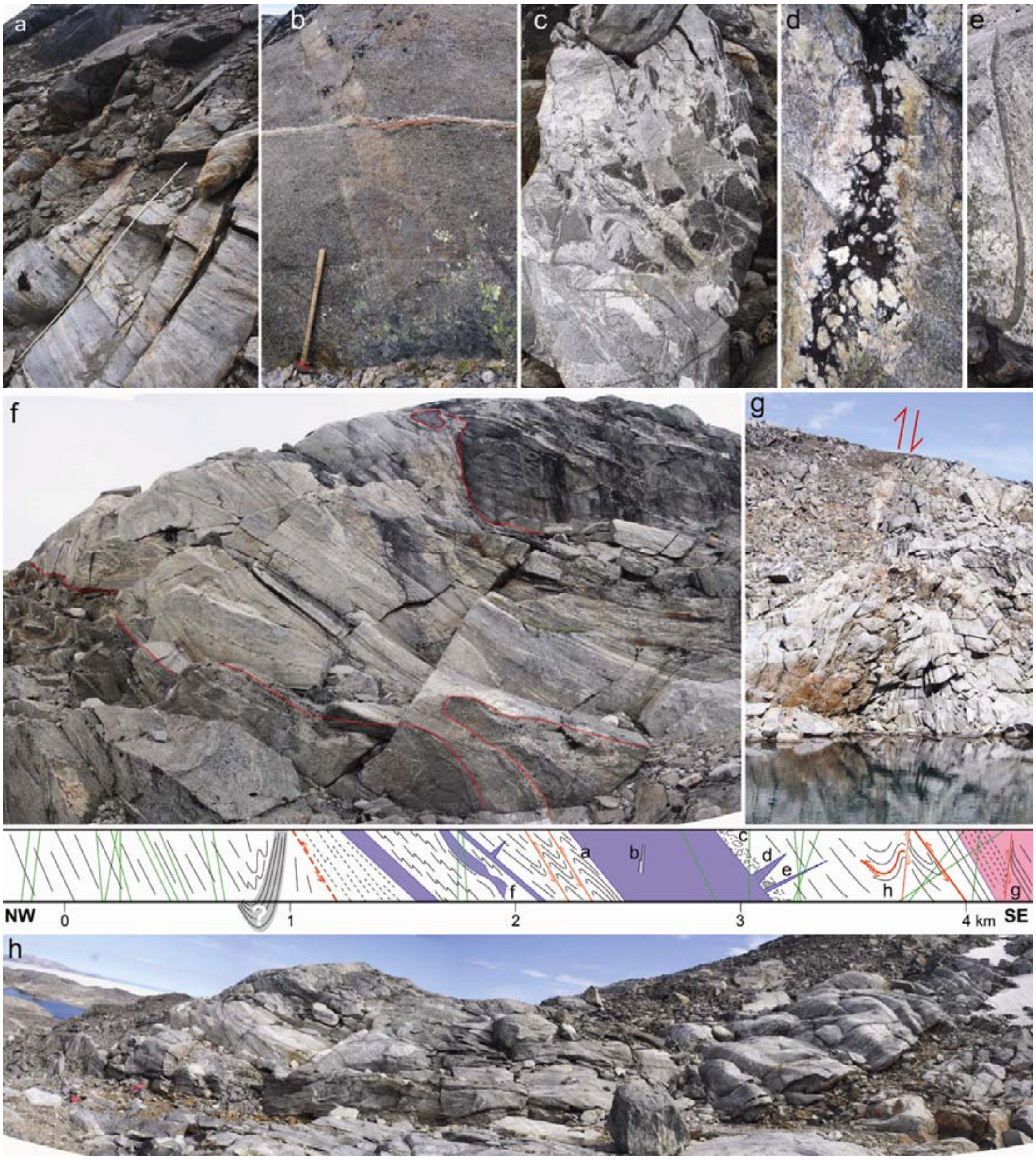

Figure 11. *Structural and lithological variations along a c. 4.5 km long composite section across the regional foliation (black lines), a lamprophyre dyke swarm (green lines), amphibolite units (grey), meta-gabbro (purple), a late-kinematic granite (red), and narrow shear zones in the camp 5.6 area (located in Fig. 10a). On Kangaarsuup Nunaa photographs (f) and (h) are inverted in order to conform to a consistently SW-facing cross section. (a) Basal contact of meta-gabbroic intrusion (upper darker rocks) to concordantly foliated TTG (lowermost pale rocks; note a 2 m long measuring rod for scale). Looking N. (b) Medium grained meta-gabbroic brittle intrusion into coarse grained and more foliated meta-gabbro. Hammer shaft with 10 cm markers provides a scale. (c) Breccia near top of meta-gabbroic intrusion, with 10–30 cm large angular blocks. (d) An irregular and <20 cm wide mafic pegmatite in the TTG above the meta-gabbro. (e) A < 5 cm thick and slightly folded meta-basaltic dyke. (f) Contorted TTG foliation between two large meta-gabbroic blocks within a c. 10 m high cliff surface. (g) SE-dipping foliation within a late-kinematic granite bends into a narrow NW-dipping protomylonitic shear zone (outcrop is c. 25 m high), consistent with apparent SE-block downward displacement. (h) A <2 m thick protomylonitic shear zone and surrounding sub-parallel foliation define an open synform. Two red rucksacks in lower left corner provide a scale.*

The regional foliation varies around a *c*. 045/58°SE mode orientation (Fig. 10b) and are mostly consistent with the top-to-NW directed shear regime inferred for the previous camps 5.5 and 5.4; albeit somewhat more northerly. Such regional foliations in the TTG with steeper foliations within amphibolite lenses (Fig. 10b) are interpreted as part of similar NW-verging fold structures as observed around camp 5.5 (Fig. 3b). Parasitic folds are commonly observed in the area and especially in the vicinity of the meta-gabbro and amphibolite bodies (cf., Fig. 11). Unlike other camps, however, there are foliation measurements that cannot simply be related to a top-to-NW directed shear regime. This is evident from poles to some foliation planes lying on great circles with either a slightly S-plunging or a horizontal E–W trending fold axis (circles and squares, respectively, in Fig. 10b).

