DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/29

Correlation of Precambrian geology in Labrador and southern Greenland

with reference to the Voisey's Bay nickel-copper deposit, Labrador, Canada

Jeroen A.M. van Gool, Adam A. Garde,
and Lotte M. Larsen

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Introduction

This report was written on request from PF&U Mineral Development ApS as an aid to define possible nickel prospecting targets in Greenland, similar to known ones in north-eastern Labrador. It is based on in-house knowledge at GEUS and a brief literature study and describes the main aspects of the Precambrian orogens and terranes that can be correlated from Labrador to Greenland, and specific lithologies and lithotectonic settings that could be of interest in the nickel prospecting.

It is well-known that the geology of north-eastern Labrador in Canada correlates with south-western Greenland and that the Archaean gneisses on both sides once formed one coherent Archaean crustal block, named the North Atlantic craton, surrounded by the Palaeoproterozoic Nagssugtoqidian, Torngat, Makkovik and Ketilidian orogenic belts (Fig. 1; Bridgwater *et al.* 1973, 1990; Bridgwater & Schiøtte 1991; Korstgård *et al.* 1987; Garde *et al.* 2002; van Gool *et al.* 2002). The Archaean North Atlantic craton was split into a Canadian part in Labrador, referred to as the Nain Province, and a Greenland part, referred to herein as the Archaean shield of southern Greenland, during the opening of the Labrador Sea and Davis Strait in the Cretaceous to Eocene. It is therefore to be expected that Precambrian mineralisations that occur on one side of the Strait may have equivalents on the other side.

The Voisey's Bay deposit in northern Labrador is hosted by a troctolitic phase of the Nain Plutonic suite, in which nickel and other base metals were concentrated during intrusion through graphite- and sulphide-rich Palaeoproterozoic metasediments (Ryan *et al.* 1995; Naldrett & Li 2000; Li *et al.* 2001; Ripley *et al.* 2002). The key features of the deposit are that a primitive, hot magma was able to rise to upper crustal levels, where it was contaminated by sulphide-rich metasediments and created sulphide deposits in a dynamic feeder system where they were upgraded by later undepleted magma pulses. It is a world class nickel deposit, and prospecting for similar occurrences has been quite intense in the remainder of Labrador in the middle to late 1990's (Kerr & Ryan 2000). Also large parts of southern Greenland were staked at the time. The purpose of this report is to summarise existing publications that are relevant to the correlation across the Labrador Sea and Davis Strait, with specific emphasis on geological settings resembling those of the Voisey's Bay deposit. Although it is not the intention of this report to identify specific prospecting targets, the general environments within Greenland which might resemble that of Voisey's Bay will be addressed.

There are three aspects to this correlation: 1) a purely geometrical reconstruction of the Archaean craton prior to opening of the Labrador Sea and Davis Strait, based on off-shore geophysical data; 2) correlation of the Palaeoproterozoic belts and the main Archaean geological features; 3) an outline of geological environments in Greenland that are similar to the one that controlled the mineralisation of the Voisey's Bay region. In this report first the Voisey's Bay deposit is introduced, after which the geometric reconstruction is presented. Subsequently, the different correlations are discussed, in order of decreasing age.

An overview of the main geological units in north-eastern Labrador and southern West Greenland

The geology of southern Greenland and eastern Labrador is dominated by rocks of a composite Archaean shield surrounded to the north, west and south by Palaeoproterozoic orogenic belts (Fig. 1). This Archaean shield forms a complex of smaller terranes which were amalgamated during the late Archaean, to form the North Atlantic craton (NAC; Bridgwater *et al.* 1973), of which the Labrador part in Canada is referred to as the Nain Province. The Palaeoproterozoic Ketilidian orogen of south Greenland represents an Andean-type continental margin and is correlated with the Makkovik Province in Labrador. The Nagssugtoqidian orogen in West Greenland and the Torngat orogen in Labrador form the northern and western limbs of a presumably once continuous orogenic belt, due to the collision of the NAC with, a continental plate to the north, now part of the Rinkian belt (van Gool *et al.* 2002 and references therein), and a plate to the west, the core zone of the south-eastern Churchill Province in Labrador (Wardle *et al.* 2002a and references therein).

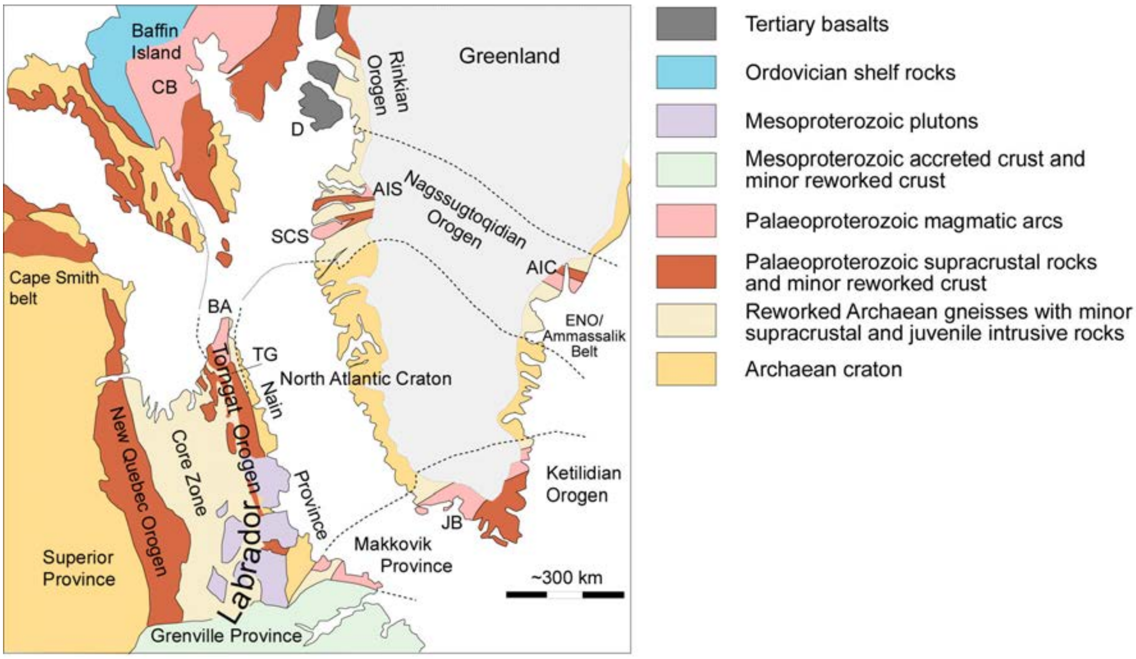

Figure 1. *Generalised geology of the reconstructed North Atlantic Craton and surrounding Palaeoproterozoic belts. AIC = Ammassalik intrusive complex, AIS = Arfersiorfik intrusive suite, BA = Burwell arc, CB = Cumberland batholith, D = Disko Island, ENO = eastern Nagssugtoqidian Orogen, JB = Julianehåb batholith, SCS = Sisimiut charnockite suite, TG = Tasiuyak gneiss. Modified from Bridgwater et al. 1990.*

The Archaean rocks of the North Atlantic craton consist predominantly of deeply exhumed early to late Archaean orthogneisses, including the largest exposures of some of the oldest rocks in the world, which are alternating with greenstone belts and minor clastic metasediments. In the Nagssugtoqidian orogen, and to a lesser extent also the Torngat orogen, these orthogneisses still predominate, in a reworked state. Arc magmatism occurred in both flanks of the belt, but is volumetrically less significant. Palaeoproterozoic metasediments occur mainly in narrow belts, with the exception of the Tasiuyak gneisses in Labrador, which form up to 40 km thick successions that occur along the whole exposed length of the orogen. For both flanks, the North Atlantic craton is interpreted to be the overriding plate.

In contrast to the northern and western margin of the Archaean shield, the Makkovik and Ketilidian belts on the southern boundary are sites of juvenile crustal accretion in an Andean-type margin. After having persisted as passive continental margins, these belts became the loci of subduction, arc magmatism and the formation of a clastic accretionary wedge around 1850 Ma, starting at the time of collision in the Nagssugtoqidian/Torngat system.

While the Ketilidian and Nagssugtoqidian belts are laterally truncated by sea and the icecap of Greenland, the Torngat and Makkovik belts are truncated to the south and southwest by the Mesoproterozoic Grenville province. Furthermore, the Nain Plutonic Suite intruded through the core of the southern part of the Torngat orogen in the Mesoproterozoic, hampering the reconstruction of the geology of this part of the Torngat orogen.

