Mineralogical Magazine, August 2015, Vol. 79(4), pp. 815–855

Metallogeny of the North Atlantic Craton in Greenland

JOCHEN KOLB[1],*, LEON BAGAS[2] AND MARCO L. FIORENTINI[2]

[1] Department of Petrology and Economic Geology, Geological Survey of Denmark and Greenland,
Øster Voldgade 10, 1350 Copenhagen K, Denmark
[2] Centre for Exploration Targeting, ARC Centre of Excellence for Core to Crust Fluid Systems, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

[*Received 30 October 2014; Accepted 22 January 2015; Associate Editor: R. Mitchell*]

ABSTRACT

The North Atlantic Craton (NAC) extends along the coasts of southern Greenland. At its northern and southern margins, Archaean rocks are overprinted by Palaeoproterozoic orogeny or overlain by younger rocks. Typical granite-greenstone and granite-gneiss complexes represent the entire Archaean, with a hiatus from ~3.55–3.20 Ga. In the granulite- and amphibolite-facies terranes, the metallogeny comprises hypozonal orogenic gold and Ni-PGE-Cr-Ti-V in mafic-ultramafic magmatic systems. Gold occurrences are widespread around and south of the capital, Nuuk. Nickel mineralization in the Maniitsoq Ni project is hosted in the Norite belt; Cr and PGE in Qeqertarssuatsiaq, and Ti-V in Sinarsuk in the Fiskenæsset complex. The lower-grade metamorphic Isua greenstone belt hosts the >1000 Mt Isua iron deposit in an Eoarchaean banded iron formation. Major Neoarchaean shear zones host mesozonal orogenic gold mineralization over considerable strike length in South-West Greenland. The current metallogenic model of the NAC is based on low-resolution data and variable geological understanding, and prospecting has been the main exploration method. In order to generate a robust understanding of the metal endowment, it is necessary to apply an integrated and collective approach. The NAC is similar to other well-endowed Archaean terranes but is underexplored, and is therefore likely to host numerous targets for greenfields exploration.

KEYWORDS: Archaean, Greenland, mineral deposit, economic geology, exploration.

Introduction

ARCHAEAN cratons globally stand for a major contribution to the world's production and resources in many commodities, such as Au, Fe, Cu and Ni. Archaean gold deposits account for ~13% of the cumulative world gold production (Dubé and Gosselin, 2007), with >220 known gold deposits with resources >1 t Au in the Superior Province and Slave Craton of Canada (Robert and Poulsen, 1997) and >160 deposits with resources of >1 t Au known in the Yilgarn Craton in Western Australia (Hagemann and Cassidy, 2000). Other Archaean cratons host world-class and giant deposits, such as the Dharwar Craton of India that includes the Kolar and Hutti deposits, the Sao Francisco Craton in South America, the Kaapvaal Craton in South Africa and the Zimbabwe and Tanzania Cratons in Africa (Goldfarb *et al.*, 2005). Regarding nickel production, the largest contribution derives from komatiite-hosted nickel deposits, where the occurrence of sulfide-hosted Ni is dominated by the Kalgoorlie terrane of the Yilgarn Craton (Barnes and Fiorentini, 2012). In addition, a significant amount of Cu, Au, Zn and Pb production stems from volcanic-hosted massive

---

* E-mail: jkol@geus.dk
DOI: 10.1180/minmag.2015.079.4.01

This paper is published as part of a special set in *Mineralogical Magazine*, Volume **79(4)**, 2015, arising out of the March 2014 NAC Conference on the North Atlantic Craton.

sulfide (VMS) deposits in Archaean greenstone belts in Canada (Lydon, 2007). Archaean iron formations containing >30–45 wt.% Fe account for a major part of the world's Fe ore production and may be the precursor to high-grade martite-goethite or hematite deposits (Clout and Simonson, 2005).

In Southern Greenland, Archaean rocks extend over ~700 km along the western coast and ~500 km along the eastern coast (Fig. 1). These rocks represent the North Atlantic Craton (NAC), which has its largest areal extent in Greenland, although it is covered by the Inland Ice in the central part. The NAC is correlated with the Nain Craton of Canada and the Lewisian complex of Scotland (Bridgwater *et al.*, 1973; Myers, 1976*a*; St-Onge *et al.*, 2009). In the northern cratonic parts, Archaean rocks are deformed and metamorphosed by the ~1900–1680 Ma Nagssugtoqidian orogeny with the southern orogenic front ~100 km south of a proposed suture (Kolb, 2014; Nutman *et al.*, 2008; van Gool *et al.*, 2002). In the south, the NAC is overlain unconformably and intruded by rocks of the Palaeoproterozoic Ketilidian terrane, although ~1800 Ma sinistral strike-slip shear zones represent the contact locally (Garde *et al.*, 2002). The oldest rocks of the craton are ~3890 Ma and the youngest ~2560 Ma, an age span that records almost the entire Archaean aeon with a single gap between ~3550 and 3200 Ma (Nutman *et al.*, 2007*a*, 2010; Næraa *et al.*, 2012).

Total annual exploration expenditure for the whole of Greenland has averaged US$ 90 million (DKK 500 million) since 2007 (Government of Greenland, 2013), but most of this is spent outside the NAC. This a modest expenditure compared to other parts of the world; e.g. ~US$ 350 million spent on gold exploration in Canada alone during 2005 (Lydon, 2007). This reflects the relatively low level of exploration activity in the Archaean of Greenland, where only one gemstone project (Aappaluttoq ruby deposit) is currently developed, one Ni project (Maniitsoq Ni project) is currently drilled, and only ~20 exploration licences are granted.

In this contribution, we review the Archaean geology of the NAC in Greenland and its known mineral deposits and important occurrences. Although large parts of the craton around the capital Nuuk and in the whole of eastern Greenland are granulite-gneiss terranes with complex tectonometamorphic and magmatic evolution, there are still vast areas of granite-greenstone belts that largely resemble those of well endowed Archaean cratons in other parts of the world. Except for the Isua greenstone belt, these areas are located predominantly south of Fiskenæsset and north of the Ketilidian terrane (Fig. 1), which has attracted very little modern research and exploration, despite significant gold occurrences in the region and access *via* ice-free fjords all year round (Kolb *et al.*, 2013*a*). New discoveries of gold occurrences and komatiite horizons during studies by the Geological Survey of Denmark and Greenland (GEUS) in 2008–2010 suggest that the region has significant mineral prospectivity. In this contribution, we also document a series of Au, Ni and Fe mineralized areas hosted in granulite-gneiss terranes that include promising exploration targets and reflect the mineral potential hidden in these terranes.