An important clue to explain the apparently larger number of slightly deviating foliations in the camp 5.6 area, compared to other areas, comes from a single <2 m wide, and distinctly curved protomylonitic shear zone (Fig. 11h). The poles to 14 measurements along this curved shear zone lie on a great circle with a 182→18° plunging fold axis (red curve through grey circles in Fig. 10b). All foliation measurements indicated as circles in Fig. 10b conform better to this great circle than the regional foliations, even if no additional field evidence confirms such a model interpretation. Likewise, the poles to deviant N-dipping foliations probably also lie on a great circle with an E–W orientated and sub-horizontal fold axis (dashed red line through squares in Fig. 10b). Thus, it is tentatively believed that a component of more E–W directed compression was locally superimposed onto the SE-dipping regional foliation measurements, which at Kangaarsuup Nunaa could have resulted from a component of left-lateral transpressional shear. Applying the same model reasoning to explain a subsequent E–W compression (i.e., at right-angles to the square's N–S trending and horizontal fold axis in Fig. 10b), it is possible to infer an opposite, right-lateral transpressional shear, which is consistent with a similar offset of the proposed Frederikshåb Isblink tectonic boundary, just north of Kangaarsuup Nunaa (Fig. 2), as well as more southerly dipping, dragged TTG-foliation closer to such an offset.

The relatively dense swarm of SW–NE trending lamprophyre dykes across Kangaarsuup Nunaa (mainly monchiquites straddling the Jurassic-Cretaceous boundary; Larsen 2006), extrapolates south-west to a nearly 5 km wide and circular aeromagnetic and gravimetric anomaly with geophysical characteristics of a carbonatite centre, located beneath the Frederikshåb Isblink (Fig. 2). One *c*. 1.5 m thick and particularly porphyritic dyke, with a high concentration of flow-segregated olivine, clinopyroxene and phlogopite grains, resembles another dyke near camp 5.5 (Fig. 6).

Camp 5.3

The geological map (Fig. 12a) indicates an isolated anorthosite outcrop (grey) near camp 5.3, which otherwise only occurs in abundance farther north, around Bjørnesund and the Fiskenæsset area (Myers 1985). This supposed anorthosite band, and bounding TTG and amphibolite, also exhibits a NNW–SSE trending and sub-vertical foliation (*c*. 157/88°SW in Fig. 12b) that strikes almost at right angles to the moderately SE-dipping foliation in most other parts around Frederikshåb Isblink.

The local anorthosite is more likely an unusually pale, plagioclase-rich but quartz bearing TTG unit, characterised by a conspicuously low mafic index (very little biotite) and in places with an equigranular texture where plagioclase grains are very difficult to distinguish from quartz grains. At least three <10 m thick and sub-parallel amphibolite bands bound the sub-vertical and NNW–SSE trending margins of this paler TTG unit (cf., A's in Fig. 13). In detail, a mapped curvature towards a more northerly striking foliation in the northernmost end of the outcrop suggests a slightly sigmoidal along-strike geometry.