The Voisey's Bay mineral deposit and its geological environment

The Voisey's Bay mineral deposit is hosted by intrusions of the Mesoproterozoic Nain plutonic suite near the suture in the southern part of the Torngat orogen in central/northern Labrador (Ryan *et al.* 1995; Naldrett *et al.* 1996; Ryan 2000). The mineral deposit consists of three magmatic Ni-Cu-Co sulphide bodies connected by a mineralised troctolite feeder dyke which intruded into sulphide-bearing Palaeoproterozoic metasediments and Archaean gneisses (Fig. 2; Lightfoot & Naldrett 1999; Naldrett & Li 2000 and references therein; Ripley *et al.* 2002).

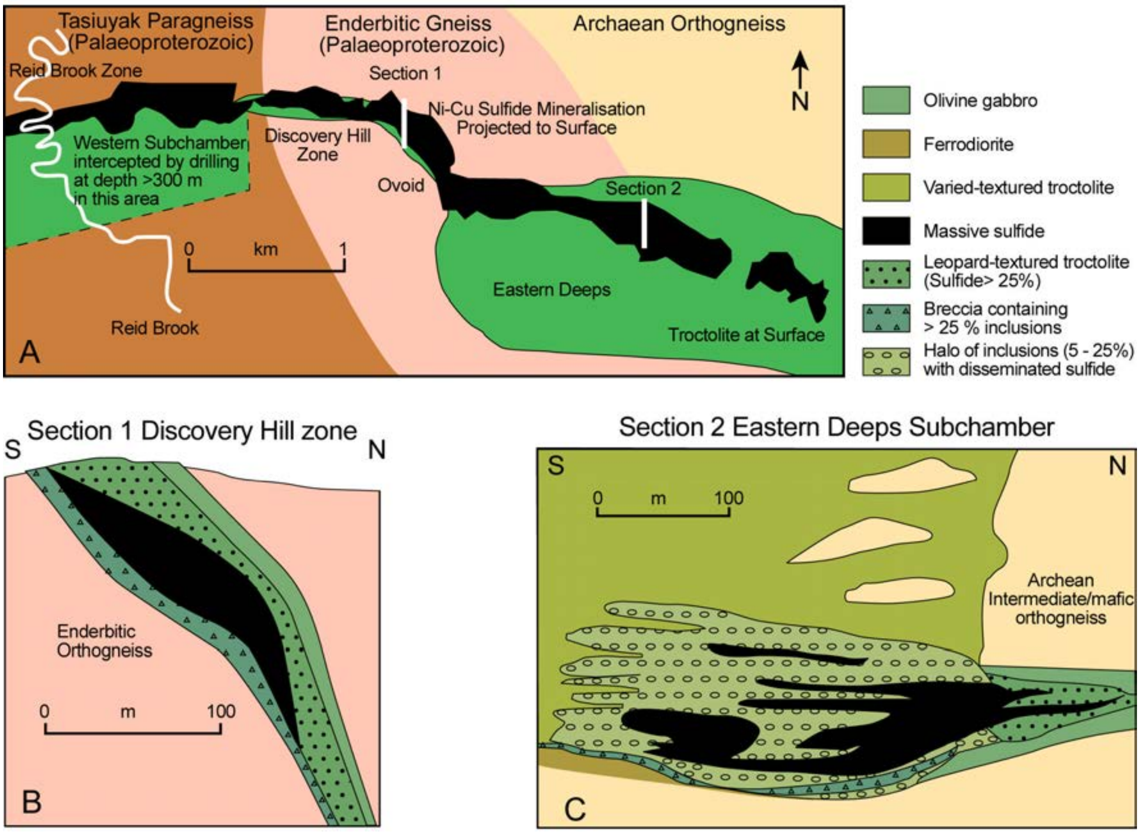

Figure 2. *Overview of the Voisey's Bay Ni-Cu mineral deposit site. A) map of the site, with the mineralised bodies projected to the surface (after Lightfoot & Naldrett 1999). Sections 1 and 2, indicated in the map, cut through two of the main mineral deposits. B) section 1 through the feeder dyke in the Discovery Hill zone (after Li & Naldrett 1999). C) section 2, showing the Eastern Deeps chamber at ca 1000 m depth, with the mineralised body at the base, near the entrance of a feeder conduit (after Lightfoot & Naldrett 1999).*

The mineralisation process

The dyke and the plutons it is feeding into form a complex of both layered and massive troctolitic rocks (troctolite, melatroctolite, leucotroctolite, norite, gabbro and gabbro-norite containing cumulus plagioclase and olivine) and are derived from a high-temperature, olivine-rich magma. The deposit formed by sulphur contamination of a primitive basic magma which was originally sulphur undersaturated (Naldrett & Li 2000 and references therein; Li *et al.* 2001; Ripley *et al.* 2002). The dyke is in direct contact with sulphur- and graphite-rich Palaeoproterozoic Tasiuyak pelitic gneiss, and the abundance of hornfelsed metasedimentary gneissic inclusions within the plutons east of the dyke, which are hosted by Archaean orthogneisses, indicates substantial incorporation of Tasiuyak gneiss during magma ascent (Fig. 2). Sulphur isotope studies indicate that much of the sulphur in the deposits is derived from the Tasiuyak gneiss, but also from Archaean gneisses at depth. The addition of reduced sulphur from the paragneisses to the Ni-, Cu- and Co-containing magma resulted in sulphide saturation and subsequent segregation of immiscible sulphide liquids from the magma (Ripley *et al.* 2001 and references therein). The sulphidic magma was subsequently upgraded in metals by a new surge of undepleted magma, rising through the conduit where the sulphides resided. The sulphides were subsequently concentrated in wider parts of the conduit system and at its entry in an upper chamber, in sites where the velocity of the rising liquid decreased (Fig. 2). Parts of the unmineralised silicate melt that are associated with the deposit are strongly depleted in metals as a result of the upgrading of the sulphides.

Regional context of the Voisey's Bay deposit, the Nain Plutonic Suite

The rocks of the Mesoproterozoic Nain Plutonic suite (NPS, Fig. 3) that host the deposit form a large complex of anorthosite - mangerite - charnockite - granite (AMCG) plutons 1.29 – 1.35 Ga old, presently extending over *c.* 20.000 km^2 (Emslie *et al.* 1994). Many of the plutons are in the order of 100 kilometres wide and the majority is formed by anorthosites. The plutons are derived from magma chambers near the upper mantle – lower crust interface which formed a continuously replenished mafic magma pond. Granitic phases stem from crustal partial melting near these heat sources, while assimilation of the depleted parts of the lower crust caused saturation of plagioclase and formation of anorthositic plutons. Small volumes of primitive magma managed to ascend rapidly through the crust and crystallised as troctolitic plutons.

The NPS straddles the southern part of the suture of the *c.* 1850 Ma Torngat orogen and the Palaeoproterozoic, crustal-scale Abloviak strike-slip shear zone, which runs along most of the length of the orogen (Fig. 3; Wardle *et al.* 2002a). Near the Voisey's Bay deposit, the NPS rocks intrude both Archaean gneisses of the Nain Province and Palaeoproterozoic Tasiuyak gneisses. The latter are pelitic, sulphide-rich rocks, which form an up to 40 km wide and 13 km thick zone west of the suture in the region (Fig. 3). The NPS is generally interpreted as an anorogenic plutonic complex, intruding in an extensional setting, distal to any continental margin at the time. Time-equivalent continental margin arc rocks occur in

