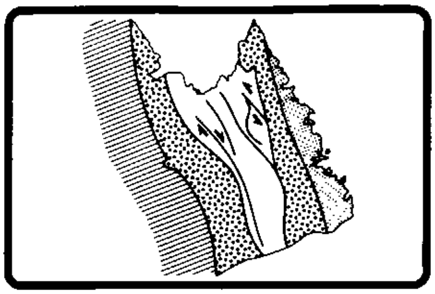

The Proterozoic Nagssugtoqidian mobile belt of southeast Greenland: A link between the eastern Canadian and Baltic shields

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Summary
The Nagssugtoqidian mobile belt is a *ca.* 300 km wide Proterozoic tectonic zone, extending across Greenland, in which Archean basement rocks have been tectonically reworked and subjected to high-grade metamorphism. It is regarded as part of an originally continuous orogenic belt (Figure 1) which included the Torngat Orogen of Labrador (Korstgård *et al.*, 1987) and the thrust belts of Northern Norway and the Kola peninsula (Marker, 1988). All the segments are dominated by thrust tectonics and pressures up to 12 kb. In North Norway and West Greenland, juvenile Proterozoic sialic crust formed in association with sutures within the mobile belt. In East Greenland, juvenile Proterozoic magmas are represented by basic intrusions emplaced into Archean continental crust. The location of the East Greenland section of the mobile belt is thought to have been controlled by pre-existing Late Archean and very early Proterozoic structures.

Overview

The main Proterozoic structures in the Nagssugtoqidian mobile belt trend approximately E-W and are dominated by thrusting in which a northern Archean block overrode the North Atlantic Archean Craton to the south. High pressure (>10 kb) granulite-facies assemblages developed in several areas. In East Greenland, the high-grade assemblages were retrogressed in the centre of the belt by fluid movements and folding that continued after the thrust movements. The basement gneisses are tectonically interlayered with sequences of paragneiss, which are lithologically distinct from paragneiss units in the unreworked, high-grade basement of the mobile belt forelands and are thought to have been deposited in the very late Archean or the earliest Proterozoic. Widespread basic dyke swarms were intruded into the gneiss complex after the end of Archean plutonic activity *ca.* 2.65 Ga. These dyke swarms provide a regional field criterion for the distinction of Archean from Proterozoic units, and a first guide to the degree of Proterozoic tectonic reworking in different parts of the mobile belt.

At an early stage in the research, it was suggested that the Nagssugtoqidian represented a Proterozoic plate boundary (Bridgwater *et al.*, 1973). Isotopic results from the central to northern part of the West Greenland section of the belt (Kalsbeek *et al.*, 1984; Kalsbeek *et al.*, 1987) showed that parts of both the sedimentary and orthogneiss units were derived at 1.8 to 1.9 Ga from material with a short crustal history. These authors proposed that in West Greenland the mobile belt contains a hidden suture zone. In Southeast Greenland, although there are major tectonic breaks in the area, there is neither evidence that the major units of paragneiss were derived from a Proterozoic source nor evidence for the formation of juvenile sialic material in the period 1.7–2.0 Ga (Pedersen and Bridgwater, 1979; Kalsbeek and Taylor, 1989). Mantle-derived Early Proterozoic igneous rocks within the mobile belt (basic dyke swarms, syntectonic basic charnockites and basic components of post-tectonic plutons) show evidence of interaction with earlier crust, ranging from contamination at depth prior to intrusion, to *in situ* mixing with crustal melts (Austrheim *et al.*, 1987). The differences between the mobile belt on either side of Greenland have led some authors to rename the area described in this review the "Ammassalik mobile belt" (see papers in Kalsbeek, 1989).

Overall structure of the mobile belt in southeast Greenland

The mobile belt is a 300±30 km wide structural province with a dominant E-W structural grain (Figure 2). It is flanked to the north and south by unreworked Archean gneiss. For descriptive purposes, the Southeast Greenland section of the mobile belt has been subdivided into five zones on the basis of dominant lithologies and the extent of Proterozoic reworking (Figure 2).