The foliation pattern in Fig. 12a abruptly changes from the NNW–SSE trending and sub-vertical band to a surrounding, more moderately SSE-dipping regional foliation, in a fashion that is consistent with it being the eastern part of a large right-lateral shear zone. No supporting right-lateral shear indicators were observed but a domino-faulted amphibolite lens (Fig. 14) records an additional component of SW-block-down shear. The implications for such a vertical shear component will be discussed below.

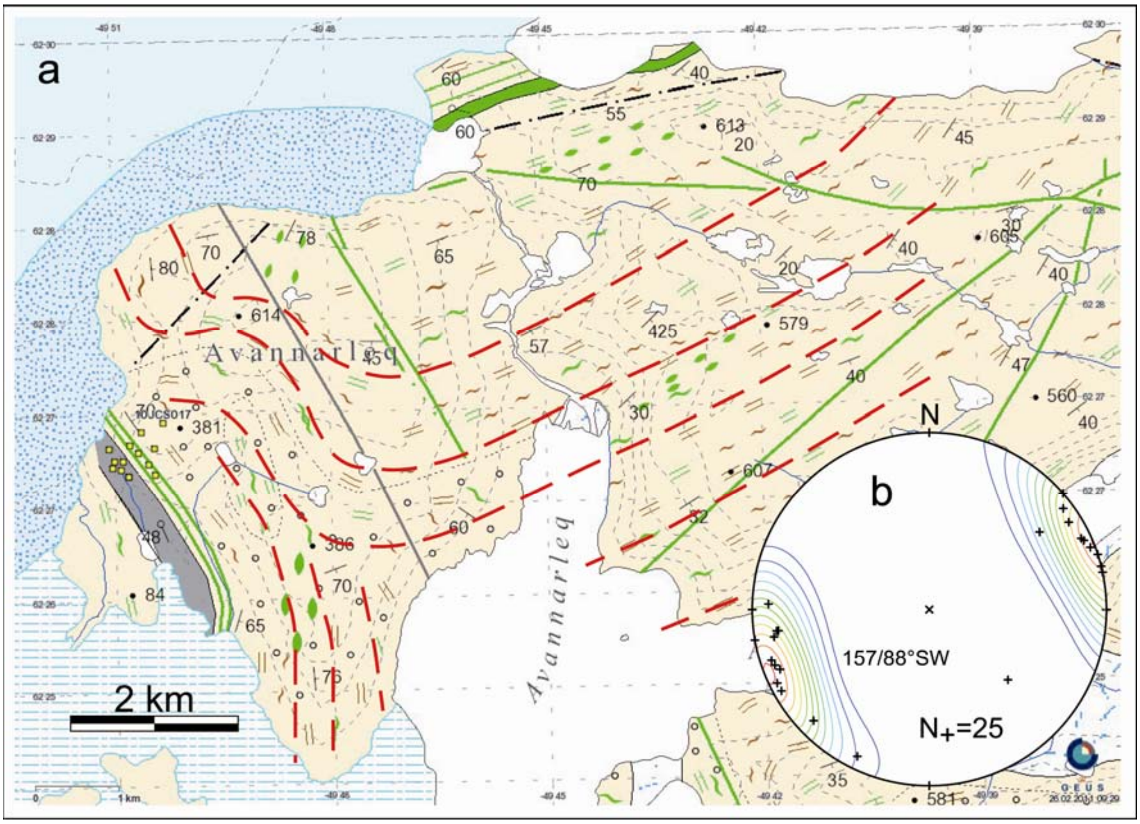

***Figure 12**. Structures around camp 5.3. (a) Geological map with enhanced trace of curved foliation (dashed red lines). (b) Stereographic projection of contoured poles to planes (as in Fig. 3b) of anomalously steep and NNW–SSE trending gneissic foliation. Yellow squares indicate field localities visited during field work in 2010. Legend as Fig. 2.*