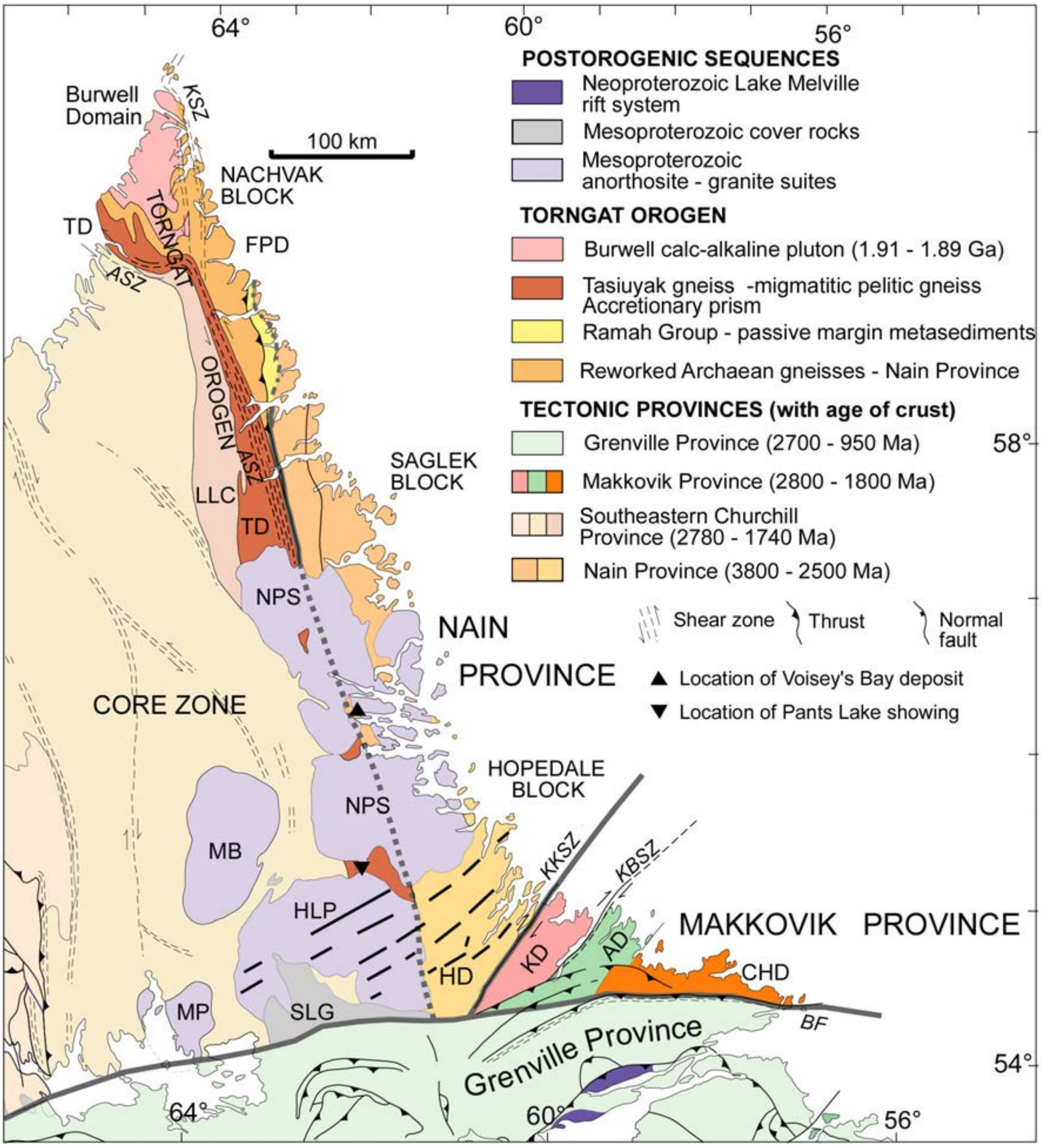

Figure 3. *Geology of northern Labrador and northeastern Quebec (after Wardle et al. 2000) with the Torngat and Makkovik orogens. ASZ, Abloviak shear zone; BD, Burwell Domain; FPD, Four Peaks Domain; KSZ, Komaktorvik shear zone; LLC, Lac Lomier complex; TD, Tasiuyak domain. In the Makkovik Province: AD, Aillik domain; BF, Benedict fault; CHD, Cape Harrison domain; KBSZ, Kaipokok Bay shear zone; KD, Kaipokok domain; KKSZ, Kanairiktok shear zone.Post-orogenic assemblages: HD, Harp Dykes; HLP, Harp Lake Pluton; MB, Mistastin batholith; MP, Michikamau pluton; NPS, Nain plutonic suite; SLG, Seal Lake Group.*

the south-western Grenville Province, which led Rivers (1997) to propose an extensional back-arc setting, while Emslie *et al.* (1994) associate the basic magmatic activity to a mantle plume.

The eastern limit of the NPS is unknown, but no similar rocks of that age are known from Greenland. Because the location of the NPS appears pinned to the north-south-trending suture of the Torngat orogen, and does not extend to northernmost Labrador, it is unlikely that this intrusive suite continues into Greenland following the Torngat-Nagssugtoqidian belt.

The search for Voisey's Bay equivalents

After the discovery of the Voisey's Bay deposit, exploration activity in northern Labrador increased enormously for several years, concentrating on rocks of the NPS (Kerr & Ryan 2000). However no other economic deposits were found, and most of the mineralised parts of the NPS, have different characteristics, with one exception. The Pants Lake intrusions, 80 kilometres south of the Voisey's Bay deposit, show great similarity to the latter and are also mineralised. However, the lack of a late surge of undepleted magma in this area prevented the sulphides from being upgraded to economical values (Li *et al.* 2001; Kerr 2003).

It is the general impression that an equivalent of the Voisey's Bay deposit, should be searched for in a geological setting that combines the main features of the deposit: a primitive, hot magma ascending to upper crustal levels, coupled with contamination by sulphide-rich metasediments to create sulphide deposits in a dynamic feeder system.

Geometrical correlation: closing the Labrador Sea - Davis Strait - Baffin Bay

Correlation of the geology across the Labrador Sea and Davis Strait is hampered by the separation as a combined result of stretching of the continental crust, creation of ocean floor, and transcurrent movements. Furthermore, hundreds of kilometres of continental crust are presently submerged which further complicates the correlation.

The Labrador Sea was formed during a series of events, of which the most important ones are the following:

1. Mesozoic (mainly Cretaceous) to early Palaeocene: stretching and thinning of the lithosphere. The direction was approximately NE–SW, and stretching factors (width after stretching/width before stretching) are in the order of 2–3.
2. Palaeocene, 61–55 Ma, geomagnetic chron 27n–24r (sea floor linear magnetic anomaly 27 normal to 24 reversed, Cande & Kent 1992, 1995). Continental break-up, drift, and formation of ocean floor; direction approximately NE–SW.
3. Eocene, 55–33 Ma, geomagnetic chron 24r–13. Continued continental drift and formation of ocean floor, but with the direction changed to NNE–SSW to almost N–S. Strong transcurrent movements along the Ungava transform fault zone. Spreading between Canada and Greenland stopped around geomagnetic chron 13, *c.* 33 Ma.

Many aspects of these events are well constrained, but others are not. In particular, accurate rotation poles for the movements of the continental plates are not agreed on, mainly because of plate deformations in the northern areas, and this has prevented agreement on quantitative plate reconstructions back in time. Moreover, the Baffin Bay area remains relatively poorly known.

We have based our reconstruction on the latest geophysical data from GEUS and Canadian co-workers (Chalmers & Pulvertaft 2001). The present configuration of the sea floor is as shown in Fig. 4. We have then simply gone mechanically through the steps 3–2–1 mentioned above and successively removed the sea floor, then overlapped the thinned continental margins to adjust for the stretching during phase 1. Constraints from the Labrador Sea and Davis Strait were used, whereas the areas around Baffin Bay passively followed suit.

