Reassessment of the north-western border zone of the Palaeoproterozoic Ketilidian orogen, South Greenland

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As part of ongoing research into the plate tectonic setting of the Palaeoproterozoic Ketilidian orogen led by the Geological Survey of Greenland and Denmark, four geologists from Denmark and the U.K. re-examined parts of the north-western border zone in July–August 1997. The field work was generously supported by the Danish Natural Science Research Council and the Carlsberg Foundation. One team studied the Proterozoic (Ketilidian) sedimentary and volcanic rocks and the regional structure, working from six inland camps along the variably deformed Archaean–Proterozoic unconformity between Midternæs and Qoornoq and on Arsuk Ø (Fig. 1). A second team investigated the plutonic and kinematic evolution of the Kobberminebugt area at the north-western margin of the Julianehåb batholith (Fig. 1); the latter forms the central part of the Ketilidian orogen (Chadwick & Garde 1996). In addition, samples of volcanic and granitic rocks were collected for geochemical studies and dating of depositional and tectonic events.

The first systematic study of the Ketilidian orogen took place in the 1960s and was largely concentrated in its western and southern parts (Allaart 1976). Essential new data from the central and eastern parts of the orogen were acquired during the Survey's SUPRASYD project (1992–1996; e.g. Garde & Schønwandt 1994, 1995; Garde *et al.* 1997; Stendal *et al.* 1997), which was initiated with the aim of assessing the potential for mineral resources in supracrustal sequences (Nielsen *et al.* 1993). In the course of the SUPRASYD project a new plate-tectonic model for the entire orogen was also published (Chadwick & Garde 1996), in which the orogen is viewed as the result of oblique convergence

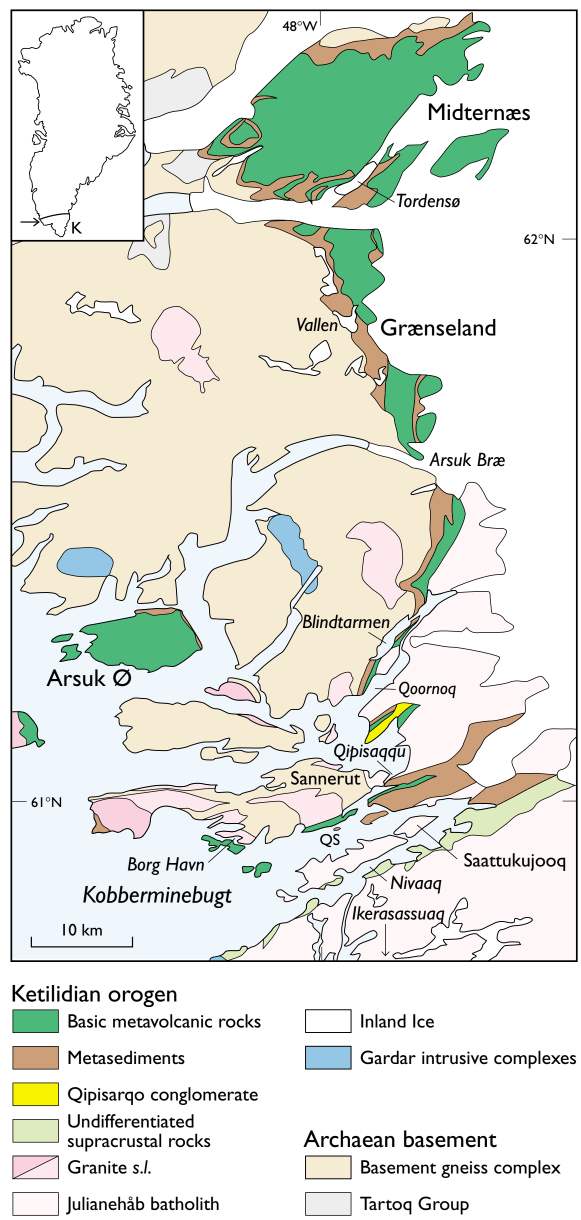

Fig. 1. Simplified geological sketch map of the north-western border zone of the Ketilidian orogen, with place names mentioned in the text. QS: Qaqortup Sallersua. K (index map): Ketilidian orogen. Map based on Geological map of Greenland, 1:500 000, Sydgrønland, sheet 1 (Allaart 1975).