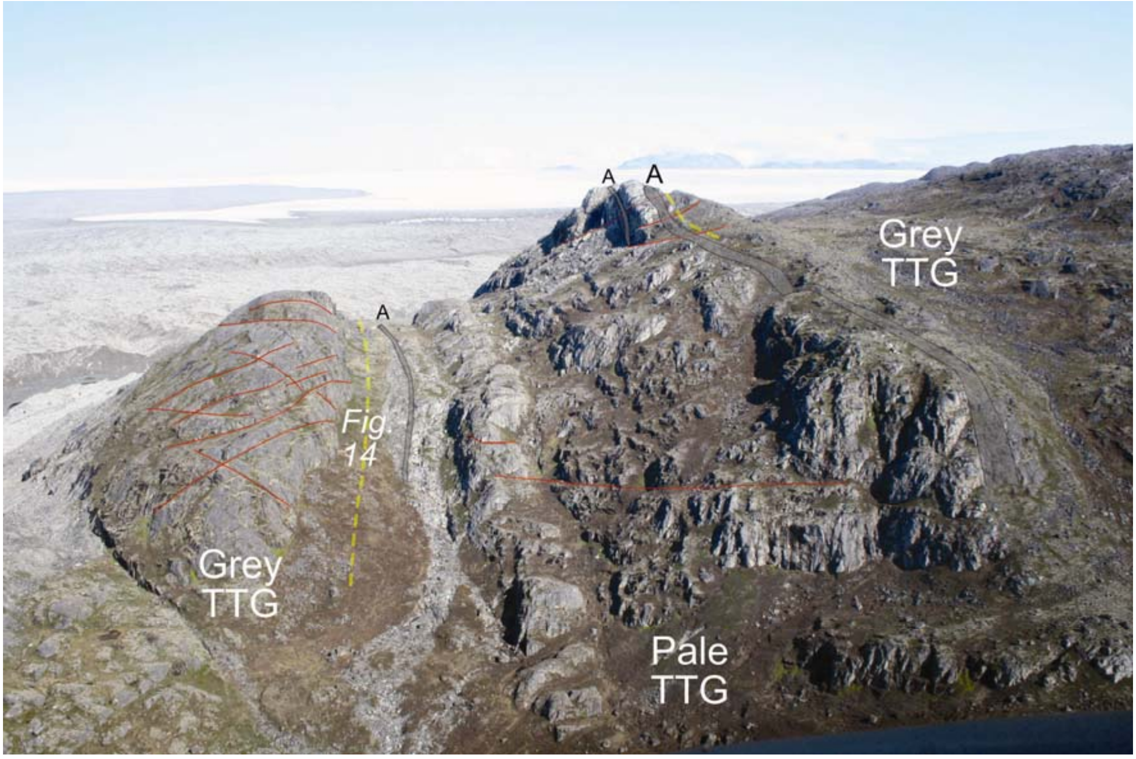

Figure 13. *Looking north over the supposed anorthosite outcrop close to Camp 5.3 on western Avannarloq, south of Frederikshåb Isblink. Sub-vertical amphibolite bands (labelled A and outlined by thin black lines) lie within the TTG with sub-parallel foliation. The so-called 'anorthosite' appears alongside paler, and possibly quartz-poor, TTG units. The TTG outcrops are cut by several Phanerozoic and lamprophyric cone sheets (red lines), which dip gently toward the same sub-glacial alkaline complex that extrapolated SW–NE dyke trends from the Kangaarsuup Nunaa intersect.*

The camp 5.3 area is also cut by several <0.5 m thick lamprophyric sheets which gently dip towards the same proposed carbonatite centre beneath the Frederikshåb Isblink that lamprophyre dykes across Kangaarsuup Nunaa extrapolate towards. This adds further field evidence for the presence of an alkaline ring complex as the source to both local cone sheets and a more extensive lamprophyre swarm of SW–NE trending dykes. The structure, petrography and geochemistry of this alkaline complex will be presented elsewhere (Klausen unpublished data).