Exploration and mining history

Mineral exploration in Greenland started with colonization and was intensified in the 19th century resulting in the discovery of the Ivittuut cryolite deposit in South Greenland, which was mined for >130 years (1854–1987). Mining operations in Greenland recently came to an end with the closure of the Nalunaq gold mine at the end of 2013. Two projects in the NAC are advanced and exploitation licences have been granted for mining the Isua iron deposit and the Aappaluttoq ruby deposit (True North Gems). The Seqi olivine deposit north of Nuuk is currently on care-and-maintenance. The company that operated the Kryolite mine at Ivittuut started the first systematic exploration program in the 1960s by regional reconnaissance and subsequent selection of targets for further exploration. Amongst these targets were the Isua iron deposit, the Seqi olivine deposit and the Maniitsoq Ni project. These promising exploration targets attracted other companies that investigated the deposits further, but with varied success. The Ni, platinum-group elements (PGE), Cr and ruby occurrences in the Fiskenæsset area were discovered by the geological survey. Recently, exploration in the NAC has focused on targets in western Greenland, namely the Maniitsoq Ni project (North American Nickel), the Ikertoq Ni project (Northern Shield Resources), various targets in the Fiskenæsset complex (Greenland Gold Resources) and the Storø and Qussuk gold projects in the Godthåbsfjord gold province (Greenland Resources). In the northern NAC area around

FIG. 1. Schematic map of Greenland showing the extent of the Archaean rocks of the North Atlantic Craton (NAC).

Maniitsoq and Sisimiut, Phanerozoic mineralization has been explored in various diamond occurrences and the Sarfartoq *REE*-Nb deposit (Hudson Resources).

The Geological Survey of Greenland (GGU), now GEUS started detailed mapping, geophysical surveys and stream-sediment sampling projects in the late 1960s, which have been continued in regional mineral assessment projects since the early 1990s. The economic geology of Greenland was reviewed in Ball (1922) and only updated in 1973, 1976 and 2009 (Henriksen *et al.*, 2009; Nielsen, 1973, 1976). Geological maps at a scale of 1:100,000 are available for western Greenland from the Godthåbsfjord area southwards, whereas the rest of the NAC is covered at 1:500,000 scale (cf. Fig. 5; www.greenmin.gl). More detailed field maps and reports are stored in the GEUS archives for many parts of southern West Greenland. The NAC of western and eastern Greenland is covered with high-quality regional geophysical data that was acquired by two projects: (1) the AEM Greenland 1994–1998 project including electromagnetic, magnetic and, locally, radiometric surveys; and (2) the Aeromag project for magnetic surveys (Rasmussen and van Gool, 2000; Rasmussen *et al.*, 2001). Airborne hyperspectral data was acquired around Sisimiut in western Greenland (Tukiainen and Thorning, 2005) and airborne radiometric data was acquired in the 1970s (Tukiainen *et al.*, 2003).

Eoarchaean (3850–3600 Ma): the Itsaq gneiss complex

Eoarchaean rocks are widespread in the Nuuk area where they form the Itsaq gneiss complex in the Færingehavn and Isukasia terranes (Fig. 2; Nutman *et al.*, 1996). Two smaller terranes are the Qarliit Tasersuat and Aasivik terrane in the Maniitsoq area (Fig. 2; Nutman *et al.*, 2004; Rosing *et al.*, 2001). Inherited Eoarchaean zircons have been reported from younger Archaean orthogneiss in the Timmiarmiut area of South-East Greenland (Kolb *et al.*, 2013*b*; Næraa *et al.*, 2014) and the Sermiligaarsuk area in South-West Greenland (Nutman *et al.*, 2004). The Qarliit Tasersuat area consists of amphibolite facies banded to migmatitic orthogneiss, augen orthogneiss, amphibolite and magnetite-quartz banded iron formation (Hall, 1978). Sensitive high-resolution ion micro probe (SHRIMP) U-Pb zircon age determination of the orthogneiss define protolith ages of ~3700–3600 Ma with metamorphism at ~3600 Ma (Nutman *et al.*, 2004). The Aasivik terrane is a small granulite-gneiss complex bound by Neoarchaean (~2700 Ma) shear zones to Mesoarchaean terranes (Fig. 2; Rosing *et al.*, 2001). The Aasivik terrane is composed of tonalitic to monzogranitic gneiss and bands of mafic granulite. Age determination using U-Pb SHRIMP on zircon in the orthogneiss yields protolith ages of ~3780–3550 Ma (Rosing *et al.*, 2001).

Orthogneiss of the Itsaq gneiss complex show variable ages interpreted as different pulses of protolith intrusion at 3850, 3810, 3760 and 3690 Ma (Friend and Nutman, 2005*a*). The oldest rocks are ~3890–3840 Ma tonalitic orthogneiss in the Færingehavn terrane and southwest Isukasia terrane (Horie *et al.*, 2010). Migmatitic equivalents have ages of ~3650–3600 Ma similar to monzogranite and mafic intrusive rocks (Friend and Nutman, 2005*a*; Horie *et al.*, 2010; Nutman *et al.*, 1996). Tonalite and quartz diorite gneiss, which display geochemical signatures similar to modern arc rocks, occur in the southwest Isukasia terrane and yield ages of ~3820–3795 Ma (Nutman *et al.*, 1999). Orthogneiss south of Færingehavn and around the mouth of Ameralik Fjord have protolith ages of ~3750–3660 Ma and ~3700 Ma north of the Isua greenstone belt (Horie *et al.*, 2010). The evolution of the Itsaq gneiss complex remains largely unresolved, but can generally be described as development of TTG-like crust starting at ~3890 Ma by hydrous partial melting of mafic crust (Nutman *et al.*, 2007*a*). Orthogneiss with protolith ages of >3840 Ma and ~3750–3700 Ma are geographically distinct, suggesting an evolution in separate terranes (Horie *et al.*, 2010; Nutman *et al.*, 2007*a*). Leucosomes and metamorphic assemblages in the Færingehavn terrane indicate low- to medium-pressure granulite-facies metamorphism at ~3650–3540 Ma (Friend and Nutman, 2005*a*; Horie *et al.*, 2010; Nutman and Friend, 2007; Nutman *et al.*, 2000). Similar ages are reported for the juxtaposition of different terranes in the Isua greenstone belt at upper greenschist- to lower amphibolite-facies conditions (Crowley, 2003; Nutman and Friend, 2009).