The northern marginal zone. This zone extends from *ca.* 66°30′ to 66° and shows a gradual increase in the intensity of Proterozoic reworking from north to south. In the north, about 85–90% of the gneiss complex consists of LIL-depleted granulite-facies orthogneiss. These have yielded Rb-Sr whole rock (H. Austrheim, unpublished data) and multigrain U-Pb concordia intercept (B.T. Hansen, unpublished data) ages of 2.9–3.0 Ga and lower intercept results of *ca.* 1.8 Ga. There is no isotopic evidence for the existence of crust markedly older than 3.0 Ga. The remaining 10–15% of the gneiss complex consists of granulite-facies Archean supracrustal rocks dominated by basic material. The granulite-facies rocks were intruded by amphibolite-facies pegmatites. Rb-Sr whole rock ages for these suggest emplacement at 2630±65 Ma, Sr_i 0.7016; (Pedersen and Bridgwater, 1979). The gneisses were retrogressed along *ca.* 2.63 Ga sub-vertical shear zones. The retrogression was accompanied by considerable addition of LIL elements.

The northern marginal zone was intruded by major swarms of Fe-tholeiite dykes, some of which are over 100 m wide and can be traced for tens of kilometres across regional Archean structures. Many of the dykes were emplaced in Late Archean shear zones during Proterozoic reactivation of these structures. Composite dykes occur with later non-foliated centres intruded into earlier foliated dyke material. The synkinematic emplacement of the dykes is comparable to that of the Kangamiut dykes immediately south of the Nagssugtoqidian thrust front in West Greenland (Escher *et al.*, 1976). Whole rock isotope studies across a single zoned dyke yielded a scatter about a 2.2 Ga Sm-Nd reference isochron and a Rb-Sr age of 1.8 Ga (the age of regional metamorphism). For appreciable scatter about a Sm-Nd isochron to be produced during a metamorphic episode at 1.8 Ga implies that the dykes must be at least as old as 2.2–2.4 Ga. The field relations with the Late Archean pegmatites show that the dykes were emplaced later than 2.63 Ga.

In the north of the zone, the gneisses contain complex Archean fold structures and, except for local reactivation of shear zones, appear very little affected by Proterozoic tectonism. Proterozoic metamorphic effects as recorded by assemblages in the dykes continue tens of kilometres north of the main tectonic boundary. The centres of the Proterozoic dykes contain orthopyroxene-clinopyroxene-garnet-plagioclase assemblages replacing earlier igneous minerals (including primary plagioclase phenocrysts). P-T estimates suggest metamorphic conditions of 650°–750°C at 8–11 kb. The presence of high pressure and temperature assemblages in little-deformed dykes suggests that they recrystallized under deep-crustal conditions prior to being thrust into their present position. The thrusting was accompanied by retrogression, possibly controlled by the upward movement of fluids from amphibolite-facies gneisses buried underneath the granulite-facies gneisses, as these were thrust from the north toward the centre of the mobile belt. The majority of the dykes show retrogressed, foliated margins characterized by lower pressure (*ca.* 6–8 kb) amphibolite-facies assemblages. P and T studies on the gneisses surrounding the dykes give similar results to the assemblages in the dykes. This suggests that their mineral assemblages were partly re-equilibrated during the Proterozoic even though the field differences between amphibolite- and granulite-facies rocks (developed prior to dyke injection) are preserved.

At *ca.* 66°05'N (Figure 2), the gneiss complex contains a concordant, complexly folded supracrustal belt which can be traced for tens of kilometres. This unit contains a higher proportion of sedimentary material (including marbles) than supracrustal units within the Archean gneiss complex immediately north of the mobile belt, and is regarded as a post-3.0 Ga, Late Archean or very early Proterozoic sequence infolded into the Archean granulite-facies gneiss complex. Dawes (1989) reports that the supracrustal rocks do not contain the granulite-facies assemblages seen in the regional gneisses. Our own observations suggest that the supracrustal units are cut by dykes which contain Proterozoic granulite-facies assemblages.

In the southern part of the northern marginal zone, the dykes and the supposed Proterozoic supracrustal units become progressively more intensely deformed along thrust planes, which dip at a shallow angle to the north, and are folded about structures which verge toward the centre of the mobile belt.