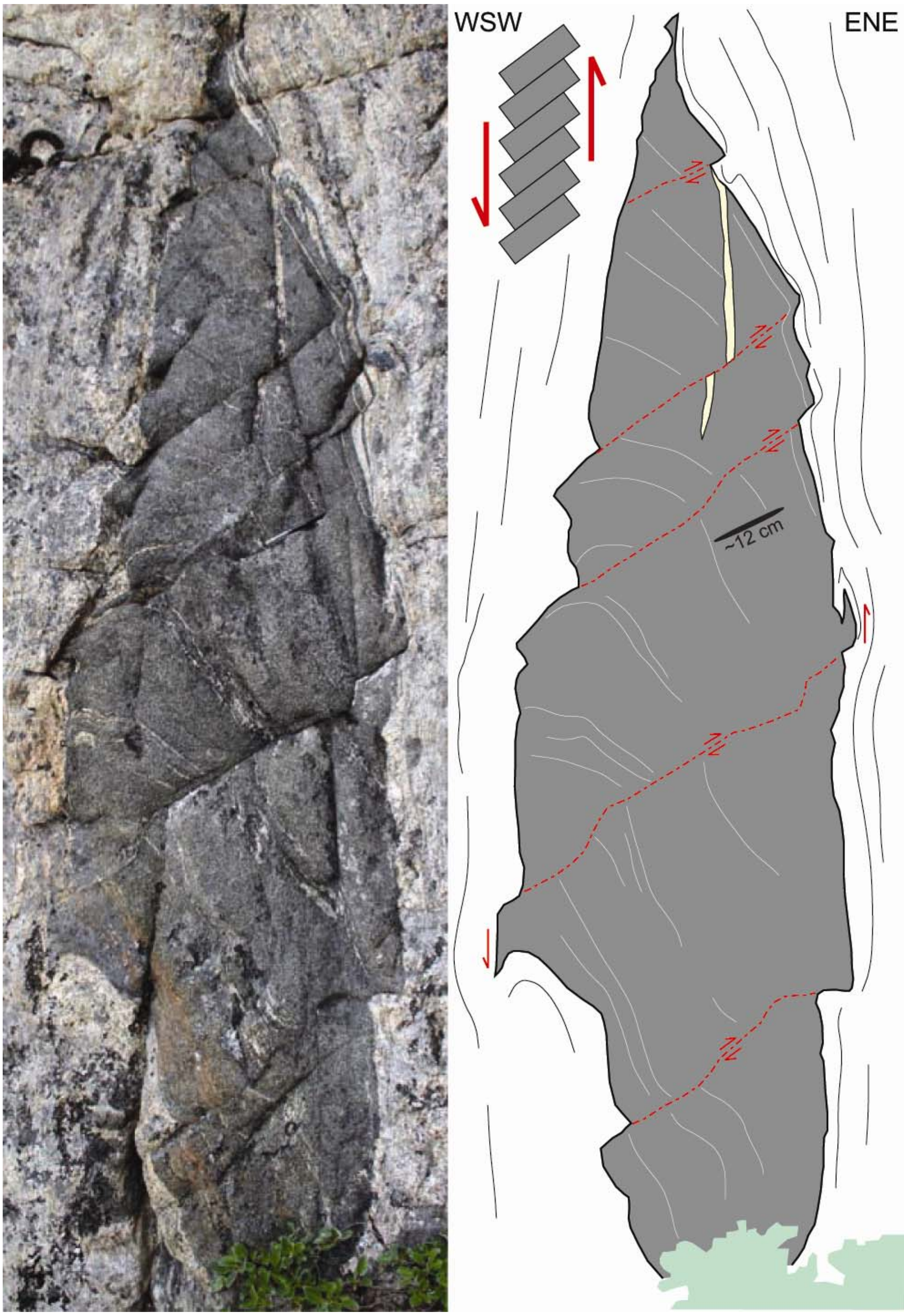

Figure 14. *A c.2 m long and domino-block faulted amphibolite raft, indicating a SW-block-down shear component within the sub-vertically foliated 'anorthosite', in the camp 5.3 area (located in Fig. 13). Looking towards NNW along the strike of the foliation. Bic pen (c. 12 cm) provides a scale.*

Discussion

All the camp areas around the Frederikshåb Isblink are characterised by similar stages of structural evolution: (1) Mesoarchaean protolith structures, formed through predominantly tectono-magmatic processes, (2) superimposed Neoarchaean development of a regional foliation, (3) solid state folding and shearing during medium to high grade metamorphic conditions, and (4) late open flexuring, which may be temporarily associated with a late syn-tectonic emplacement of granitoid-gabbroic intrusions or transverse shear zones, and (5) the emplacements of at least two generations of Proterozoic dolerite dykes and a roughly NE–SW trending swarm of Mesozoic alkaline dykes.

Primary Mesoarchaean protolithic structures are mainly related to the emplacement of TTGs into amphibolitic and ultramafic rock units, and their contemporaneous deformation. Locally, late-kinematic intrusions into the TTG are evidenced by dykes, pegmatites and breccias in and around the gabbros/diorites on Kangaarsuup Nunaa (Camp 5.6; Fig. 11b–e). The petrogenesis of these igneous rock units will be discussed elsewhere, but they likely represent (1) early supracrustal sequences (evidenced by calc-silicate sediments and meta-basalts with rare pillow structures), including ultramafic layered intrusions and possibly even mantle slivers, (2) TTG intrusions, including several generations of associated aplitic to pegmatitic sheets, and (3) late-kinematic granite and gabbro/diorite intrusions, including even younger aplitic to pegmatitic sheets. During these predominantly magmatic rock-forming stages, migmatites could locally have developed through partial melting along intrusive contacts. However, such detailed igneous structures are often obscured by different degrees of solid state deformational overprint, primarily expressed as a pervasive and regional foliation.