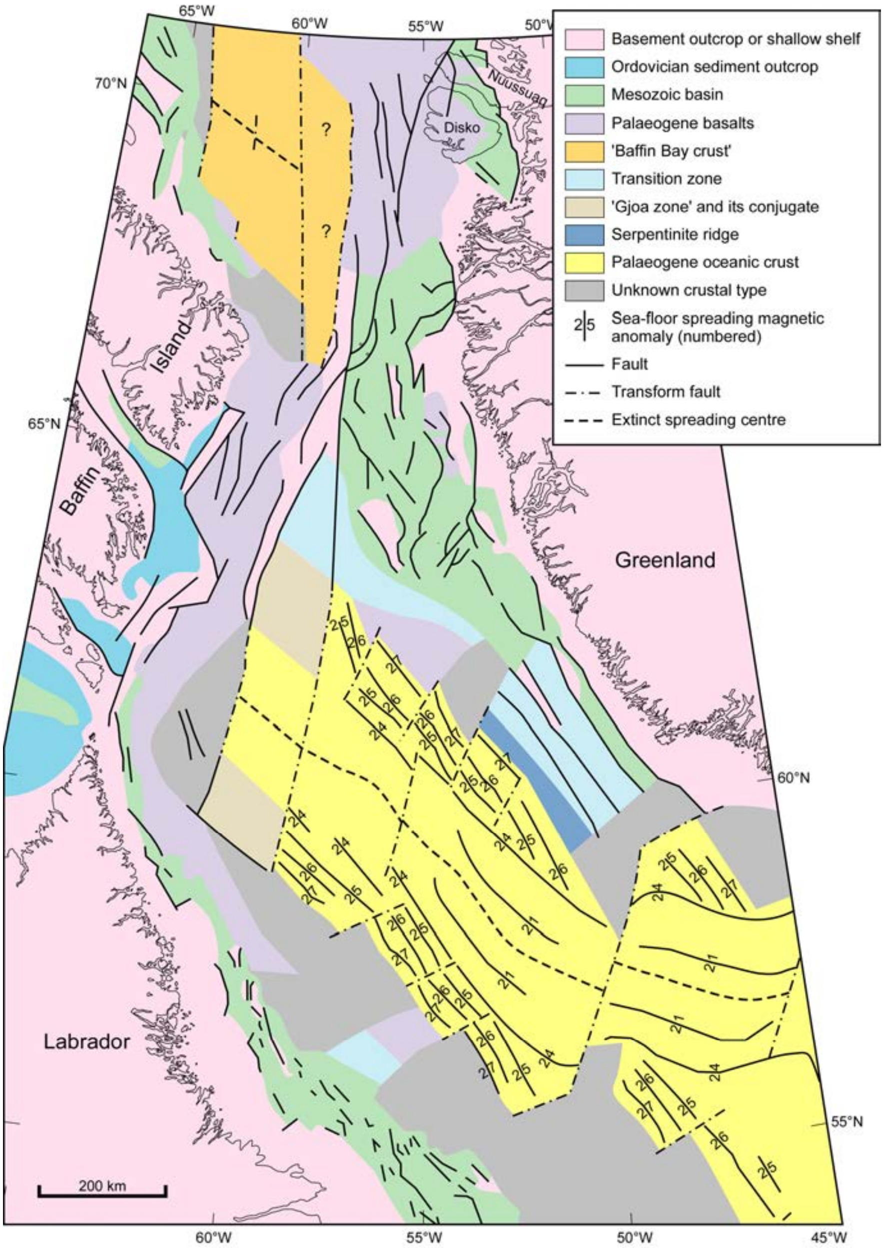

Figure 4. *Present configuration of the Labrador Sea–Davis Strait region, from Chalmers & Pulvertaft (2001). The data in this figure were used for the geometric reconstruction of Labrador and Greenland prior to rifting.*

The resulting pre-Mesozoic reconstruction is shown in Fig. 5. The net movement of the two coast lines is nearly 600 km in SSW–NNE direction, and they end up being nearly parallel with 300–400 km separation, underlain by the presently submerged and stretched continental crust. This leaves a considerable gap across which the geology has to be correlated.

At first inspection, it is only the Ketilidian and Makkovikian fronts that align in this reconstruction. The eastern continuation of the Grenville front runs south of Greenland. The Torngat and Nagssugtoqidian orogens are almost at right angles and their correlation is not significantly enhanced by this geometric reconstruction. The geometries of terranes in the North Atlantic craton are commonly poorly defined and cannot be traced across the gap.

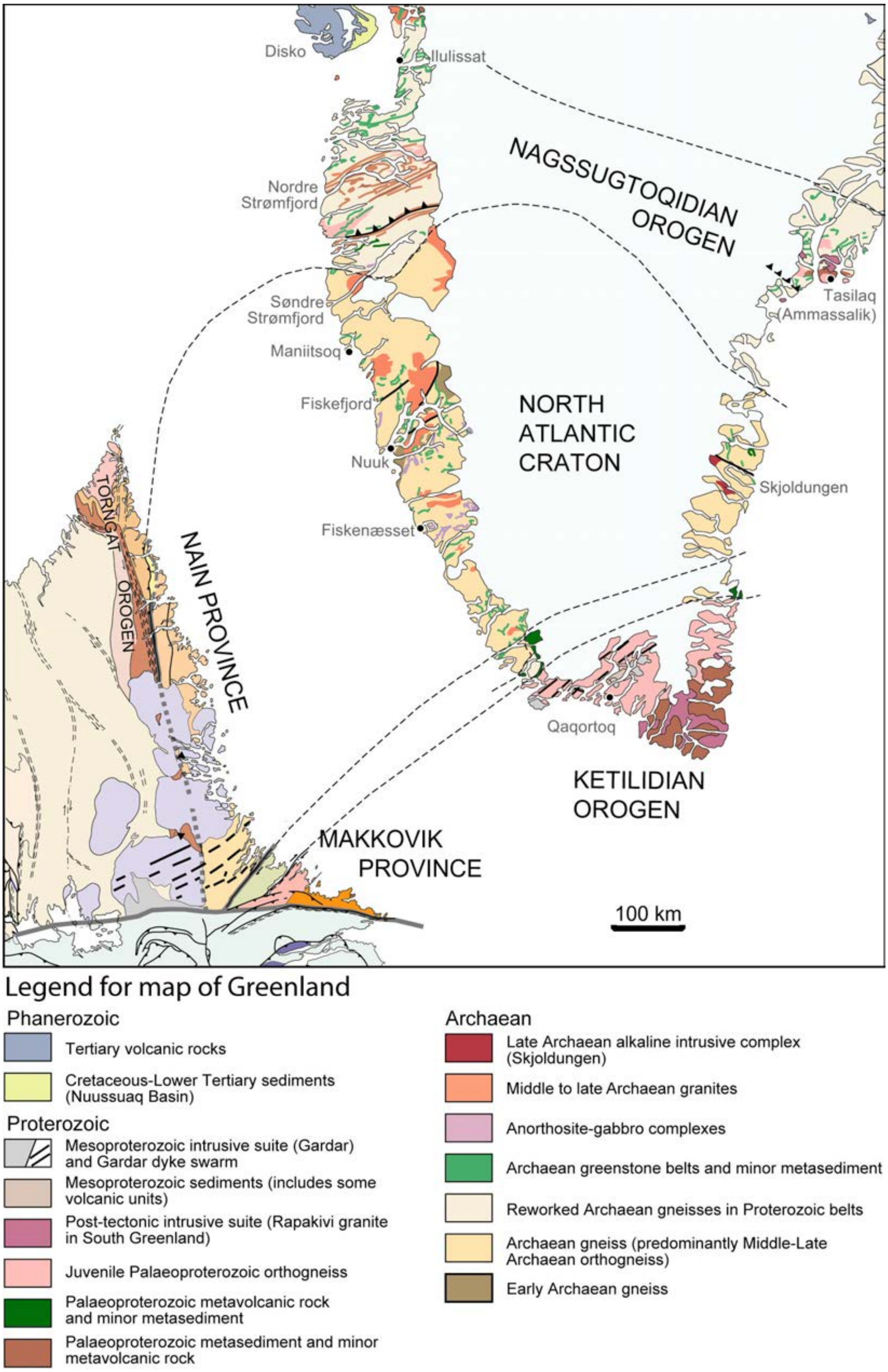

Figure 5. *Reconstruction to pre-Mesozoic time of the southern West Greenland – north-eastern Labrador region. Legend for Labrador geology in Fig. 3. See text for explanation.*

Nain Province – Archaean shield of southern Greenland: the North Atlantic craton

Correlation of the Archaean rocks between the two exposed parts of the once contiguous North Atlantic craton has focused on known occurrences of early Archaean rocks (e.g. Bridgwater & Schiøtte 1991; Friend & Nutman 1994). In southern West Greenland these occur within the Aasivik and Akulleq terranes in the northern and central parts of the craton, near Søndre Strømfjord (Kangerlussuaq) and Nuuk respectively (Fig. 6). In Labrador such rocks occur in the Saglek region (Fig. 3). However, the unexposed pre-drift distance of 300-400 km between the two separated parts of the craton seriously hinders, and possibly precludes, a direct correlation between specific rock units or terranes.

Recent and ongoing detailed studies of the Archaean magmatic and tectonic evolution of the Archaean craton in Greenland, especially within the Nuuk region (e.g. Nutman *et al.* 1989; Friend *et al.* 1996; Crowley 2002) reveal the complex nature of the Archaean crust. These investigations have shown that the North Atlantic craton comprises a still unknown number of distinct tectono-stratigraphic terranes or microplates, with individual sizes varying from tens of kilometres to at least a couple of hundred kilometres. Each of these small continental blocks experienced their own magmatic, tectonic and metamorphic evolution independently of their neighbours, until they were apparently all amalgamated into the North Archaean craton at around 2.7 Ga. Within southern West Greenland alone there are thus several terranes that have almost identical protoliths or peak metamorphic ages, but which were nevertheless accreted independently of each other.

The North Atlantic craton in West Greenland

Figure 6 shows three adjacent tectono-stratigraphic terranes in the Nuuk region within the central part of the North Atlantic craton. The northernmost, Akia terrane consists of 3.2 and 3.0 Ga orthogneisses which have intruded into older supracrustal rocks and were metamorphosed at up to granulite facies conditions at around 2.97 Ga. The middle, Akulleq terrane comprises at least two different groups of early Archaean supra- and infracrustal rocks *c.* 3.5–3.8 Ga in age, including the famous Isua supracrustal belt (e.g. Nutman *et al.* 1996, 2000), besides *c.* 2.8 Ga orthogneisses. The southernmost, Tasiusarsuaq terrane largely comprises *c.* 2.8 Ga rocks but does not contain early Archaean components.