Figure 2 (opposite page) *Metamorphic and structural zones in the Nagssugtoqidian mobile belt of South East Greenland.*
(a) *Sketch map showing zones described in text.* ***Solid black****, the Angmagssalik meta-leuconorite complex and associated charnockites;* ***small triangles****, post-tectonic intrusive complexes;* ***stars****, site of U-Pb multigrain zircon analysis. The U-Pb ages given from the gneisses in the north central zone and the northern marginal zone are minimum ages for the late Archean granulite-facies metamorphism; those in the central and southern zones are interpreted as the age of igneous events.*
(b) *Generalized composite cross section from NNE (Storø) to SSW (Umivik) to give impression of intensity of Proterozoic deformation.* ***Solid blocks and triangles****, as for 2a;* ***solid lines****, Early Proterozoic dykes;* ***elongate crosses****, Early Proterozoic mafic tonalite;* ***dashed lines****, Proterozoic shear foliation;* ***dots****, paragneiss unit surrounding Angmagssalik meta-igneous complex.*

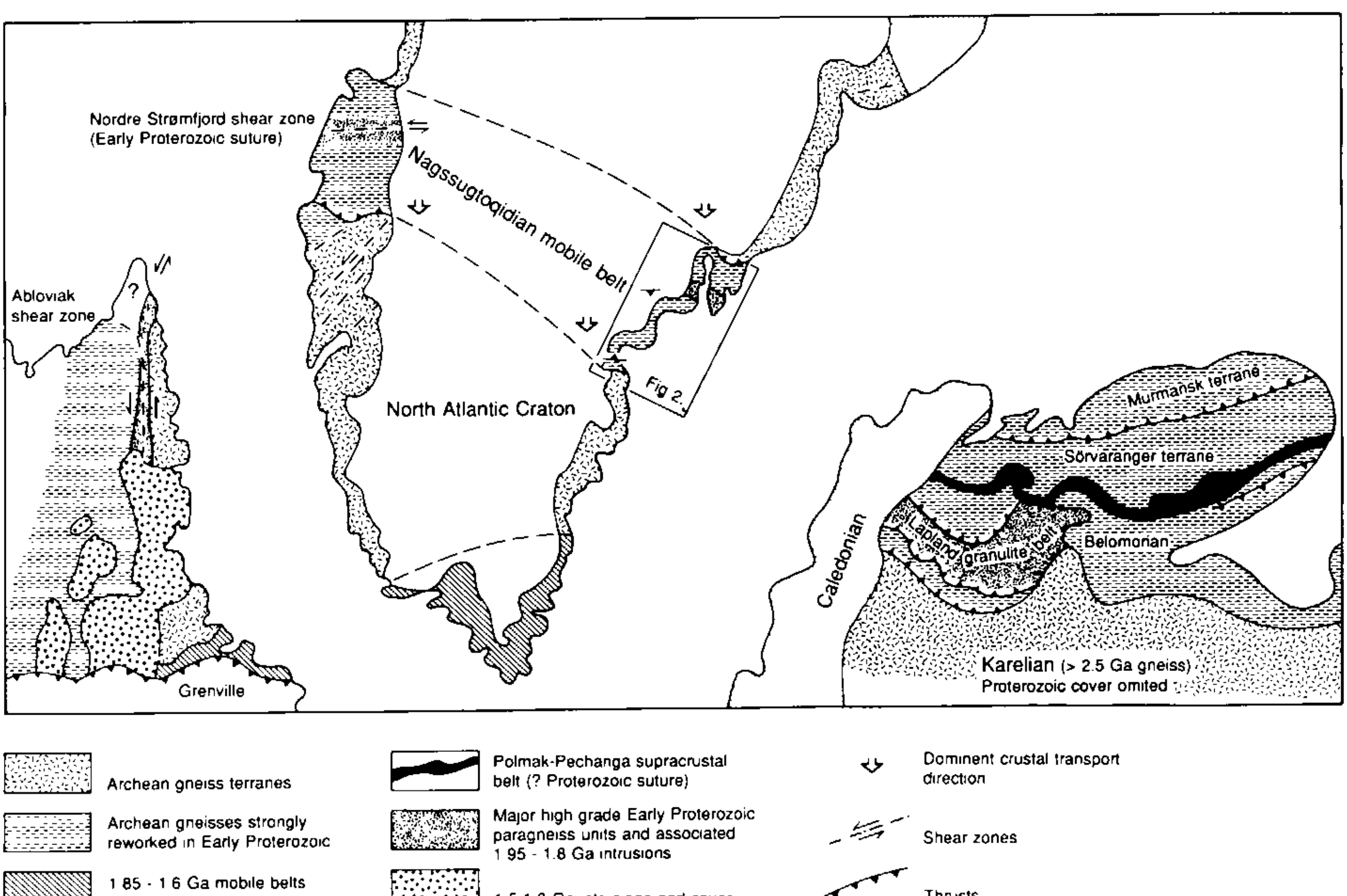
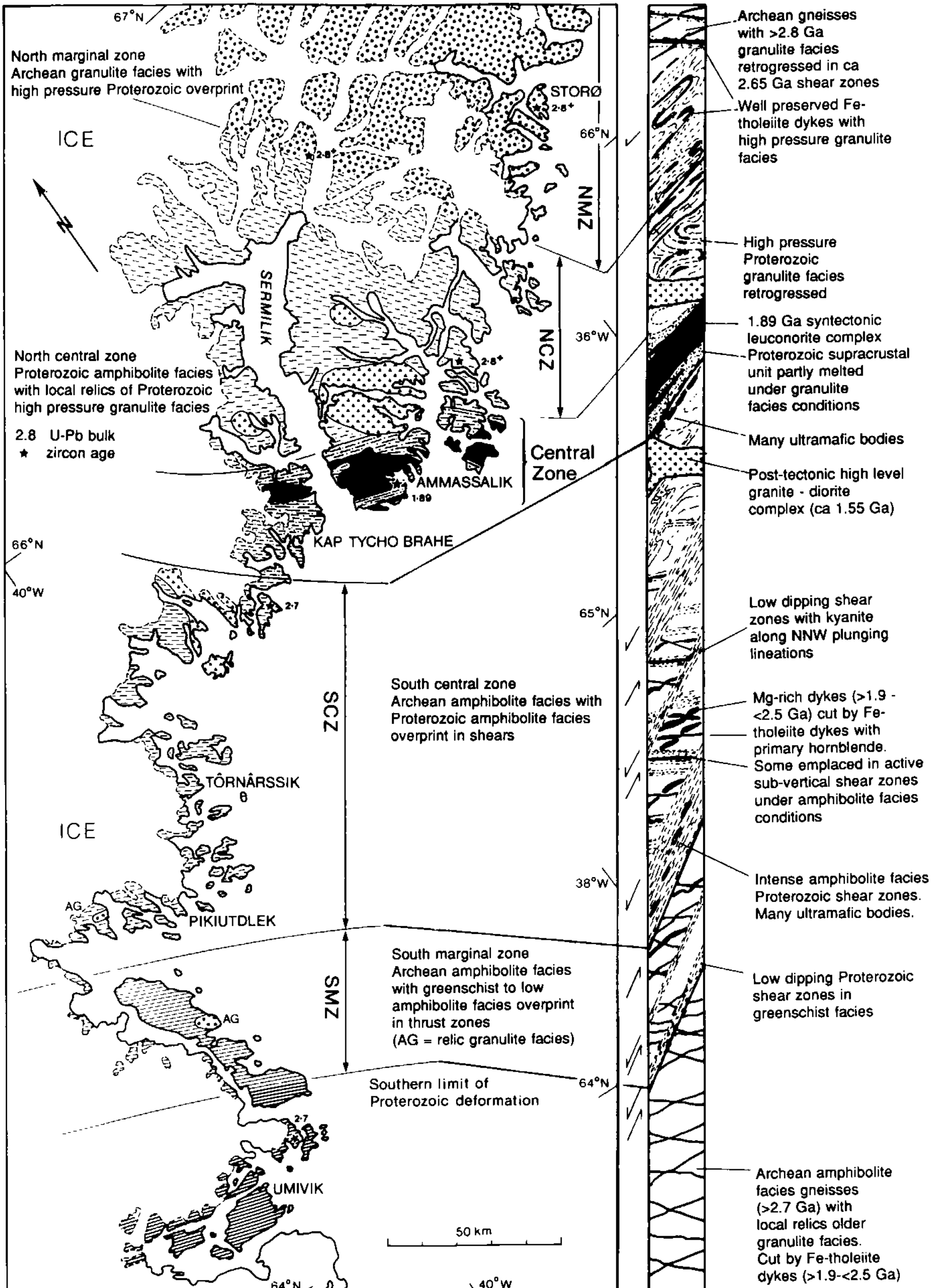