Table 1. Lithostratigraphy of Ketilidian supracrustal rocks in the Grænseland area

- Sortis Group
- Vallen Group
  - Grænsesø Formation
  - Blåis Formation
  - Zigzagland Formation
    - Upper Zigzagland Formation
      - Dolomite Shale Member
      - Banded Quartzite Member
      - Ore-Conglomerate Member
    - Lower Zigzagland Formation
      - Rusty Dolomite Member
      - Varved Shale Member
      - Lower Dolomite Member
      - Residual deposits on the sub-Ketilidian surface

Simplified after Bondesen (1970)

between the Archaean craton of southern Greenland and a supposed oceanic plate located south of the present orogen, which was subducted towards the north. Chadwick & Garde (1996) also suggested a new division of the Ketilidian orogen into a 'Border Zone' adjacent to the Archaean craton, the 'Julianehåb batholith' (formerly the Julianehåb granite) in the central part of the orogen, and the 'Psammite Zone' and 'Pelite Zone' to the south-east, which largely consist of deformed and metamorphosed erosion products derived from the evolving batholith.

The north-western border zone and the Ketilidian supracrustal sequences were mapped in the 1960s by Harry & Oen Ing Soen (1964), Watterson (1965), Bondesen (1970), Higgins (1970), Muller (1974), Berthelsen & Henriksen (1975) and Pulvertaft (1977). It was shown that an Archaean gneiss complex (part of the Archaean craton of southern West Greenland) and Palaeoproterozoic basic igneous rocks (the so-called 'MD' (metadolerite) dyke swarms and related intrusions), and the unconformably overlying Ketilidian supracrustal rocks are progressively affected by Ketilidian deformation and metamorphism towards the Julianehåb batholith in the south and south-east. Boundary relationships were reviewed by Henriksen (1969). Where the Ketilidian supracrustal rocks are best preserved at Midternæs and Grænseland, Bondesen (1970) and Higgins (1970) divided them into the Vallen Group, which largely consists of sedimentary rocks (Table 1), and the overlying Sortis Group, in which basic pillow lavas and related doleritic to gabbroic sills predominate. Supracrustal rocks of presumed Palaeoproterozoic age further south have previously been referred to as the Qipisarqo and Ilordleq Groups (Berthelsen & Noe-Nygaard 1965; Allaart *et al.* 1969).

Based on data collected in the 1960s, the earliest plate-tectonic interpretation of the Ketilidian orogen included a prominent suture in Kobberminebugt (Windley 1991). However, other critical aspects of Windley's model were not substantiated during the Survey's studies in 1992–1996 (Chadwick *et al.* 1994; Chadwick & Garde 1996), and a re-evaluation of the north-west border zone was therefore a natural focus of subsequent investigations.

Banded iron formation in central Grænseland and related rocks on Arsuk Ø

We have little to add to the original lithological descriptions of most sedimentary and metavolcanic-metagabbroic rock units by previous workers. However, based on observations in the lowermost part of the Vallen Group in central Grænseland 3 km south of lake Vallen (Fig. 2), we propose a reinterpretation of the Ore-Conglomerate Member of the Upper Zigzagland Formation (Table 1; Bondesen 1970) as an iron formation.

A few metres of the Archaean orthogneisses immediately below the Ketilidian supracrustal sequence were leached and carbonate-enriched by percolating groundwater in Ketilidian time (Bondesen 1970). A basal conglomerate with unsorted clasts of orthogneiss, pegmatite, vein quartz, dolomite and green mica schist, up to *c.* 20 cm in size, rests unconformably on the altered basement and is overlain by the Lower Dolomite and Varved Shale Members, each *c.* 15 m thick: the latter member comprises dark laminated slates with grading and fine-scale cross-bedding. The Rusty Dolomite Member is 0.5 to 1 m thick. The overlying unit (Table 1) was named the Ore-Conglomerate Member by Bondesen (1970), who described it as an oligomict conglomerate consisting of boulders of grey to white cherty quartzite set in a matrix of magnetite or locally pyrite. Chert-podded banded iron formations in the Archaean Hamersley Group, Australia (Trendall & Blockley 1970; Trendall 1983), are very similar in appearance to the Ore-Conglomerate Member seen by us in Grænseland. Consequently, we interpret this Member as a chert-podded banded iron formation, in which some chert pods superficially resemble rounded clasts of chert. About 3 km south of Vallen it has a total thickness of 16 m and is largely composed of variably podded chert layers 8–10 cm thick which alternate with 2–3 cm thick