Isua greenstone belt

The Isua greenstone belt is divided into three units (Nutman and Friend, 2009): (1) the southern ~3800 Ma terrane; (2) the <3750 Ma dividing sedimentary unit; and (3) the northern ~3700 Ma terrane (Figs 2–3). The southern terrane consists of ultramafic rocks, amphibolite and felsic schist. The amphibolite has locally preserved pillow structures and an island arc tholeiite chemical affinity. The dividing sedimentary unit overlies the southern terrane and consists of metamorphosed banded iron formation (BIF), chert and carbonates. The meta-sedimentary rocks are generally deformed strongly and exhibit local mylonitic fabrics. The overlying northern terrane consists of ultramafic rocks, boninitic and tholeiitic amphibolites, felsic schist, mica schist, garnet-biotite paragneiss and metamorphosed BIF, chert and carbonates (Nutman and Friend, 2009). The BIF of this terrane hosts the Isua iron deposit (Fig. 3). The geochemical affinity of the

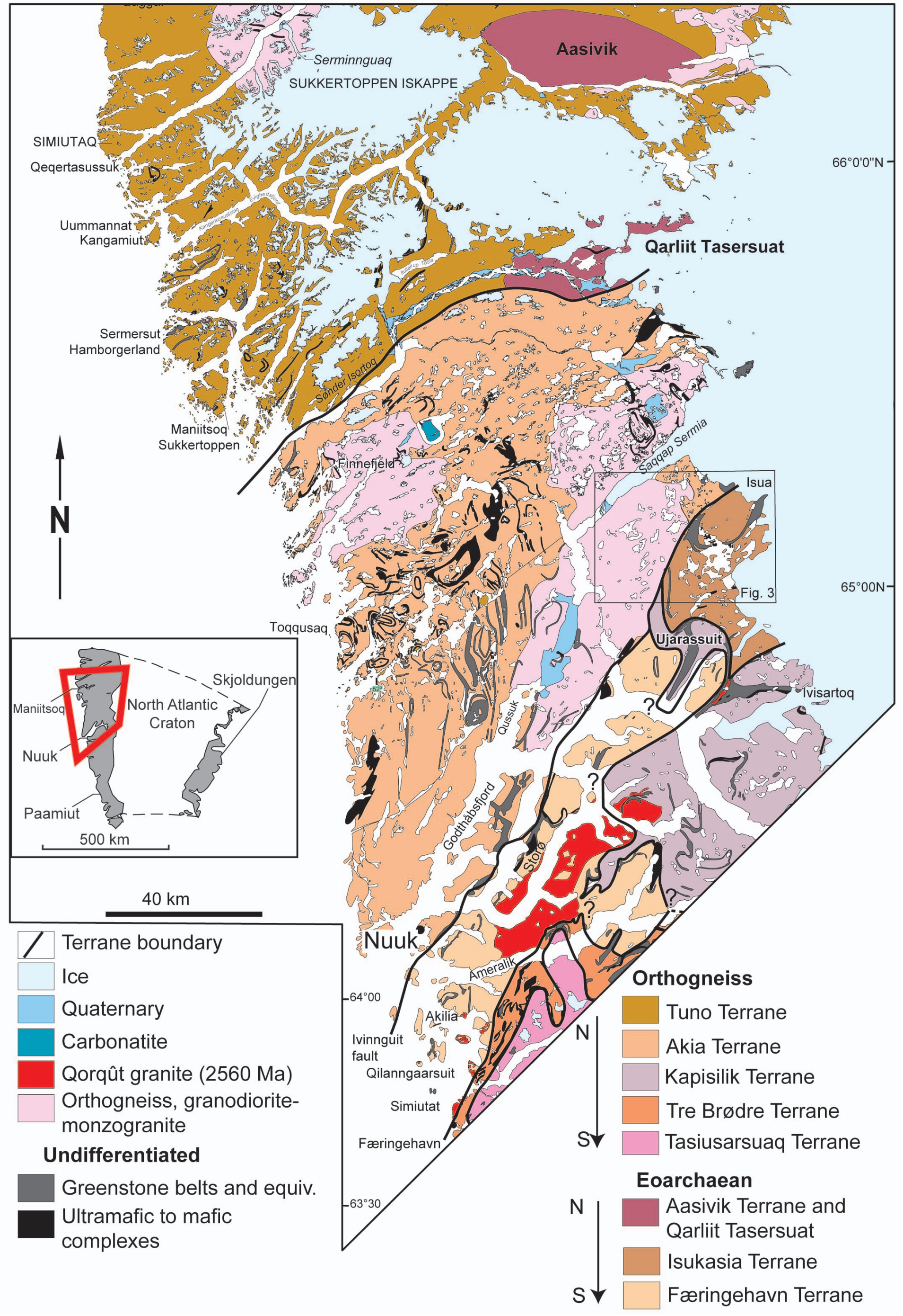


FIG. 2. Schematic geological map of southern West Greenland showing fragments of Eoarchaean terranes; i.e. Aasivik, Qarliit Tasersuat, Isukasia and Færingehavn, of the NAC in tectonic contact with mainly Mesoarchaean terranes (modified after: Allaart, 1982; Rosing *et al.*, 2001; see also Fig. 5).