Figure 1 *Suggested relative geographical position of Canadian, Greenlandic and Baltic shields during the Middle Proterozoic. (After Hoffman, 1989, figure 13; geological divisions after the original papers cited in the text).*


67°N
North marginal zone
Archean granulite facies with
high pressure Proterozoic overprint
ICE
STORØ
2·8+
66°N
NMZ
SERMILIK
North central zone
Proterozoic amphibolite facies
with local relics of Proterozoic
high pressure granulite facies
2.8 U-Pb bulk
★ zircon age
36°W
NCZ
2·8+
Central
Zone
AMMASSALIK
1·89
KAP TYCHO BRAHE
66°N
40°W
2·7
65°N
South central zone
Archean amphibolite facies with
Proterozoic amphibolite facies
overprint in shears
SCZ
TÔRNÂRSSIK
ICE
38°W
AG
PIKIUTDLEK
South marginal zone
Archean amphibolite facies
with greenschist to low
amphibolite facies overprint
in thrust zones
(AG = relic granulite facies)
SMZ
AG
Southern limit of
Proterozoic deformation
64°N
2·7
UMIVIK
50 km
64°N
40°W
Archean gneisses
with >2.8 Ga
granulite facies
retrogressed in ca
2.65 Ga shear zones
Well preserved Fe-
tholeiite dykes with
high pressure granulite
facies
High pressure
Proterozoic
granulite facies
retrogressed
1.89 Ga syntectonic
leuconorite complex
Proterozoic supracrustal
unit partly melted
under granulite
facies conditions
Many ultramafic bodies
Post-tectonic high level
granite - diorite
complex (ca 1.55 Ga)
Low dipping shear
zones with kyanite
along NNW plunging
lineations
Mg-rich dykes (>1.9 -
<2.5 Ga) cut by Fe-
tholeiite dykes with
primary hornblende.
Some emplaced in active
sub-vertical shear zones
under amphibolite facies
conditions
Intense amphibolite facies
Proterozoic shear zones.
Many ultramafic bodies.
Low dipping Proterozoic
shear zones in
greenschist facies
Archean amphibolite
facies gneisses
(>2.7 Ga) with
local relics older
granulite facies.
Cut by Fe-tholeiite
dykes (>1.9-<2.5 Ga)

Both the dykes and basic horizons in the supracrustal units crop out as boudins within strongly foliated amphibolite-facies quartzofeldspathic gneiss in which earlier granulite-facies assemblages are only very locally preserved. The granulite-facies assemblages in the dykes are progressively replaced by lower pressure amphibolite-facies assemblages (*ca.* 6–8 kb). Decompression occurred almost isothermally. Amphibolite-facies granitic pegmatites, which intrude the supracrustal sequences and dykes, are deformed and partially transposed into the regional structural trend.

Northern central zone. South of *ca.* 66°N, Archean structures and mineral assemblages in the gneiss complex and high-pressure granulite-facies assemblages in the dykes are progressively overprinted by pervasive Proterozoic deformation. Early thrust structures are folded and medium pressure (6–8 kb) assemblages are developed in both country rocks and the majority of dykes. High pressure assemblages are preserved in the centres of larger boudinaged dykes.

Pedersen and Bridgwater (1979) showed that the Rb-Sr system in the Archean gneisses in the northern central zone was reset *ca.* 1.8–1.9 Ga in samples weighing less than 1 kg. Kalsbeek and Taylor (1989) obtained Rb-Sr whole rock ages between 1.87 and 1.65 Ga from presumed Proterozoic metasedimentary rocks from this zone. Sm-Nd mineral studies on partly retrogressed high pressure assemblages from the centres of dyke remnants give similar ages. They also report T_{DM} values from the metasedimentary rocks suggesting derivation from an Archean source. This is in agreement with Sr isotopic values of 0.7054 at 1.9 Ga obtained by Pedersen and Bridgwater (1979) on garnet-rich paragneiss surrounding the Angmagssalik meta-igneous complex (see below). The isotopic results generally constrain the age of amphibolite-facies metamorphism as between *ca.* 1.95 and 1.6 Ga in the centre of the mobile belt. Kalsbeek and Taylor (1989) also report Sm-Nd model ages of *ca.* 2.2 Ga from units of deformed mafic tonalite from this zone. The rock type dated is thought to correspond to a major gneiss unit which our field observations suggest post-dates Archean tectonism and at least some of the basic dykes, but which predates the main Proterozoic deformation in this zone.