Foliations within the mafic rocks, in most cases, are parallel to the main foliation in the surrounding TTG. Superimposed tight to isoclinal folds and shear zones at camps 5.4–5.6 are in most cases also parallel to the regional foliation, and thereby likely products of the same compressional regime. These types of deformation patterns are recorded at different scales throughout most of the area, whereas strain phenomena along narrower shear zones are scarce (see Fig. 7). Thus, there appears to be a consistent SE-dipping foliation throughout most areas along both sides of the Frederikshåb Isblink, which could reflect a dominant top-to-NW directed shear regime (Fig. 16a). This regional shear affected older TTG as well as younger granites and gabbros/diorites, and may even have stretched more bulbous intrusions into plunging sheath-shaped geometries (camp 5.4 area). At least north-west of the Frederikshåb Isblink (i.e. camp 5.5 area), such top-to-NW directed shearing also appears to be connected to a number of overturned folds between <2 m thick protomylonitic shear zones, with consistent parasitic S and Z-folds. Such overturned folds may also explain the over representation of steeper foliation measurements within amphibolite units (Figs 3b and 10b), because these relatively narrow belts are more often exposed along their steeper fold limbs close to the shear zones (cf. Fig. 7).

A similar pervasive style of deformation continues farther north, well into the Bjørnesund area (Keulen *et al.* 2010), and thereby becomes more difficult to reconcile with any localised high-strain zone along the Frederikshåb Isblink. As preliminary geo-barothermometric constraints by Schumacher *et al.* (2011) suggest that many of the metamorphic grade constraints previously attributed to various terranes across southern West and South-West Greenland need to be revised, the importance of proposed terrane boundaries may also diminish. More relevant for this study is the significance of garnet-bearing TTG and proposed granulite metamorphism in the Sioraq block (McGregor & Friend 1997), south of the Frederikshåb Isblink, which may previously have been exaggerated. Reduced relative crustal movements along the Frederikshåb Isblink tectonic boundary would be in agreement with the apparent absence of a localised high-strain zone accommodating any large displacement along the Frederikshåb Isblink. This opens up for alternative mechanisms of how the regional SE-dipping foliation may have been produced, such as Archaean crustal building through continuous, one-sided and bottom-to-SE directed accretion of oceanic crust (Davies 1992), followed by syn-tectonic TTG emplacement.

More open flexuring of the regional and sub-parallel pattern of foliations, parasitic folds and shear zones, discussed above, is locally variable. Deviations from the regional SE-dipping foliation appears to be restricted to the camp 5.3 and 5.6 areas, which are both located south of the proposed Frederikshåb Isblink tectonic boundaries and close to what is tentatively interpreted as highly oblique (*c*. NW–SE) striking transverse shear zones (cf. Fig. 15); most likely generated in response to late-stage transpressional deformation (Fig. 16b–c). A right-lateral transpressional component is more consistent with (1) the apparent offset of the proposed tectonic boundary north of Kangaarsuup Nunaa (Fig. 2), (2) more southerly dipping TTG-foliations close such an offset, north of Camp 5.6, as well as (3) the curved foliation around camp 5.3 (Fig. 12a). However, even within a left-lateral transpression regime – required to explain the superimposed N–S striking folds near camp 5.6 – a dip-slip component, like the SW-block-down displacement recorded near camp 5.3 (Fig. 16d), may also explain locally deviating structures such as the curved foliation around camp 5.3. In order to resolve these alternatives, absolute shear directions need to be better constrained by more stretching lineation measurements.

After these Archaean ductile deformations formed within an amphibolite facies and predominantly compressional regime, the stabilised crust was cut by dolerite dykes during a predominantly extensional Palaeoproterozoic regime, where the WNW–ESE trending dyke through Kangaarsuup Nunaa (Fig. 15) probably belongs to the youngest MD3 swarm (*c*. 2030–2050 Ma in Nilsson *et al.* 2010). Late, brittle and predominantly normal faults are more difficult to date, but may tentatively be related on the basis of their strike directions to sub-parallel dyke swarms. In this context it is noted that MD2 dykes (older than MD3) and a swarm of presumed Mesozoic lamprophyre dykes; mainly monchiquites straddling the Jurassic-Cretaceous boundary (Larsen 2006; Larsen *et al.* 2009) strike conspicuously parallel to the SW–NE trend of the Frederikshåb Isblink, but that any associated rifting has not displaced an intersecting MD3 dyke. Thus, it appears unlikely that the Frederikshåb Isblink hides any major SW–NE trending tectonic boundary that is younger than *c*. 2050 Ma.