Fig. 2. The basal part of the Ketilidian succession at Vallen in central Grænseland with the Archaean basement in the left background, viewed towards west-north-west. Relief is about 500 m with tents in right foreground.

layers of recrystallised, fine-grained magnetite (Fig. 3). Planar millimetre-scale chert-magnetite layering occurs in a *c.* 10 cm thick zone near the base of the member. In a *c.* 1 m thick zone in the middle of the member the podded chert layers are only 2–3 cm thick and alternate with few millimetre-scale magnetite seams. Near the top of the member the chert layers increase in thickness and the magnetite content decreases. The lowermost 10 m of the overlying unit, the Banded Quartzite Member of Bondesen (1970), comprises calcareous and quartzitic chert-pebble conglomerates and impure bedded quartzites and siltstones.

A second possible category of iron formation was found in shoreline outcrops of the Isua Formation of Muller (1974) on the headland in the extreme north-west of Arsuk Ø. Intensely deformed greywackes with local graded bedding pass westwards into pyritic black phyllites and cherts which are followed on the headland itself by bedded and podded cherts with intervening amphibole garbenschiefer with disseminated pyrite and pyrrhotite; veins of carbonate are common. We suggest that the coarsely bedded chert-amphibole-sulphide-carbonate association on Arsuk Ø is an iron formation of mixed silicate-sulphide-carbonate facies.

Structure and kinematics of the border zone between Midternæs and Arsuk Ø

Strongly aided by the meticulous investigations of previous workers (Bondesen 1970; Higgins 1970; Muller 1974; Berthelsen & Henriksen 1975; S.B. Jensen, unpublished Survey documents) we were able to establish the deformation chronology and kinematics in each of the areas examined along the Archaean-Proterozoic boundary (Fig. 1). However, it proved difficult to integrate these observations into a coherent structural and kinematic model for the entire region. Furthermore, it was difficult to distinguish between Archaean and Proterozoic deformation structures in the basement terrain.

In the Ketilidian supracrustal rocks between Midternæs and Qoornoq we recognised two principal Ketilidian phases of deformation, here designated D1 and D2. Deformation is generally much more pronounced in the sedimentary rocks than in the basic igneous lithologies. A third phase, D3, was observed locally but does not appear to have regional significance. An interpretative sketch of the Ketilidian structure in the area between Midternæs and Qoornoq is shown in Figure 4.

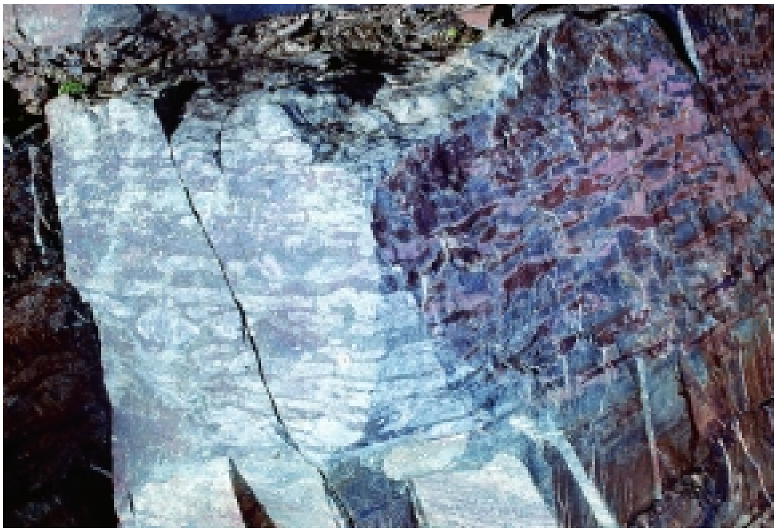

Fig. 3. Podded banded iron formation in the Lower Zigzagland Formation, central Grænseland *c.* 3 km south of Vallen. Height of photograph *c.* 80 cm.

In the south-western part of Midternæs, west of Tordensø, NNE-trending upright folds with subhorizontal plunges and coaxial stretching lineations indicate NNW–SSE shortening. Similar structures in sedimentary rocks of the Sortis Group in the extreme north-east part of Grænseland suggest a structural link with Midternæs.