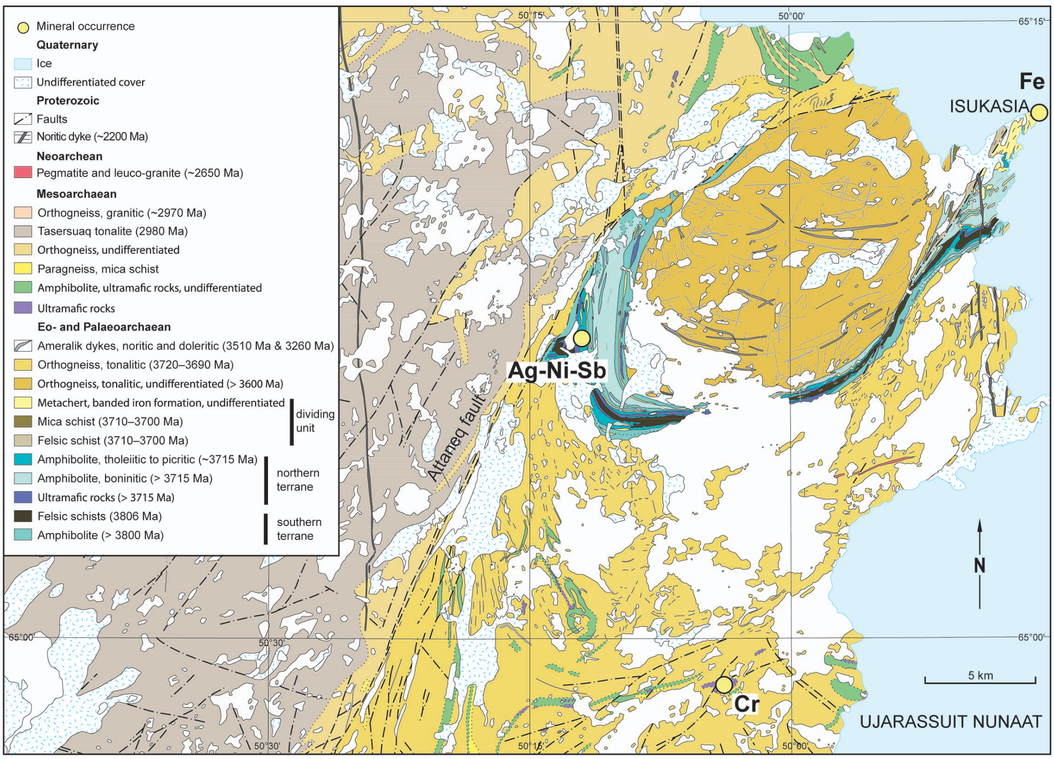


FIG. 3. Geological map of the Isua greenstone belt and Ujarassuit Nunaat area, showing the location of the Fe and Ag-Ni-Sb deposits in the belt and the Cr deposit in ultramafic rocks (modified after: Chadwick and Coe, 1988; Garde, 1995; Nutman and Friend, 2009).

meta-volcanic rocks with island arc tholeiitic and boninitic characteristics was used to interpret the evolution of both terranes in an island arc setting (Polat and Hofmann, 2003). The terranes were subsequently juxtaposed between 3690 Ma and 3660 Ma, based on age data from crosscutting tonalitic dykes (Nutman and Friend, 2009). Crustally-derived granite sheets were emplaced into shear zones 3650−3600 Ma (Nutman and Friend, 2009). Titanite was dated at ~3610 Ma, indicating regional metamorphism at ~500ºC and ~5 kbar during deformation and monzogranite intrusion (Boak and Dymek, 1982; Crowley, 2003; Hayashi *et al.*, 2000).

Akilia group

The Akilia group includes enclaves of mafic and siliceous rocks in the Eoarchaean orthogneiss south of Nuuk with the type locality on Akilia island (Fig. 2; McGregor and Mason, 1977). The group consists of hornblende-diopside amphibolite, garnet amphibolite, hornblende pyroxenite, biotite-garnet-feldspar-sulfide gneiss, aluminous gneiss, serpentinite and BIF, and has an age of ⩾3850−3600 Ma (Friend *et al.*, 2008; Kamber and Moorbath, 1998; Myers and Crowley, 2000; Nutman *et al.*, 1997, 2002; Whitehouse *et al.*, 1999). The BIF has a similar geochemical signature to BIF in the Isua greenstone belt, indicating deposition in a marine setting (Friend *et al.*, 2008). These rocks underwent polyphase or prolonged granulite-facies and upper amphibolite-facies metamorphism and deformation during the Eoarchaean (Friend and Nutman, 2005*a*; Nutman *et al.*, 2000).

Mineral deposits and mineralization

Isua iron deposit

The Isua iron deposit was discovered in 1965 by Kryolitselskabet Øresund A/S during an aeromagnetic survey along the hinge of a large-scale antiform (Nielsen, 1973). The deposit is an oxide-facies BIF in the eastern part of the Isua greenstone belt in the northern ~3700 Ma terrane of the Isua greenstone belt (Figs 3–4*a*). The banding is folded and an axial planar foliation defined by amphibole and magnetite developed at high angles to the banding (Frei *et al.*, 1999). The ore body contains 1107 Mt graded 32.6% Fe and forms a steeply eastward-dipping, 2 km long and 180–450 m thick sheet that increases in thickness with depth (London Mining, 2014). Several other exploration targets consisting of hematite-bearing ore bodies are located underneath the Inland Ice (London Mining, 2014). Only loose boulders of hematite ore are found, which have hematite- and quartz(-magnetite) banding or deformed hematite bands in a yellow jasper matrix (Appel, 1980).

In the Isua iron deposit, the ore consists of <0.30 m wide magnetite bands alternating with quartz bands (Fig. 4*b*; Appel, 1980; Frei *et al.*, 1999; Nielsen, 1973). The mineralization formed as an Algoma-type BIF at 3691 ± 22 Ma by hydrothermal fluids percolating through mid-ocean ridge-type rocks (Frei *et al.*, 1999). A quartz-magnetite-grunerite-stilpnomelane assemblage at the deposit is distinguished from a quartz-magnetite-actinolite-grunerite-ferrodiopside assemblage, which indicates amphibolite-facies metamorphism (Frei *et al.*, 1999). The silicate bands contain specks of disseminated magnetite. In places, magnetite, calcite, dolomite and pyrite form cm-scale discordant veins as a hydrothermal alteration product with ~5 mm alteration zones, which formed during amphibolite-facies metamorphism at 3630 ± 70 Ma (Frei *et al.*, 1999; Nielsen, 1973). Locally, 10 cm wide L-type mylonites are present with cigar-shaped composite aggregates of magnetite, actinolite and quartz, and 10–15 cm wide magnetite-quartz breccia with a magnetite matrix (Appel, 1980). Magnetite is locally replaced by fine-grained hematite (Appel, 1980; Nielsen, 1973).

Other mineral occurrences

In the Isua greenstone belt, polymetallic Ag-Ni-Sb sulfide mineralization is hosted by <5 m wide shear zones and <0.5 m wide quartz veins (Fig. 3; Appel, 1982). The host rocks are weakly carbonatized amphibolite consisting of hornblende, plagioclase, quartz and minor biotite and epidote. The quartz veins are characterized by fuchsite and sulfides. Sulfides (<10 vol.%) form disseminated lenses in the host rock and, locally, semi-massive to massive sulfide lenses (>60 vol.%). The main sulfides are pyrrhotite, chalcopyrite and galena. Ullmannite (NiSbS) is associated spatially with galena or forms inclusions. Ullmannite itself has inclusions of greenockite (CdS), acanthite (Ag_2S) and tetrahedrite. Galena contains inclusions of breithauptite (NiSb), native antimony and dyscrasite (Ag_3Sb). Silver-rich bravoite ($(Fe,Ni,Co)S_2$) is associated spatially with chalcopyrite. Locally, sphalerite and siegenite ($(Ni,Co)_3S_4$) are present instead of the complex Ag-Ni-Cd-Sb sulfide assemblage. The silicate facies BIF of the Isua greenstone belt has local gold content of up to 1.2 g/t, which has not been investigated further (Appel *et al.*, 2003).