The terranes outside the Nuuk region are not all well defined. The southern part of the craton from the Tasiusarsuaq terrane and southwards comprises several different terranes which range from *c.* 2.8 to 3.0 Ga in age (Friend & Nutman 2001), apparently without older components. They mainly comprise orthogneisses besides supracrustal amphibolites and a large anorthosite-gabbro complex with chromitite horizons at Fiskenæsset (e.g. Myers 1985). The early Archaean Aasivik terrane is located north of the Akia terrane near the southern margin of the Nagssugtoqidian orogen and largely consists of *c.* 3.78–3.55 Ga orthogneisses (Rosing *et al.* 2001) . The Archaean orthogneisses still farther north that are

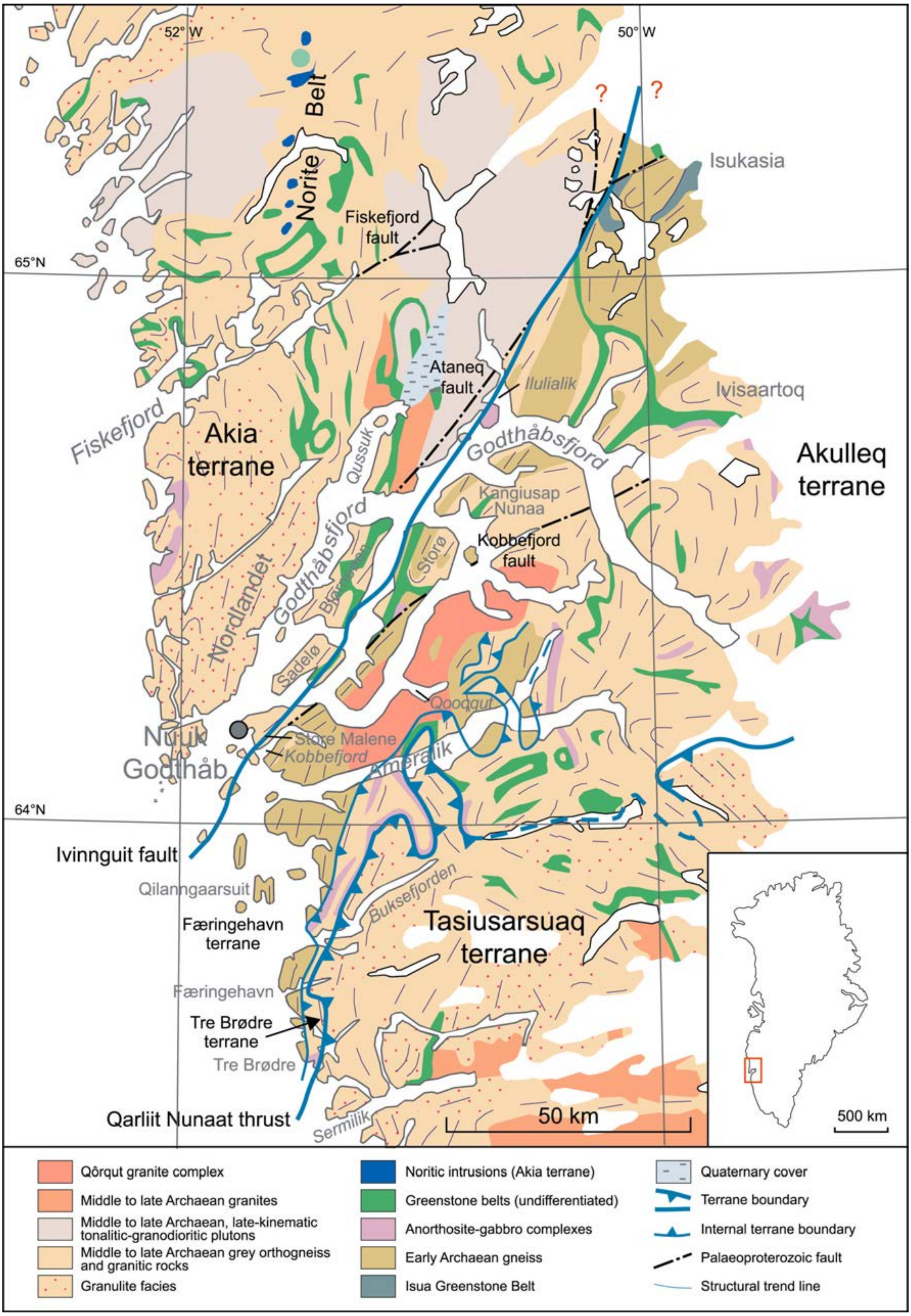

Figure 6. *Geology of the Nuuk region, showing the three main Archaean terranes in the region. From Garde (2003).*

reworked by the Nagssugtoqidian orogeny are generally 2.7–2.85 Ga in age, with a prominent granulite facies event at around 2.72 Ga. Protolith ages in Archaean gneisses north of the assumed Nagssugtoqidian suture are similar to those in the NAC.

The North Atlantic craton in south-east Greenland

The Archaean of south-east Greenland is very poorly known and correlations with West Greenland are not feasible. For prospecting purposes, the Skjoldungen alkaline province is the most interesting (see below). The majority of the Archaean rocks in south-east Greenland consists of granulite- to amphibolite facies orthogneisses, with minor inclusions of amphibolite. The best known part is the Ammassalik region (Fig. 5), in which 3.0–2.8 Ga Archaean gneisses are overprinted during Nagssugtoqidian orogeny (Kalsbeek *et al.* 1993). This range of ages is consistent with known ages of the Archaean gneisses further south (Kalsbeek & Taylor 1993). An Archaean terrane boundary is inferred just north of Skjoldungen island at around 63°N (Fig. 5), separating unnamed southern and northern terranes which consist of respectively agmatitic orthogneisses and a complex of ortho- and paragneisses (Nielsen & Escher 1988). South of this boundary, in a transitional zone, ortho- and paragneisses are intruded by syn- to post-tectonic rocks of the *c.* 2.7 Ga Skjoldungen alkaline province, consisting of gabbro and hornblende diorite to (nepheline-) syenite (Rosing *et al.* 1988: Nielsen & Rosing 1990; Nutman & Rosing 1994; Blichert-Toft *et al.* 1995). No equivalent of the Skjoldungen alkaline province is known from West Greenland. Complexly folded Archaean supracrustal rocks are also common in the Archaean orthogneiss terrain south of Timiarmiut Fjord. This most southerly Archaean terrain appears separated from the agmatite-dominated terrain between Skjoldungen and Timiarmiut by a major shallowly south-dipping shear zone along the south shore of Timiarmiut Fjord.

Anorthosite suites and associated rocks of specific interest as exploration targets

Anorthositic suites in the North Atlantic region comprise two compositionally and genetically different types. The first type is represented in West Greenland by the Fiskenæsset complex south of Nuuk. This 'Fiskenæsset' type of anorthosite is Archaean in age and generally intruded by precursors of the Archaean orthogneisses that form the bulk of the Archaean continental crust. The anorthosite is always found in association with leucogabbro and gabbro, and the association probably represents intrusive mafic complexes. We believe that these are genetically related with the tholeiitic pillow lava precursors to the common supracrustal amphibolites. The Fiskenæsset-type anorthosites themselves are characterised by white, very calcic plagioclase (generally above An_{70}) that likely represents early crystallisates that were separated from the mafic magmas. Besides the Fiskenæsset complex, also the Boye Sø anorthosite complex on Nuussuaq in central West Greenland and several smaller occurrences e.g. in the Nuuk region belong to this type.

The second type of anorthosites, such as the Nain intrusive suite in Labrador, forms large anorogenic plutonic complexes that were emplaced into older continental crust from mantle sources. This type of anorthosite is less calcic and is characterised by grey plagioclase of more intermediate composition, which readily exsolves on a fine scale to give the well-known labradorising effects. There are no large, well-known examples of this type in southern West Greenland, although members of the 1.3–1.1 Ga Gardar province in South Greenland contain components that may have affinity to such anorthositic rocks.