In other parts of northern and central Grænseland there is repeated evidence of thrust movements with hanging wall transport towards the west-south-west and south-west. The principal detachments appear to be within the Dolomite Shale Member of the Upper Zigzagland Formation and in the Grænsesø Formation just below the massive igneous rocks of the Sortis Group (Table 1; see Bondesen 1970 for details of the stratigraphy). There are few signs of Proterozoic deformation in the Archaean orthogneisses immediately below the Ketilidian sediments in central Grænseland; no observations were made within the basement terrain further west.

In the area south of Arsuk Bræ, both the supracrustal rocks and the underlying crystalline basement were affected by Ketilidian deformation (Henriksen 1969; Berthelsen & Henriksen 1975). Within the basement we observed several moderately steep, E- to ESE-dipping mylonite zones with sinistral displacements affecting Palaeoproterozoic 'MD' dykes and hence presumably of Ketilidian age; the mylonites are correlated with penetrative D1 deformation in the adjacent cover rocks.

At Blindtarmen the Ketilidian supracrustal rocks west of the Qôrnoq augen granite (Berthelsen & Henriksen 1975) form a steep NNE-trending belt of intensely deformed schists and amphibolites bounded by Archaean orthogneiss to the west. In the east, sheets of Qôrnoq augen granite were intruded into the supracrustal rocks prior to or during D1, and there is clear evidence of non-coaxial D1 deformation with subhorizontal sinistral displacement both in the supracrustal rocks and within the granite; correlation with D1 sinistral displacement south of Arsuk Bræ seems straightforward. A large asymmetric fold of D2 age in the south-east of the area may likewise be linked with sinistral non-coaxial deformation. In the intensely deformed basement gneisses immediately west of the supracrustal belt the predominant sense of movement appears to be dextral, but it is uncertain if these structures are Proterozoic, and correlation with kinematics in the adjacent supracrustal rocks is unclear.

In the western and north-western parts of Arsuk Ø we confirmed previous recognition of an early phase of deformation by Muller (1974). His D1 upright, N–S trending folds in the sedimentary rocks indicate E–W compression. The F1 folds were folded by a large upright F2 syncline plunging west-south-west, with its axial trace through the south-eastern part of the island. Both sets of structures seem unrelated to the structures between Midternæs and Qoornoq, although the F2 syncline on Arsuk Ø may correlate with the D1 curvature and steepening of the Ketilidian cover rocks between Arsuk Bræ and Qoornoq (Fig. 4). Furthermore, it is uncertain to what extent the Archaean basement participated in the Ketilidian deformation events on Arsuk Ø, and whether a major unexposed detachment zone exists near the base of the supracrustal sequence.

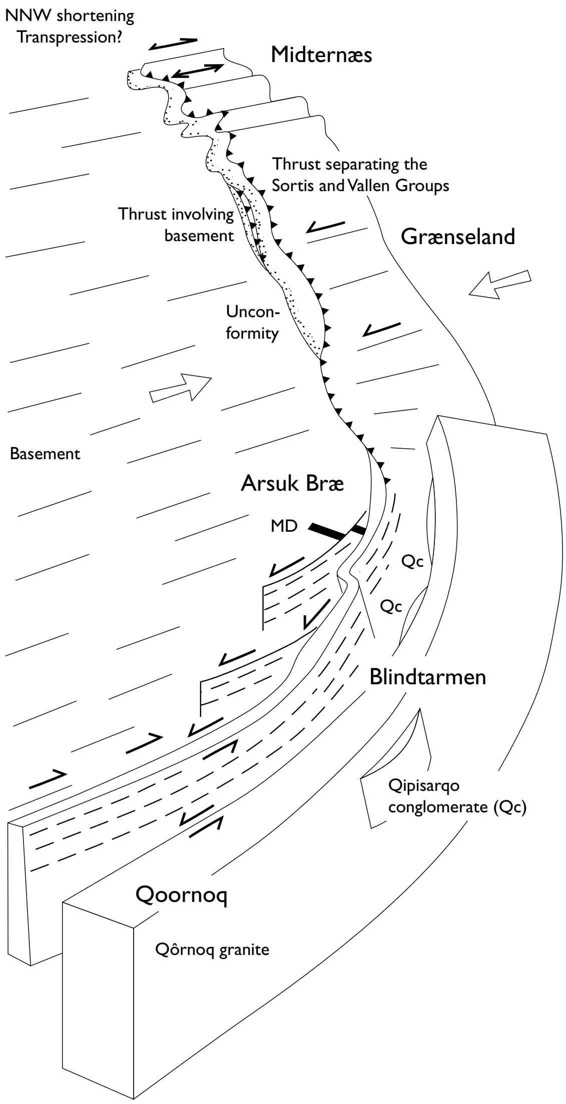

Fig. 4. Interpretative sketch of the Ketilidian structure in the area between Midternæs and Qoornoq.