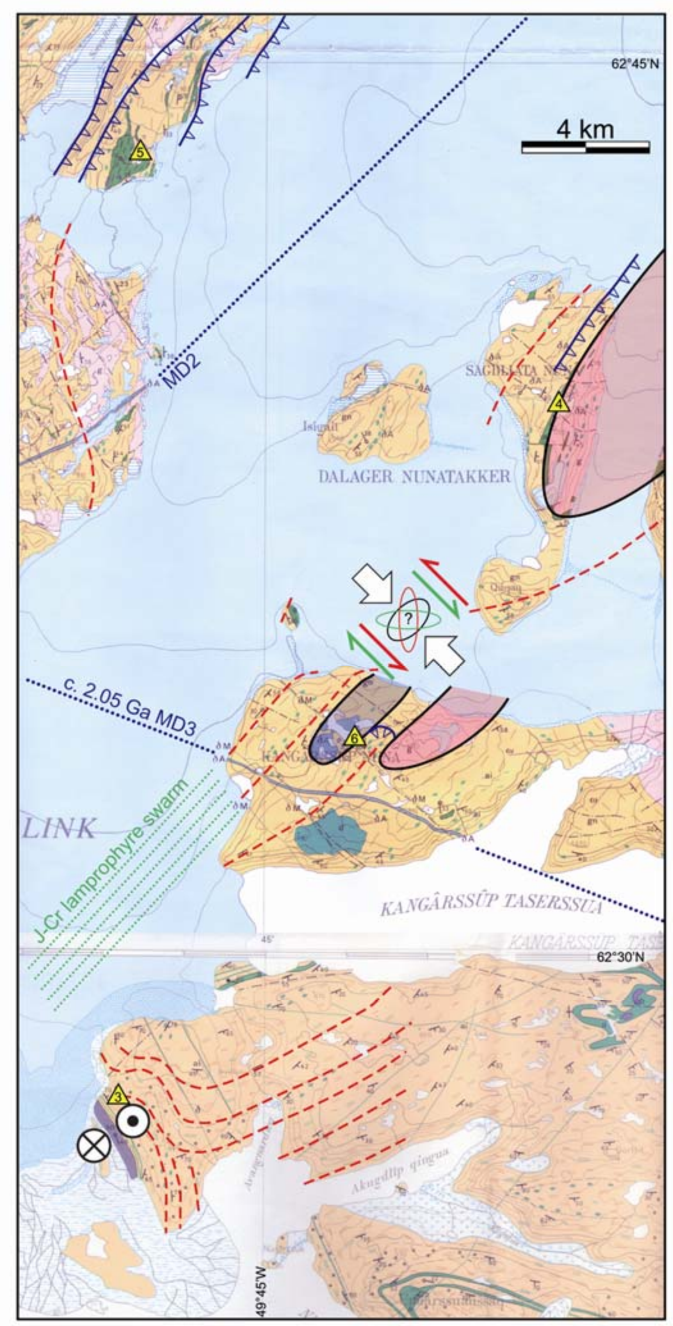

Figure 15. *Summary of structural observations and interpretations within camp areas 5.3, 5.4, 5.5 and 5.6, superimposed on scanned copies of a southern segment of Bjørnesund 62 V. 1 Nord and a northern segment of the Nerutussoq 62 V. 1 Syd (both 1:100,000 map sheets) used in the field. Red dashed lines emphasise some of the foliation patterns on the map, including a few modifications from this study. Thrusts are outlined by solid blue lines with shark teeth pointing towards a shallow to moderate dip direction SE. Two late-kinematic granites (red) and one metagabbroic/dioritic intrusion (blue) are emphasised. The trends of one c. 2.05 Ga MD3 and an older MD2 dyke are extrapolated across the Frederikshåb Isblink as dotted blue lines. The sub-glacial continuation of a SW–NE trending lamprophyre dyke swarm on Kangaarsuup Nunaa (Dawes, 1970) is indicated by dotted green lines. Pure regional shear (white arrows around a black strain ellipse) with a local component of either a right-lateral transpression (red arrows and strain ellipse), or left-lateral transpression (green arrows and ellipse) could have occurred near camp 5.6. Evidence of additional SW-block-down displacement around camp 5.3 along another transverse structure is located by a circle with a dot (upward relative movement) and a circle with a cross (downward relative movement). Camps marked by numbered yellow triangles.*