The **Greenland norite belt** in the Akia terrane east of Maniitsoq forms a 15 x 75 km belt of isolated bodies of basic rocks which intruded into the regional gneiss complex (Fig. 6). They have been the target of nickel-copper exploration since 1965 (Nielsen 1976; Secher 1983, 2001; Shore 2000 and references therein). The rocks consist predominantly of melagabbronorite to leucogabbro, with minor true norites and leuconorites. Igneous textures and primary igneous layering are locally preserved. The bodies range from just a few metres to several kilometres in size, the largest covering 2 x 4 km. Elevated Ni and Cu concentrations were found in sulphide showings of magmatic origin, with some degree of metamorphic remobilisation. The showings were estimated to be of sub-economic size, generally a few tens of metres long (Secher 1983; Shore 2000). The age of the norite belt is uncertain, but likely around 3.0 Ga (Secher 2001 and references therein), and there are no obvious correlatives in Labrador. 2975 ± 13 Ma old, post-kinematic diorite intrusions in the Fiskefjord region, south of the Greenland norite belt, have many aspects in common with the norite belt rocks and may be cosanguineous with them (Garde 1991, 1997; Garde *et al.* 2000).

Other minor bodies of mafic and ultramafic intrusive rocks occur throughout the Archaean complexes of the NAC. Most are isolated and of minor extent. However, a well-documented and large exposure occurs in the central Fiskefjord area (Fig. 6). Here, layered ultrabasic, noritic and metagabbroic rocks form the cumulate and intrusive members of a large basic magmatic complex that extends for *c.* 25 km (Garde 1997). This complex is locally associated with thin sheets of metasediments.

The North Atlantic craton in Labrador - The Archaean Nain Province

The Nain Province (or Nain craton in the recent literature) exposed in northern Labrador comprises the Saglek block in the north and the Hopedale block in the south on either side of the Nain Plutonic suite (Fig. 3). Like the West Greenland terranes, also the Saglek and Hopedale segments had different magmatic and tectonic histories until they were amalgamated at *c.* 2.7 Ga (e.g. James *et al.* 2002 and references therein). Their mutual contact relationships are obscured by the Nain Plutonic suite, which extends across the Nain province in the border region. The Saglek block, with protolith zircon ages between 3.8 and 2.5 Ga, has the longer history of the two. The thrust front of the Torngat orogen truncates the Saglek block to the north, and Archaean rocks northwest of this front are strongly reworked by Palaeoproterozoic tectonism; This segment of the Nain craton appears different from the Saglek block and is in some publications referred to as the Nachvak block (e.g. James *et al.* 2002). The occurrence of Archaean gneisses in the northern Burwell domain of the Torngat orogen was only established fairly recently. They comprise gneisses with protolith ages similar to the reworked Archaean gneisses in the Nagssugtoqidian orogen (van Kranendonk *et al.* 1994; Scott 1995; Connelly & Mengel, 2000).

The Saglek block comprises the early Archaean tonalitic to granodioritic Uivak gneisses (two phases at 3.86–3.73 Ga and 3.6–3.3 Ga, Bridgwater & Schiøtte 1991), as well as inclusions of older metavolcanic rocks, of which one felsic phase was dated at 3.78 Ga (Schiøtte *et al.* 1989). The porphyritic mafic Saglek dykes that intrude the Uivak gneisses but not the younger Lister gneisses (*c.* 3.2 Ga, Schiøtte *et al.* 1989), were likened to the Ameralik dykes of the Nuuk region in Greenland by Bridgwater & Schiøtte (1991). However, more recent studies have shown that both the Saglek and Ameralik dykes include widely variable components ranging from Early to Late Archaean in age and are not suitable for correlation purposes. Bridgwater & Schiøtte (1991) also suggested a correlation of the Malene supracrustal rocks in the Nuuk region with the Upernavik supracrustal rocks of the Saglek block. However, it has subsequently been shown that also these units comprise supracrustal sequences of different ages, which are not genetically related to each other. Granulite facies metamorphism affected most of the Saglek block at *c.* 2.8–2.7 Ga.

The Hopedale block, bounded to the north by the Nain Plutonic suite and to the south by the Makkovik and Grenville Provinces (Fig. 3), is dominated by orthogneisses with protoliths ages between 3.3 and 2.8 Ga (Ermanovics 1993) including the 3.3–3.1 Ga tonalitic to granitic composite Maggo gneisses and the 2.89–2.82 Ga Kanairiktok Plutonic suite. The orthogneisses contain supracrustal belts that are dominated by mafic metavolcanic rocks, of which the most prominent ones are the *c.* 3.1 Ga Hunt River and the *c.* 3.0 Florence Lake volcanic belts (James *et al.* 2002). Regional metamorphism mainly overlaps the time of intrusion of the Kanairiktok Plutonic suite, while the western part of the Hopedale Block was affected by granulite facies metamorphism in the interval 2545–2578 Ma.

Correlation of the Archaean rocks across the Labrador Sea

Although the authors of this report feel that correlation of Archaean terranes across the Labrador Sea is highly speculative, some published correlations are referenced here. Friend & Nutman (1994) suggested a correlation between the Akia terrane in Greenland and the Hopedale Block in Labrador, based on *c.* 3.0 Ga metamorphism and plutonism in both, whereas an unnamed terrane south of Søndre Strømfjord was correlated with the Saglek block, based on granulite facies metamorphism at *c.* 2740 Ma in these two. However, James *et al.* (2002) pointed out that there is a significant difference in timing of metamorphism in the Hopedale block and the Akia terrane, and preferred a correlation between the Hopedale block and Tasiusarsuaq terrane, and of the Saglek block with the Akulleq terrane. Similarities in both protoliths and metamorphic ages of the Nachvak block and Archaean gneisses in the Nagssugtoqidian orogen, could suggest a correlation between these areas.

Nagssugtoqidian - Torngat orogenic belt

The Nagssugtoqidian and Torngat orogens are both collisional orogens that developed contemporaneously along the northern and western margin of the NAC (Figs. 1 and 5). The correlation is based on coincidence of timing of tectonic events and their kinematics, as well as similarity of lithotectonic units, as described by van Gool *et al.* (2002; see also Wardle *et al.* 2002a, b; Connelly *et al.* 2000). A strong correlation exists between pelitic metasediments of the Tasiuyak gneisses (Fig. 3) and similar rocks of the central Nagssugtoqidian, the Nordre Strømfjord and Nordre Isortoq supracrustal suites (Fig. 7). They have very similar detrital zircon populations derived predominantly from a 2.1–2.0 Ga source, while the age of deposition in both cases is approximately 1.95–1.90 Ga. Continental margin deposits with a predominantly Archaean provenance occur both in rocks of the Ramah Group in northern Labrador (Fig. 3), and in the Maligiaq sequence in the Ikertôq thrust zone in Greenland (Fig. 7; Marker *et al.* 1999). Rocks of both settings are tectonically interleaved with their Archaean basement in craton-directed thrust belts. Arc magmatism occurred in both belts simultaneously between ca 1.92 Ga and 1.87 Ga. In Labrador, the 1.91–1.88 Ga Burwell pluton (Scott 1995) is intrusive into Archaean gneisses of the Nain Province, while the Tasiuyak gneisses are intruded by similar metaplutonic rocks dated at 1.91–1.87 Ga in Northern Labrador (Ryan *et al.* 1991; Scott 1998). Contemporaneously with this, arc magmatism occurred in the Nagssugtoqidian orogen in two separate belts. South of the proposed suture in the Nordre Isortoq belt, calc-alkaline rocks of the Sisimiut suite intruded into Archaean ortho- and paragneisses, while north of the suture, in the Nordre Strømfjord region, arc magmatic rocks occur intrusive into allochthonous Palaeoproterozoic metasediments of the Nordre Strømfjord suite (Fig. 7).

Collision occurred in both belts at around 1.87–1.84 Ga, the age of peak metamorphism and the main tectonic interleaving. Subsequent deformational events overlap in time and, although they are on orthogonal limbs of the North Atlantic craton, they have consistent kinematics. One significant difference is the lack of a correlative to the extensive Kangâmiut dyke swarm in the southern part of the Nagssugtoqidian orogen and its foreland, which is not recognised in Labrador, in spite of the fact that its strike suggests continuation in that direction (Fig. 7).

The Nagssugtoqidian orogen is assumed to continue eastwards underneath the inland ice sheet to link up with the Ammassalik belt, or eastern Nagssugtoqidian orogen of east Greenland (van Gool *et al.* 2002). The correlation is predominantly based on the similarity in age of metamorphism on either side, and the similar ages of the calc-alkaline rocks in the Nagssugtoqidian orogen in West Greenland and the Ammassalik intrusive complex.

Mafic intrusives in sulphide-bearing supracrustal belts.