Intrusive and kinematic events in the Kobberminebugt area

Field work in 1997 in the Kobberminebugt area had two objectives: first, an assessment of the deformation history in the supracrustal rock units which are tentatively correlated with the Ketilidian rocks of the Vallen and Sortis Groups to the north-east and which occur as screens between intrusive members of the Julianehåb batholith; second, establishment of the emplacement histories, relative ages and deformation of several granitic intrusions mapped previously (see Berthelsen & Henriksen 1975; Pulvertaft 1977). A U-Pb zircon dating programme on samples from some of these intrusions and a granite clast from the Qipisarqo conglomerate south-east of Qoornoq (Berthelsen & Henriksen 1975) has been initiated in order to establish the timing of the main intrusive and tectonic events in the border zone and correlate their development with other parts of the orogen.

Rocks and structures in three subareas were investigated: (1) Ikerasassuaq south of Kobberminebugt; (2) central Kobberminebugt; and (3) the island of Sannerut. A tentative correlation between established deformation events D1–D3 in the Kobberminebugt area and the emplacement of granitic plutons is shown in Fig. 5. The deformation events designated D1–D3 in the Kobberminebugt area may not be directly correlatable with D1–D3 between Midternæs and Qoornoq (see also conclusions below).

Screens of supracrustal rocks in shoreline outcrops in central Kobberminebugt are largely mica schists and amphibolites with subordinate conglomerates, quartzites, semipelites and volcaniclastic rocks. A steep, intensely developed cleavage with a subhorizontal mineral stretching lineation suggests a high degree of flattening. Graded bedding younging south-west and a first (S1) cleavage are well preserved in semipelites on a small island in central Kobberminebugt called Qaqortup Sallersua. Prefolding pegmatite veins in the semipelites display dextral asymmetric boudinage, and a relatively consistent 'Z' geometry of upright, SSW-plunging F1 minor folds likewise suggests D1 dextral shear parallel to the trend of Kobberminebugt. Three sheet-like bodies of the Borgs Havn granite on Sannerut were emplaced parallel to bedding and S1 cleavage and deformed by D2 structures.

The second phase of deformation (D2) is confined to localised zones parallel to the general ENE–WSW trend of the orogen. Refolding of isoclinal F1 folds by tight, upright F2 folds with moderate to steep, west plunging, curvilinear fold axes gave rise to Type 1, 2 and 3 interference patterns of Ramsay (1967). The S2 cleavage commonly displays a low-angle clockwise fold transection and sinistral extensional shears, with local evidence for a progressive, sinistral, non-coaxial component to the deformation locally preserved. Early fabrics in the Nivâk granite on the south coast of Kobberminebugt indicate that it was emplaced in a sinistral shear regime of presumed D2 age.

Ikerasassuaq	Kobberminebugt	Sannerut	Deformation event
Sarqamiut granite *	Late conjugate dykes		Late NE–SW dextral shears
Red granite Uivfait granite Quaqarssuaq granite	Sâtukujoq granite	West Sánerut granite Porphyritic granites (+Qôrnoq granite *)	**D3** Dextral local shearing associated with plutons
	Nivâk granite		**D2** Sinistral progressive transpression
Monzodiorite *	Northwestern granite Monzodiorite	Borgs Havn granites *	**D1** Pervasive folding, cleavage formation with dextral/oblique shear

Fig. 5. Correlation of deformation events D1–D3 in the Kobberminebugt area with emplacement of granitic intrusions. Only the relative ages of the intrusions in the Ikerasassuaq area are known, since they are not in contact with those in the two other areas (see Pulvertaft 1977). Porphyritic granites on Sannerut have no mutual contacts with the Borgs Havn granites and may be older than indicated (syn-D1/D2 or older). Arrows indicate the relative timing of magmatic and high temperature solid-state deformation in each pluton.
* denotes sample collected for zircon geochronology.