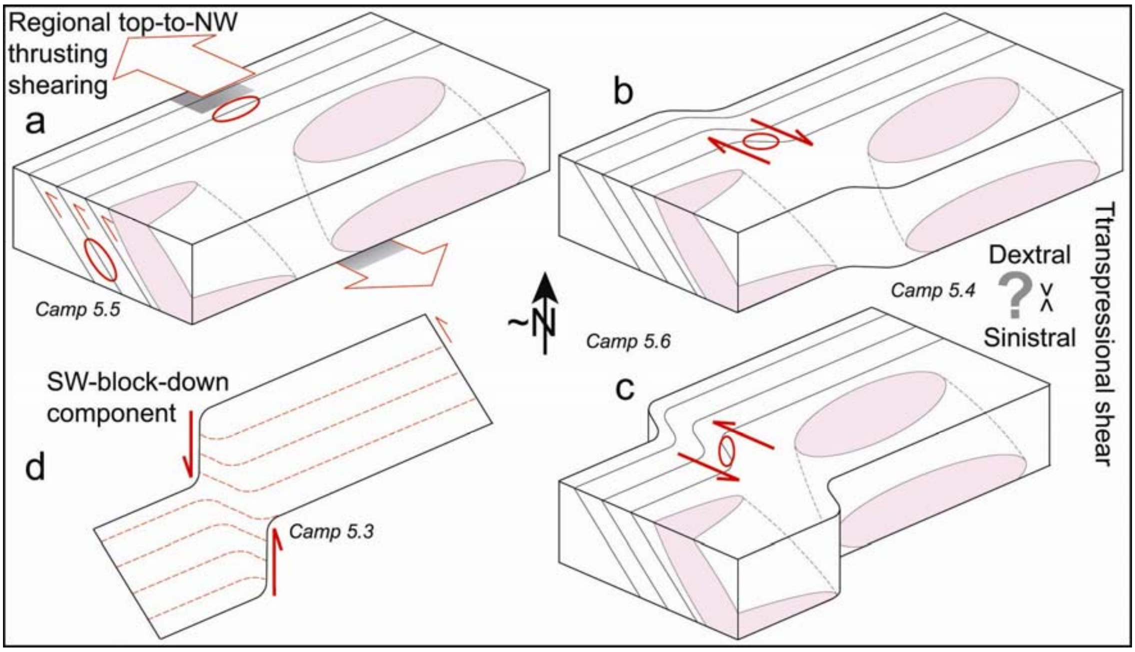

Figure 16*. Simple 3D illustration of the most prominent modes of deformation recorded around the Frederikshåb Isblink. (a) The area was mainly affected by top-to-NW directed shear (large arrows), which produced a regional foliation along the long axes of the red strain ellipses, as well as sub-parallel protomylonitic thrust planes (red small arrows) and possible late 'granite sheaths' (pink surface outlines). (b-c) Late transpression along local transverse shear zones, which (1) rotated and overprinted the regional foliation into a sub-parallel orientation and (2) flexed foliations and protomylonitic shear zones, either E–W (b) or N–S (c) with directed maximum compression on red strain ellipses between either right-lateral or left-lateral simple shear arrows, respectively. (d) An additional NE-block-up dip-slip component along such transpressional shear zones may explain the curved foliations around camp 5.3 (cf. Fig. 12a). Note that dashed red lines in (d) represent strike lines along a single deformed foliation surface.*

Conclusions

The exposed TTG-amphibolite terrain around the proposed Frederikshåb Isblink tectonic boundary is dominated by a moderately SE-dipping foliation with parasitically folded, NW-verging, tight and overturned folds, located between sub-parallel <2 m wide protomylonitic shear zones. These structures: (1) overprint most primary intrusive structures; (2) are consistent with a pervasive top-to-NW directed shear component, where the displacements may overall have 'elevated' a *deeper* crustal section to the south (i.e. Sioraq/Kvanefjord block, according to Friend & Nutman 2001 and Windley & Garde 2009, respectively) relative to a *shallower* Tasiusarsuaq terrane/Bjørnesund block to the north (Fig. 1); (3) do not appear to be related to any localised high-strain zone along the Frederikshåb Isblink, because a similar style of deformation continues to the north, well into the Bjørnesund area (Keulen *et al.* 2010). Together with uncertainties concerning the metamorphic grades of adjacent terrane blocks (Schumacher *et al.* 2011) these conclusions argue for a revision of the proposed Frederikshåb Isblink tectonic boundary as well as the overall Archaean crustal accretion model.

Local variations within the regional foliation pattern, like open folds around oblique fold axes, are tentatively attributed to deformation along late-kinematic and highly oblique (NW–SE-striking) transverse shear zones. Apparent drag folding of the regional foliation and narrow shear zones are, in most cases, consistent with a right-lateral, but in other cases with a left-lateral, shear component. A similar type of apparent right-lateral drag folding around Camp 5.3 may, on the other hand, also be attributed to a vertical SW-block-down component along one such transverse shear zone. More lineation measurements are required to resolve these alternatives.

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