The Nagssugtoqidian orogen contains one set of rocks in a geological setting that has some similarities the Voisey's Bay mineral deposit. Ultramafic to gabbroic rocks intrude into Palaeoproterozoic, locally sulphide-bearing metasediments in the Nordre Strømfjord region.

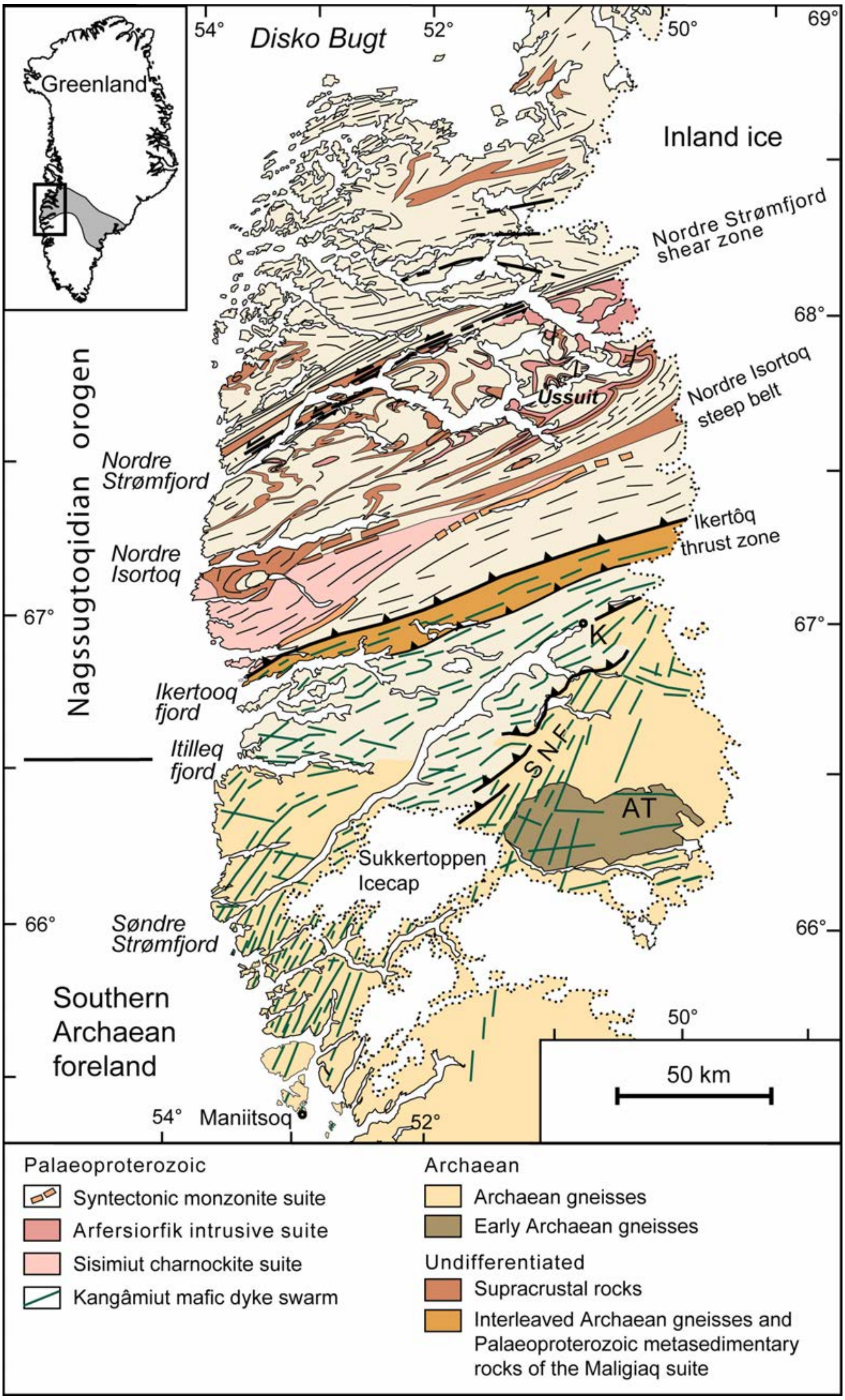

Figure 7. *Geology of the Nagssugtoqidian orogen, modified from van Gool et al. (2002). AT = Aasivik terrane; K = Kangerlussuaq airport; SNF = Southern Nagssugtoqidian Front.*

This Palaeoproterozoic sequence has many similarities to the Tasiuyak gneiss, even though it may not be the direct correlative. Ultramafic rocks in the intrusive suite have been investigated by INCO Ltd. in 1996 (Car 1997), but no economically significant mineral occurrences were found. The ultramafic rocks in this region are of two different types (Kalsbeek & Manatschal 1999), namely 1) Feldspar normative rocks of komatiitic composition, intrusive into the Palaeoproterozoic sedimentary suites; and 2) Olivine normative rocks of dunitic composition, occurring as tectonic lenses on the thrust contact of allochthonous Palaeoproterozoic terranes, and tentatively interpreted as ocean floor remnants.

Occurrences of ultramafic rocks in the inner Nordre Strømfjord region are especially abundant and well-exposed northeast of Ussuit fjord, near the inland ice (Kalsbeek & Manatschal 1999). They also occur in the remainder of the Ussuit map sheet area (see van Gool & Marker 2004, in prep), including previously unknown occurrences of ultramafic and associated mafic rocks within sulphide-bearing metasediments in the eastern part of the Nordre Isortoq belt. A significant difference from the situation in Voisey's Bay, is that the intrusion of the arc magmas occurred before peak metamorphism. Therefore, the supracrustal sequences were presumably not highly metamorphosed at the time of intrusion, and concentration of sulphides may not yet have occurred.

Lenses of ultramafic rocks occur in similar settings in metasediments in the Ammassalik region and are likely correlatives of the ones in the Nordre Strømfjord-Nordre Isortoq region.

Juvenile Palaeoproterozoic calc-alkaline rocks of the Sisimiut and Arfersiorfik intrusive suites contain locally mafic, as well as alkaline components. The former is reported to intrude into interleaved Archaean ortho-and paragneisses in the Sisimiut region (Campbell & Bridgwater 1996) and possibly also Palaeoproterozoic paragneisses. The latter intrudes into, and is closely associated with, metasediments of the Nordre Strømfjord supracrustal suite (Marker *et al.* 1999). These are best known in the Ussuit region, but also occur in the Agto map sheet, although they have rarely been mapped as such. Also these have been investigated by Car (1997).

Ketilidian - Makkovik orogenic belt

The main sources of this short overview are the recent accounts of the Ketilidian orogen by Garde *et al.* (2002) and the Makkovik province by Culshaw *et al.* (2000) and Ketchum *et al.* (2002). Following the Nagssugtoqidian/Torngat continent-continent collision at 1.87–1.84 Ga, the southern margin of the North Atlantic craton became the next important locus of orogenic activity, with the Ketilidian orogen in South Greenland (Fig. 8) and the Makkovik Province in southern Labrador (Fig. 3). There can be no doubt that these Ketilidian and Makkovik belts are on-strike counterparts on either side of the Labrador Sea and Davis Strait, but with a large, 300–400 km wide gap between them (Fig. 5).

Contrary to the collisional Nagssugtoqidian orogeny which mainly resulted in reworking of Archaean crust, the Makkovik-Ketilidian orogeny was dominated by magmatic and tectonic accretion of juvenile magmatic arcs in an overall transpressional environment (Fig. 8). However, there are obvious along-strike differences both within the two belts and between them, and their current interpretations are rather different. The Makkovik Province is characterized by tectonic accretion of several small individual arcs, with the direction of subduction flipping from southwards to northwards. In contrast, the central part of the Ketilidian orogen is dominated by one large, multi-phase, continental batholith, the Julianehåb batholith, which intruded along the southern margin of the Archaean craton over a north-dipping subduction zone. It has no direct counterpart in the Makkovik province.