Central zone. The central zone consists of the Angmagssalik meta-igneous complex, a syntectonic leuconorite-charnockite body (Andersen *et al.*, 1989), flanked by a belt of

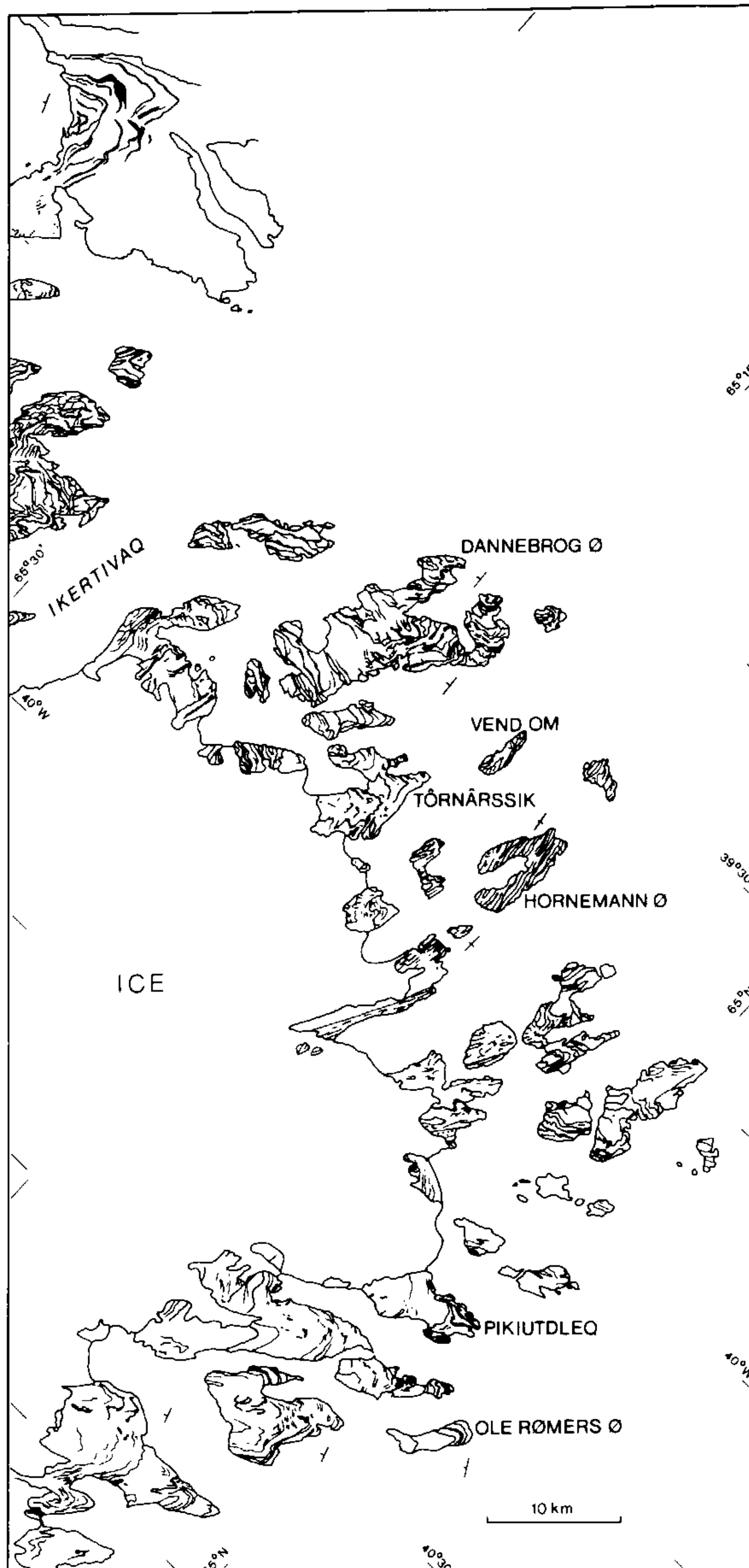


Figure 3 *Sketch map of deformed Early Proterozoic dykes in the southern central zone to show variation in intensity of Proterozoic shearing (from field mapping by Bridgwater and Gormsen (1968) and air photo interpretation (1968, GGU archives)).*