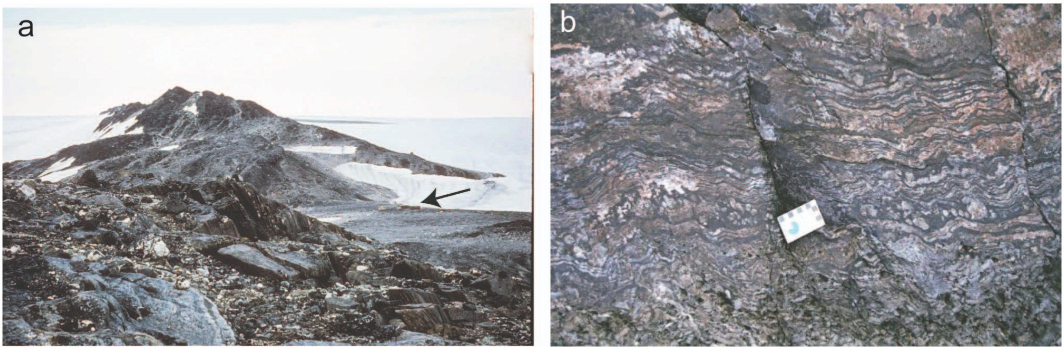


FIG. 4. (*a*) Northeastwards view of the Isua BIF at the Inland ice (M. Ghisler, GEUS). For scale, the camp is marked by an arrow, and this is the planned site for the iron ore mine. (*b*) Characteristic outcrop of the BIF, showing the cm-scale banding of magnetite (dark) and silicate (light grey) bands that are slightly folded and locally brecciated (P.W.U. Appel, GEUS).

In the Ujarassuit Nunaat area, one of the ultramafic intrusions into orthogneiss contains <3 m wide chromitite bands in a 100 m wide and 800 m long layered dunite-harzburgite-gabbro-anorthosite complex (Fig. 3; Rollinson *et al.*, 2002). Four chromitite-dunite layers with mm-scale banding have been recognized. Chromite comprises 40–60 vol.% of the banded chromitite and has Cr/(Cr+Al) ratios of 0.73–0.85 and Fe/(Fe+Mg) ratios of 0.55–0.80 (Rollinson *et al.*, 2002). The chromite is zoned, its composition varies considerably and the deposit is small (Rollinson *et al.*, 2002), which makes this chromite occurrence currently uneconomic.

Late Palaeo- and Mesoarchaean (~3250–2800 Ma)

The Palaeo- and Mesoarchaean successions in the NAC are characterized by the extensive formation of continental crust, which includes TTG-dominated orthogneiss, greenstone belts and their higher-grade metamorphic equivalents in various terranes in the craton described below (Fig. 5; Bagas *et al.*, 2013; Friend and Nutman, 2005*b*; Friend *et al.*, 1996; Kolb *et al.*, 2013*b*; Nutman and Friend, 2007; Nutman *et al.*, 2004; Rosing *et al.*, 2001; Windley and Garde, 2009).

Tuno terrane

The Tuno terrane is the northernmost terrane of the NAC in western Greenland, where the Archaean rocks are deformed during the Palaeoproterozoic Nagssugtoqidian orogeny and are locally interlayered with Palaeoproterozoic strata in thin-skinned thrust sheets (Fig. 5*a*). It is dominated by granulite-facies orthogneiss with lenses and <1 km wide belts of garnet-sillimanite-biotite gneiss and mafic granulite, but only studied on a reconnaissance basis for mapping at 1:500,000 scale (Allaart and Jensen, 1979). Locally, larger metamorphosed gabbro-anorthosite complexes occur north and south of Kangerlussuaq/Søndre Strømfjord (Fig. 5*a*). The intrusion northwest of Sukkertoppen Iskappe is a medium- to coarse-grained granodiorite, which is only deformed at its eastern margin (Fig. 5*a*; Allaart and Jensen, 1979). The granulite-facies rocks are retrogressed in narrow amphibolite-facies shear zones (Fig. 5*a*; Allaart and Jensen, 1979). Emplacement of orthopyroxene-bearing granite is dated at 2769 ± 3 Ma and granulite-facies metamorphism at 2738 ± 6 Ma (Friend and Nutman, 1994). Zircons from garnet-sillimanite-biotite gneiss yield an age range between 3000 and 2850 Ma, with a possible maximum sedimentation age at 2866 ± 8 Ma or at ~2815 Ma, which may also represent a metamorphic overgrowth (Nutman *et al.*, 2004).

Akia terrane

The Akia terrane stretches northwards from the Godthåbsfjord and Nuuk area to a boundary south of Maniitsoq and Sukkertoppen Iskappe, where it is in tectonic contact with the northern Tuno terrane (Figs 5*a*,*b*). In the north, it consists of granulite-facies diorite, quartz-diorite, tonalite, trondhjemite and granodiorite, where the oldest intrusion ages for tonalite yield ~3220 Ma and younger intrusion ages range between 3050 and 3000 Ma (Garde, 1997; Garde *et al.*, 2000). Mafic-ultramafic layered igneous complexes form lenses and bands in the orthogneiss (Figs 5*a*,*b*). Some of these intrusions host Ni-sulfide mineralization such as the Norite belt south and east of the Finnefjeld gneiss (Fig. 5*a*) and PGE mineralization in the Amikoq complex north of Qussuk (Fig. 5*b*). Mafic granulite and sillimanite-garnet gneiss form <2 km wide bands parallel to the regional foliation. Peak metamorphic conditions are estimated at 850 ± 50ºC and 7.9 ± 1.0 kbar (Riciputi *et al.*, 1990). Zircons in sillimanite-garnet gneiss yield metamorphic ages at ~3035 Ma and at 3000 Ma for the metamorphic peak in the Godthåbsfjord area (Garde *et al.*, 2000; Friend and Nutman, 1994). Further to the north, the granulite-facies peak is dated at ~2980 Ma with contemporaneous intrusion of tonalite (Garde *et al.*, 2000). Post peak metamorphic tonalitic and dioritic gneiss yield intrusion ages of ~2975 Ma (Garde *et al.*, 2000). Deformation is characterized by a triple fold interference pattern (Midterhøj, Smalledal and Pâkitsoq deformation stages) with two sets of isoclinal folds that formed during granulite-facies metamorphism (Berthelsen, 1960). The map pattern shows the retrograde amphibolite facies north- to northeast-trending regional-scale folds (Pâkitsoq deformation stage), which are intersected locally by north- to northeast-trending amphibolite-facies shear zones (posthumous deformation stage, Figs 5*a*,*b*; Berthelsen, 1960).