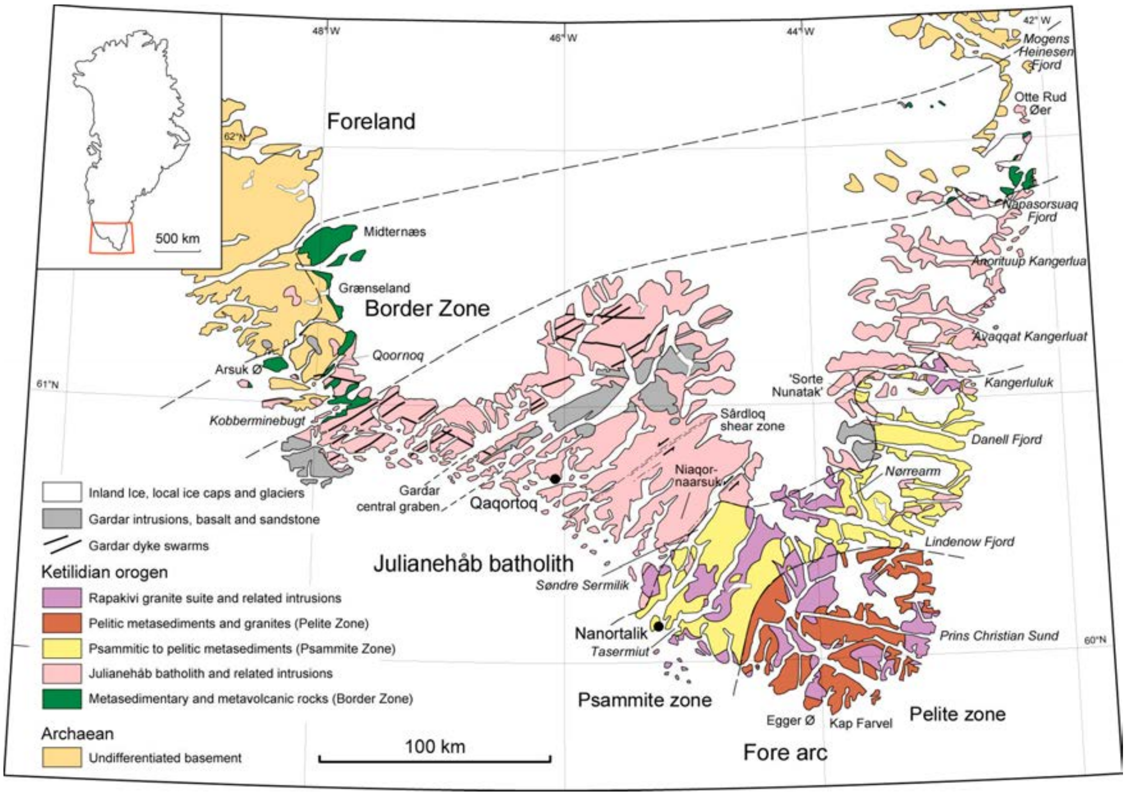

Figure 8. *Geology of the Ketilidian orogen, South Greenland. Modified from Garde et al. (2002).*

The earliest activity associated with the Makkovikian-Ketilidian orogenic cycle was emplacement of the rift-related Kikkertavak dyke swarm at 2.235 Ga in Labrador and 2.130 Ga or older Iggavik dykes in South Greenland, followed by deposition of continental margin sediments and overlying (overthrust) mafic volcanic rocks of transitional or oceanic affinity (Sortis Group in Greenland).

The subsequent evolution and southward expansion of the Makkovik Province is characterised by long-lived arc- and back-arc plutonism and the tectonic accretion of these arc rocks. The magmatic activity is expressed as the 1.895–1.87 Ga Island Harbour Bay plutonic suite, *c.* 1.86 Ga Aillik Group volcanic rocks, 1.815–1.80 Ga Cape Harrison metamorphic suite, *c.* 1.80 Ga syn- to post-collisional granites, and finally 1.74–1.71 Ga A-type granites, perhaps associated with mafic underplating. None of these magmatic suites contain large mafic or anorthositic complexes that were emplaced through thick sulphidic or graphitic metasedimentary sequences.

In the Ketilidian orogen, tectonic emplacement of the Sortis Group volcanic rocks on top of the terrigenous continental margin sediments was succeeded by the main emplacement of the Julianehåb batholith between 1.854–1.795 Ga during sinistral transpression, and tectonic reworking and metamorphism of the Archaean basement and Ketilidian cover took place in the border zone to the north-west. The most likely geographical and chronological equivalents in Labrador of the Julianehåb batholith are the in- and extrusive magmatic rocks of the Aillik and Cape Harrison domains in the central Makkovik province (Fig. 3). Erosion products of the Julianehåb batholith were deposited in a fore-arc basin immediately to the south of the batholith as immature conglomerates, sandstones and graded greywackes besides minor arc-type volcanic rocks. Late members of the batholith were locally emplaced into the proximal part of the fore-arc sediments and gave rise to hydrothermal convection cells with gold mineralisation (Stendal *et al.* 2001; Steenfelt *et al.* 2000; Schjøth *et al.* 2000). One of these gold deposits in Nalunaq is currently being mined by Crew Ltd. The *c.* 8 km large Stendalen gabbro complex was emplaced into the forearc metasedimentary rocks during their subsequent intense deformation and metamorphism at 1.790–1.785 Ga, and was prospected for Cu, Ni and Zn by Soft Rock Ltd. in 1997–1998.

Large, tabloid upper-crustal rapakivi-type magmas and smaller associated noritic bodies were emplaced along the border region between the Julianehåb batholith and fore arc at *c.* 1.755–1.732 Ga, during the final stage of sinistral transpression. These magmas, which are geochemically of A-type, were likely related to simultaneous or previous basic underplating. Granitic A-type plutons of comparable age also occur in the southern part of the Makkovik province. Neither of these intrusive suites in Labrador and Greenland are associated with known mineralisations of their own (except perhaps a small occurrence of uranium in South Greenland), but the previously formed Ketilidian gold deposits were partially remobilised by the rapakivi granites.

Mesoproterozoic rift-associated rocks: The Seal Lake Group and Harp Dykes in Labrador and the Gardar province in South Greenland

The Seal Lake Group and Harp Dykes in Labrador are situated near Hopedale, striding the boundary to the Makkovik and Grenville Provinces (Fig. 3). The Seal Lake Group is a continental, predominantly clastic succession consisting of red beds, quartzite, shale, and basalt flows, intruded by gabbroic sills (1.22–1.25 Ga, Romer *et al.* 1995). The Harp dykes (Meyers & Emslie 1977) form a NE-trending swarm of mafic dykes that intruded at shallow crustal levels into the Mesoproterozoic Harp Lake pluton and the Archaean gneisses of the Hopedale block. The Harp dykes have been interpreted as feeders of lava flows and sills in the Seal Lake Group, although link was questioned by Cadman *et al.* (1994). These 1.273 Ga old dykes (Cadman *et al.* 1994) are time equivalents of the Nain Plutonic Suite. They intruded presumably in an extensional crustal setting, likely an incipient rift, and are potential correlatives of the Gardar province in South Greenland.

The Gardar Igneous Province in South Greenland straddles the boundary between the North Atlantic craton and the Ketilidian mobile belt (Fig. 8). A prominent NE-trending rift zone and graben system was active during the period *c.* 1300 to 1120 Ma, as reviewed by Upton (1974), Emeleus & Upton (1976), Upton & Emeleus (1987), Kalsbeek *et al.* (1990) and Upton *et al*. (2003). The Eriksfjord Formation is a *c.* 3500 m thick continental succession of arkosic and quartzitic sandstones interbedded with and overlain by basalt lava flows. It is only preserved in the central, deepest, part of the rift system. NE-trending swarms of basaltic to trachytic dykes, including giant dykes, of several age groups occur throughout the province. Intrusive activity gave rise to about 15 intrusive centres with alkaline rocks ranging in composition from gabbro to syenite, nepheline syenite, alkali granite and carbonatite. Recently, the large Paatusoq pluton on the eastern side of the Inland Ice (Fig. 8) has also been shown to be of Gardar age (Grocott *et al.* 1999).

The Gardar Province has been regarded as the Greenland counterpart of the Nain Plutonic Suite. The correlation was based mainly on location (Fig. 5) and ages of the rocks, but both the tectonic setting (Gardar rift versus NPS back-arc or anorogenic arc) and lithological characteristics (alkaline suite versus AMCG suite) are different. In the Gardar Province no gabbro-anorthosite bodies are found at the surface, but xenoliths of anorthosite in dolerite dykes, near the central part of the main rift, are taken as evidence for the existence of gabbro-anorthosite bodies at depth (Bridgwater & Harry, 1968; Upton & Emeleus, 1987).

A much more likely correlation can be made between the Gardar Province and the Seal Lake group and Harp dykes. The ages are the same, the tectonic setting of both are NE-to-ENE oriented rifts, and the two parts are located almost in extension of each other across the closed-up Labrador Sea, although the Gardar rift occurs south of the Ketilidian front, while the Harp dykes occur north of the Makkovik front. Moreover, the basaltic rocks in the two parts have the same chemical character, being high-aluminium, transitionally alkaline basalts (e.g., Cadman *et al.*, 1994; Larsen, 1977; Halama *et al.*, 2003). The plutonic equivalents to such basalts are troctolitic gabbros which abound in both areas.

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