amphibolite-facies metasedimentary rocks tectonically intercalated with Archean gneiss containing remnants of Early Proterozoic dykes. The metasedimentary rocks are recrystallized and partly melted to form a suite of garnet-rich paragneisses in a zone up to 10 km wide adjacent to the leuconorite complex (Bridgwater and Gormsen, 1968). The garnet paragneiss-leuconorite association in the central zone shows marked lithological similarities with the Tasiuyak gneiss of Labrador (Korstgård *et al.*, 1987) and the slightly older Finnish granulite belt (Marker, 1988). The meta-igneous complex ranges from ultrabasic rock and layered meta-gabbro through leuconorite to intermediate and acid hypersthene-bearing rock. No sharp boundaries have been mapped between the main rock units (basic and acid charnockite), which suggests they co-existed as magmas. Sm-Nd studies (Austrheim *et al.*, 1987; Andersen *et al.*, 1989) gave an age of 1900±70 Ma with an εNd of −3.8, suggesting a significant input from an earlier crustal source, such as the adjacent paragneiss and basement gneiss. Sr isotope results do not define an isochron. Many basic samples contain high amounts of radiogenic Sr at 1.89 Ga. Crustal contamination is also shown by multigrain U-Pb zircon studies. One sample gave an intercept age of *ca.* 1.85 Ga, but with fractions falling on a discordia projected from 1.9 to 2.7 Ga (B.T. Hansen, written communication to F. Kalsbeek, April 1986). A second sample (Hansen and Kalsbeek, 1989) gave a more precise U-Pb age of 1886±2 Ma. The emplacement of the igneous complex was accompanied by a CO_2 flux into the adjacent country rocks, resulting in the formation of granulite-facies assemblages along shear zones in both the garnet gneiss and the Archean basement. The leuconorite suite was emplaced at 1000°–1100°C and pressures of 6–8 kb. The pressure estimates are comparable to those determined from the margins of the retrogressed Fe-tholeiite dykes in the north central zone. This suggests that the high pressure assemblages in the northern part of the mobile belt developed earlier than 1.89 Ga.

The central zone of the mobile belt was subsequently intruded by post-tectonic intrusions which range from picrite through norite and diorite to granite (*sensu stricto*). Field evidence for mixing of basic and acid magmas is abundant (see Bridgwater and Myers, 1979, figure 3). All members of the suite contain high abundances of LIL elements interpreted by us as due to interaction between magmas derived from earlier sialic crust and a juvenile mantle-derived basic component (Austrheim *et al.*, 1987). The intrusions yield Rb-Sr and Pb-Pb whole rock isochron ages between 1.55 and 1.68 Ga (Pedersen and Bridgwater, 1979; Taylor *et al.*, 1984; Vannucci *et al.*, 1987). We regard the isochrons as mixing lines between mantle-derived basic rocks and crustal-derived melts, and the ages obtained are thus open to interpretation.

The southern central zone. The boundary between the central zone and the southern central zone is a thrust contact between the supposed Proterozoic sedimentary rocks forming the envelope to the Angmagssalik meta-igneous complex and the basement gneisses. This thrust plane, which was later folded, was the site of considerable silica introduction. The gneiss immediately below the thrust contains abundant ultramafic pods. We suggest that this boundary and the southern boundary of the southern central zone (see below) may represent sutures. The Archean gneiss complex to the south of Ammassalik contains essentially the same lithologies as those of the northern marginal zone, although there is a higher proportion of pre-dyke metasedimentary units. There are large areas of agmatite in which early gneiss units (including gabbro-anorthosite layers and supracrustal rocks) were disrupted by a series of Late Archean granitic veins and sheets. Archean amphibolite-facies assemblages are preserved throughout the complex. Small areas of partly retrogressed, Archean granulite-facies rock occur locally (AG, Figure 2). The prevailing amphibolite-facies metamorphism and widespread agmatite formation are interpreted to reflect the exposure of a higher level of the Late Archean crust in the southern part of the belt compared with the northern marginal zone. U-Pb multigrain studies on zircons from an anorthosite pod in a pegmatitic granitoid (Nunes *et al.*, 1974) gave an age of 2.7 Ga, interpreted as the age of zircon growth in the basic rocks adjacent to granitic sheets.