Two larger greenstone belts at the southern margin of the terrane are the Bjørneøen and Qussuk greenstone belts (Fig. 5*b*), which consist of ~3070 Ma leuco-amphibolite, paragneiss and

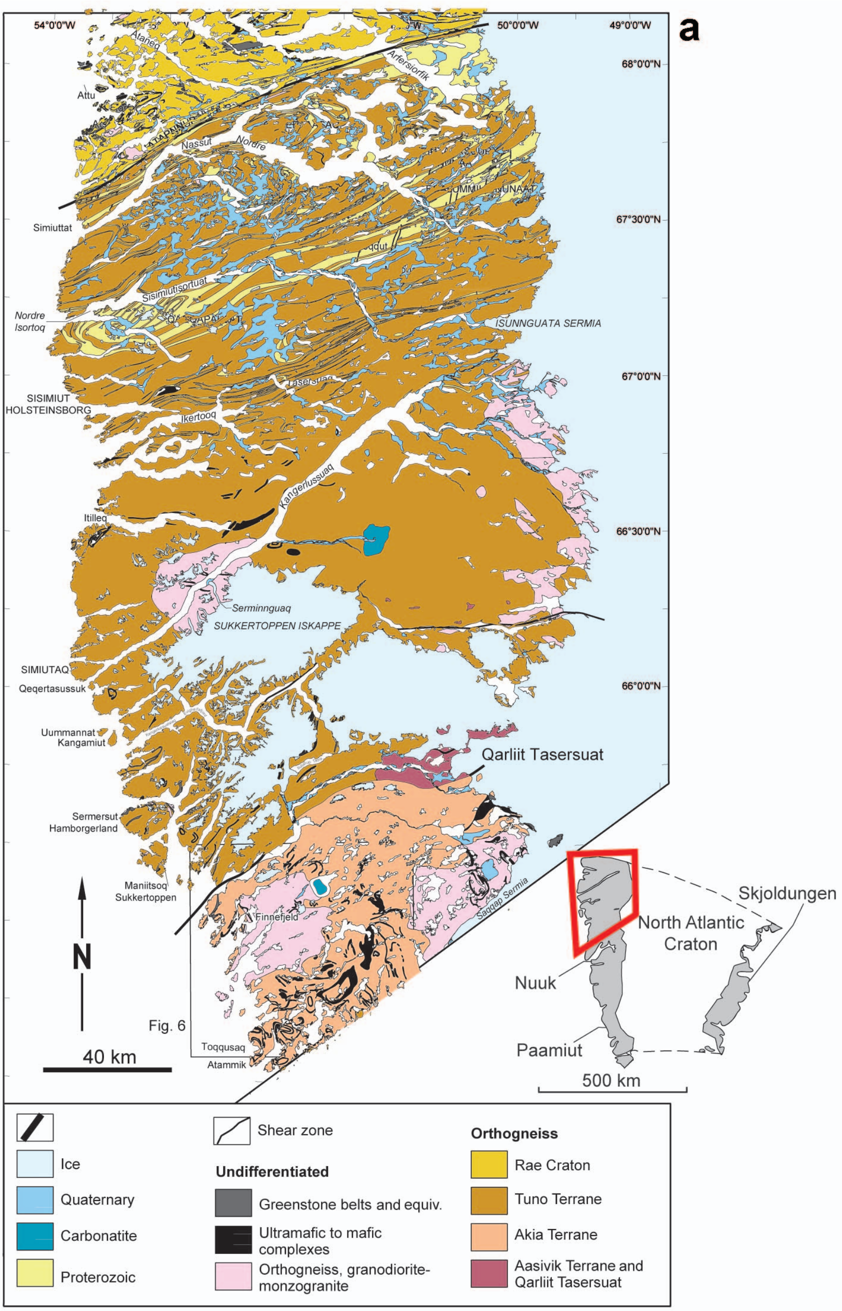
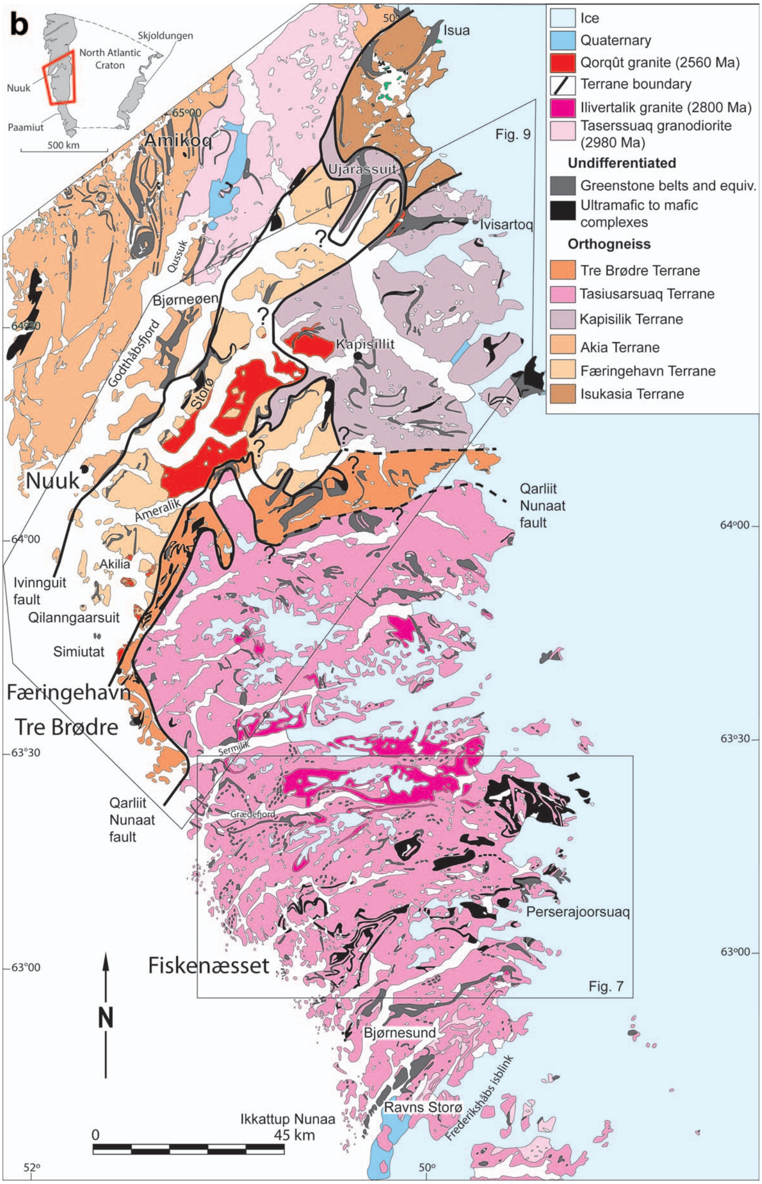
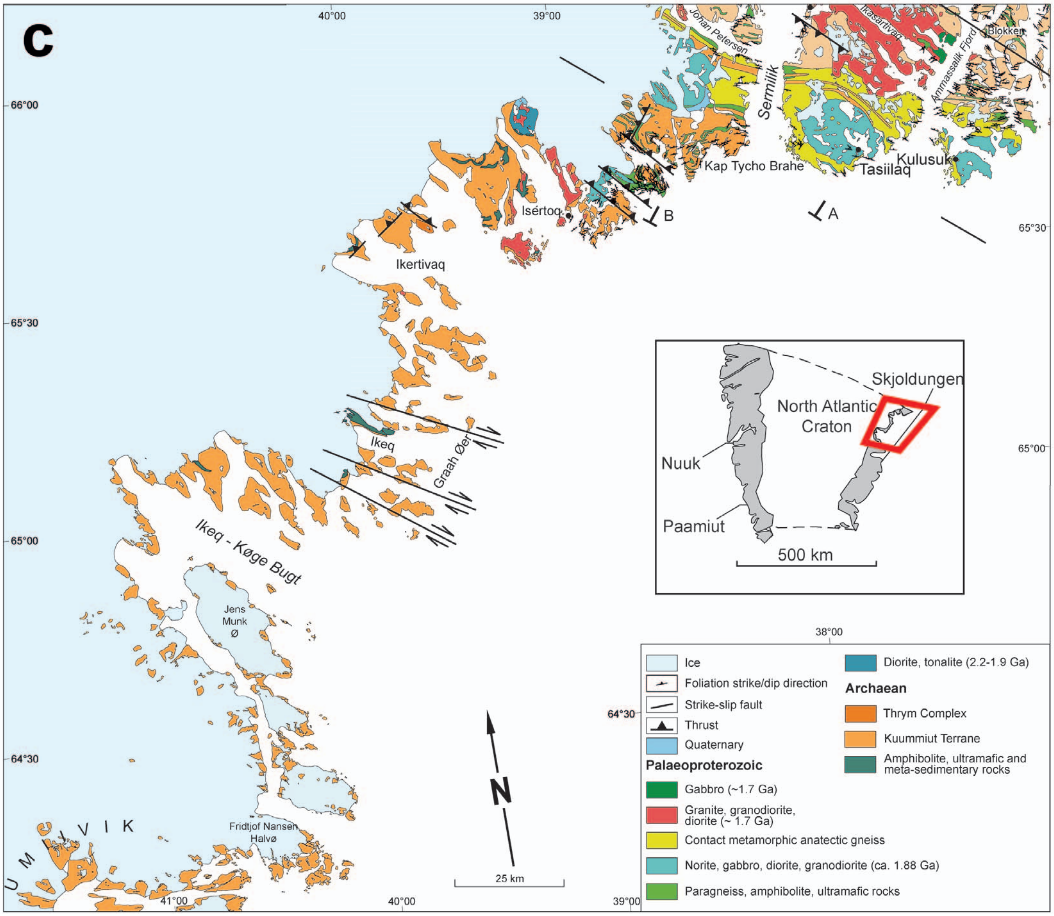