The third phase of deformation (D3) is highly localised and was only recognised at a few localities. In the Sannerut area, a well-spaced D3 crenulation cleavage has a consistent anticlockwise trend relative to the main D2 deformation. Further south, emplacement of the Sâtukujoq granite during D3 was associated with a 2 km wide zone of intense dextral, non-coaxial deformation that transposed the early fabrics in the Nivâk granite. Strong prolate fabrics are locally developed in the Sâtukujoq granite together with flattening fabrics in the host Nivâk granite. The West Sánerut granite and some members of the porphyritic granite suite (see Fig. 5) were emplaced during this stage. The names of individual granite plutons follow Pulvertaft (1977) and do not exactly correspond to modern spelling of locality names (Fig. 1).

Preliminary and tentative conclusions

The Ketilidian structures between Midternæs and Qoornoq were formed during three successive phases of deformation within a complicated transpressive system. Upright folds (which in Midternæs refold earlier folds and were designated F2 by Higgins 1970) indicate NNW–SSE shortening in Midternæs and north-east Grænseland, whereas prominent D1 folds further south in Grænseland are consistent with thrusting of the Ketilidian cover rocks from north-east to south-west and also suggest significant sinistral displacements between Arsuk Bræ and Blindtarmen (Fig. 4). South-west vergence of D2 folds in Grænseland suggests that thrust detachment continued in the cover rocks after D1 displacements. The deformation on Arsuk Ø took place during two main events and, according to earlier workers (see Berthelsen & Henriksen 1975), appears to have involved significant deformation of the surrounding Archaean basement. There appears to be no simple correlation of the history of deformation with that between Midternæs and Qoornoq.

The Kobberminebugt area is part of the northern marginal zone of the Julianehåb batholith. The complex non-coaxial deformation history of the area is characterised by kinematic and strain partitioning, shear-sense reversals, and sequential pluton emplacement. Foliation is generally steep, strikes NE–SW, and has a gently to moderately plunging stretching lineation. At central Kobberminebugt, three phases of deformation with associated syntectonic intrusions were recognised in the Ketilidian supracrustal rocks. D1 structures show consistent dextral kinematics whose late stage effects controlled intrusion of the Borgs Havn granites. D2 structures formed during progressive sinistral transpression, synchronous with intrusion of the Nivâk granite. Localised dextral reactivation gave rise to D3 structures which coincided with emplacement of the Sâtukujoq granite. Available structural data suggest that the sinistral D2 phase of deformation in the Kobberminebugt area correlates with the D1 phase between Midternæs and Qoornoq, but a firm conclusion awaits the dating of individual granite plutons. Correlation with the structural evolution on Arsuk Ø is currently considered uncertain.

Windley (1991, p. 3; 1993) had previously described the Kobberminebugt shear zone as "a 15 km wide, ENE-trending, subvertical, high deformation zone, which separates terranes of totally different type", and argued that a major metamorphic break occurs across the shear zone. He proposed that the Kobberminebugt shear zone represents a major suture that joins the continental margin, shelf and foredeep succession to the north with an Andean-type magmatic arc to the south. Our observations do not support this interpretation but suggest that the Kobberminebugt shear zone developed *in situ* in the northern marginal zone of the Julianehåb batholith; this is supported by the presence on both sides of the shear zone of Ketilidian supracrustal rocks with lithologies resembling those in Midternæs and Grænseland (see e.g. Pulvertaft 1977, p. 26 ff), which are intruded by various members of the Julianehåb batholith. The Kobberminebugt shear zone is therefore a transpressive shear zone in which the oblique convergence vector has been partitioned into components that are orogen parallel and normal to the orogen.

In conclusion, the border zone in the north-west of the Ketilidian orogen appears to represent a back-arc in which the foreland Archaean gneisses and Ketilidian basic volcanic and sedimentary rocks were affected by Ketilidian deformation, metamorphism and granite intrusion. The ongoing dating programme and geochemical study of the basic magmatism are designed to throw further light on this tentative conclusion. The results of the 1997 field work are compatible with the plate-tectonic model of Chadwick & Garde (1996) in which the Julianehåb batholith is viewed as the root zone of a major Palaeoproterozoic magmatic arc above a northerly dipping subduction zone at the southern margin of the Archaean craton.

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