The southern central zone is intruded by abundant Proterozoic dykes (Figure 3) of several petrological suites. An early, Mg-rich, Al-poor suite is directly comparable to the MD1 swarms of the Southwest Greenland coast (Bridgwater and Myers, 1979; Bridgwater *et al.*, 1985). Where relatively undeformed, these dykes are commonly sinuous, but preserve primary igneous minerals. The Mg-rich suite was intruded by garnet- and amphibole-bearing Fe-rich tholeiites. In this part of the fold belt, the Fe-tholeiites are characteristically foliated even where they intrude undeformed Mg-rich dykes. Zoned bodies with dioritic centres are common. The Fe-tholeiite dykes are interpreted as water-rich, syntectonic intrusions emplaced into subvertical active shear zones under amphibolite-facies conditions. They are comparable in both intrusion mechanics and mineralogy to the Kangamiut dyke swarm (see Escher *et al.*, 1976). In East Greenland, post-dyke Nagssugtoqidian thrusts and metamorphic effects extend for 50 km south of the zone in which syn-kinematic dykes were emplaced.

In the north of the southern central zone, the thrust planes form broad belts dipping to the north at *ca.* 30°. Locally, they contain kyanite, lineated parallel to the general N to S or NNW to SSE direction of overthrusting. P and T estimates on Proterozoic mineral assemblages in dykes just south of Ammassalik suggest conditions of 6–8 kb at 700°C. No high pressure assemblages have been found. Further south, where a higher level of the *ca.* 1.8 Ga crust is exposed, the margins to the thrust zones are more distinct and the rocks within the thrusts contain epidote-amphibolite assemblages. These are younger than amphibolite-facies assemblages found in the foliated Fe-tholeiite dykes.

Southern marginal zone. The boundary between the southern central zone and the southern marginal zone is drawn in the bay south of Pikiutdlek (Figures 2 and 3), where the gneisses are intensely foliated in a *ca.* 10 km wide thrust zone dipping at *ca.* 30° to the north. This contains numerous ultramafic bodies. To the south, the Archean gneiss complex consists dominantly of amphibolite-facies agmatite, with local relicts of earlier Archean granulite-facies gneiss (including supracrustal units). A granite which intrudes the agmatite has yielded a U-Pb multigrain zircon age of 2.7 Ga (R. Steiger, written communication, 1987). Early Proterozoic dykes in this zone are Fe-tholeiites, comparable in chemistry to the amphibole-bearing dykes in the southern central zone, but were not intruded into active shear zones. They crystallized as clinopyroxene-bearing tholeiite with normal sub-ophitic textures. The dykes are disrupted by narrow thrust zones with mylonitic textures and greenschist- to lower amphibolite-facies assemblages. The thrust planes are irregular and swing around augen of competent Archean gneiss cut by undeformed Fe-tholeiite dykes. Imbricate zones are locally developed. The gneiss between the thrust zones was locally overprinted by static greenschist-facies metamorphism and carbonate veins containing biotite. K-Ar determinations on the biotites gave ages of *ca.* 1.6 Ga. NNW-SSE trending dolerite dykes, which post-date tectonism and metamorphism in the area, give K-Ar whole rock ages of 1.5 Ga (D. Rex, written communication, 1969).

Conclusions

Archean gneisses in the Nagssugtoqidian mobile belt of Southeast Greenland, together with volumetrically subordinate Proterozoic supracrustal and igneous rocks, were affected by a complex sequence of tectonic and metamorphic events over a period of 300–500 million years. A relatively simple plate tectonic model in which a northern Archean block was thrust south over the North Atlantic Archean craton during continent-continent collision, or thrust movements within a single craton associated with orogenic activity in South Greenland (*e.g.*, the indentation model of Watterson, 1978), can explain the overall crustal shortening of the mobile belt. However, this simple single-stage collision model is difficult to reconcile with arguments from field and isotopic studies for plutonic activity extending over several hundred million years. The long history of the Nagssugtoqidian suggests that it represents a zone of crustal instability that was periodically reactivated.

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