FIG. 5 (*this and following four pages*). Maps of the various terranes of the NAC in southern Greenland: (*a*) southern West Greenland north of Nuuk at the northern contact to the Nagssugtoqidian orogen (modified after Allaart, 1982; Garde and Marker, 2010); (*b*) southern West Greenland in the Nuuk area (modified after Allaart, 1982); (*c,d*) The Thrym complex of South-East Greenland from the northern boundary in the Nagssugtoqidian orogen to the southern continuation in the Ketilidian terrane (modified after Escher, 1990; Garde, 2007*b*; Garde *et al.*, 1999; Kolb, 2014; Kolb *et al.*, 2013*b*); and (*e*) the southern blocks of South-West Greenland and the transition to the Ketilidian terrane in the south (modified after Garde, 2007*b*).



ultramafic rock of possible island arc affinity with a calc-alkaline trend (Garde, 1997, 2007*a*, 2008). The rocks were metamorphosed at amphibolite-facies conditions at ~2990–2970 Ma, at the same time as the granulite-facies peak further north (Garde, 2008). Both greenstone belts host aluminous schist with local sulfide mineralization, interpreted as syngenetic and subsequently metamorphosed mineralization (Garde, 2008; Garde *et al.*, 2012*b*).

Recently, geological features around Finnefjeld have been reinterpreted in terms of a Mesoarchaean bolide impact structure (Garde *et al.*, 2012*a*, 2014). The main arguments are the elliptical aeromagnetic anomaly, curvilinear fracture patterns and superimposed brittle and ductile fabrics, melt fabrics superimposed on migmatites, and microfabrics in quartz and feldspar grains (Garde *et al.*, 2012*a*). The proposed Maniitsoq impact structure has a diameter of 80–100 km

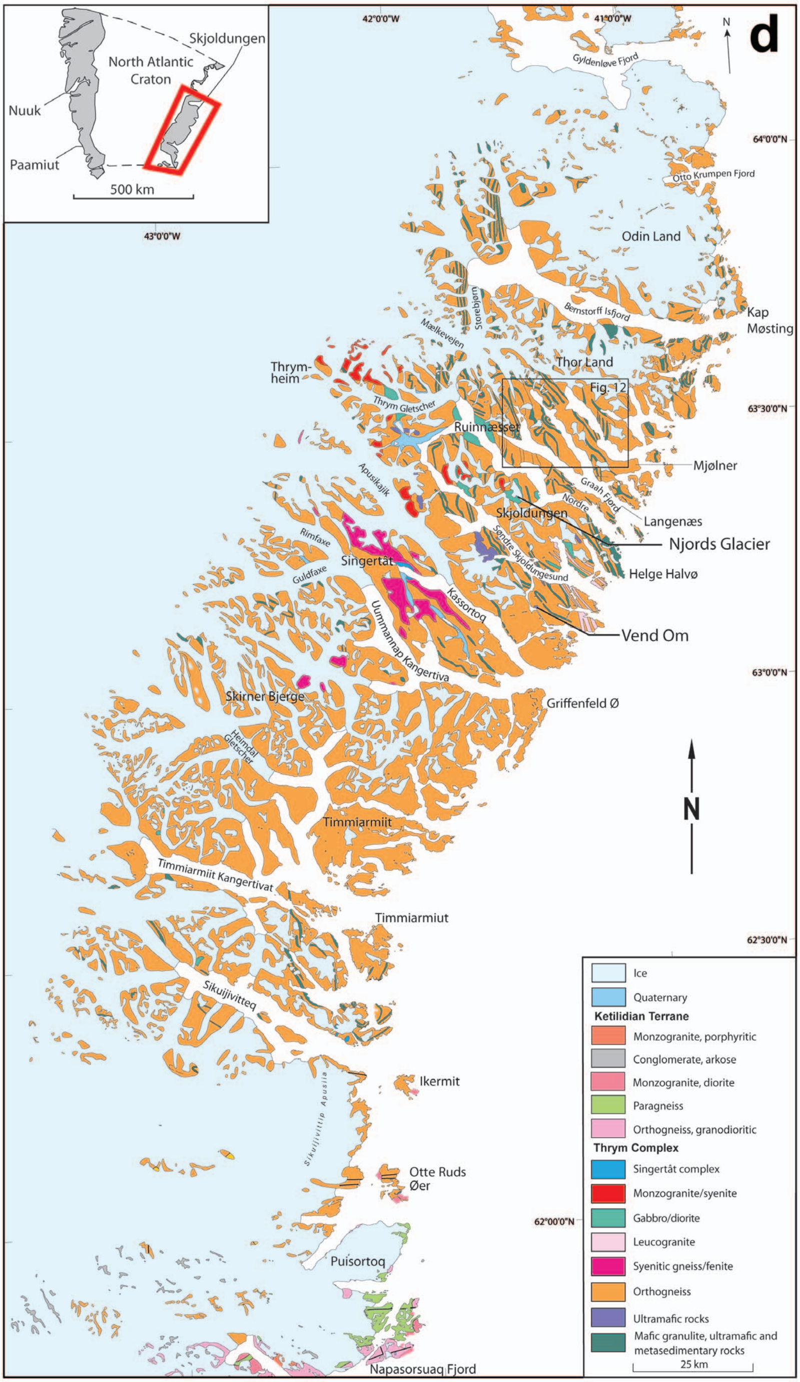


centred on the Finnefjeld gneiss (Figs 5*a* and 6). Resetting of zircons in the Finnefjeld gneiss is argued to have been caused by an impact at ~3.0 Ga (Scherstén and Garde, 2013). The Maniitsoq structure is interpreted to represent a deeply eroded bolide impact structure with no known equivalent on Earth and remains a matter of scientific discussion (Garde *et al.*, 2012*a*, 2014; Reimold *et al.*, 2013).

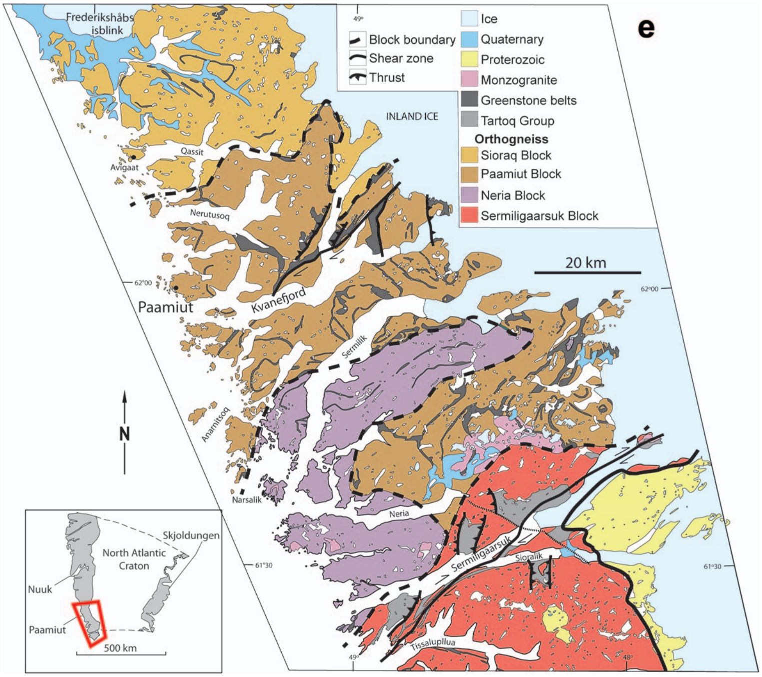
Kapisilik terrane

The Kapisilik terrane is situated northeast of Nuuk around the Kapisillit settlement to the south of the Isukasia and Færingehavn terranes (Fig. 5*b*; Friend and Nutman, 2005*b*). The Kapisilik terrane's southern contact with the Tre Brødre and Tasiusarsuaq terranes is poorly defined (Friend and Nutman, 2005*b*; Nutman and Friend, 2007). The Kapisilik terrane consists of ~3080–2950 Ma tonalitic to monzogranitic orthogneiss and lenses of amphibolite, aluminous gneiss and meta-anorthosite (Friend and Nutman, 2005*b*; Hollis *et al.*, 2006; Nutman and Friend, 2007). The ~3080–3070 Ma Ivisaartoq and Ujarassuit greenstone belts constitute larger belts in the terrane (Friend and Nutman, 2005*b*). Monzogranite and pegmatite were emplaced at ~2820–2800 Ma (Hollis *et al.*, 2006).

The ~3075 Ma Ivisaartoq greenstone belt consists of a tectonostratigraphic sequence of meta-anorthosite, meta-leucogabbro, pyrite-quartz rock, serpentinite, amphibolite, calc-silicate rocks (locally magnetite-bearing), felsic schist, meta-gabbro and meta-diorite (Fig. 5*b*; Chadwick, 1986, 1990; Polat *et al.*, 2007). Primary features such as pillows and ocelli structures indicate a volcanic origin for the amphibolite and



serpentinite (Polat *et al.*, 2007). Meta-gabbro and meta-diorite form sills in the volcanic succession, which includes only minor meta-sedimentary units (Polat *et al.*, 2007, 2008*a*,*b*). The amphibolite and serpentinite are tholeiitic and picritic in composition, respectively (Polat *et al.*, 2007,



2008*a*,*b*). Trace-element geochemical and isotopic data suggest formation in a supra-subduction zone setting from a shallow mantle source when compared to Phanerozoic rocks (Polat *et al.*, 2008*a*,*b*). The Ivisaartoq greenstone belt resembles Phanerozoic forearc ophiolites and intra-oceanic island arcs and is interpreted as dismembered Mesoarchaean supra-subduction oceanic crust (Polat *et al.*, 2008*a*). The rocks subsequently underwent two stages of hydrothermal alteration (Ordóñez-Calderón *et al.*, 2008): (1) calc-silicate alteration of mainly epidote in pillow cores, interstitially and at sill margins, interpreted as ocean-floor metasomatism at greenschist- to amphibolite-facies conditions; and (2) complex calc-silicate hydrothermal alteration during regional metamorphism, which hosts stratabound tungsten mineralization.

The Ujarassuit greenstone belt is connected to the Ivisaartoq greenstone belt and is composed of amphibolite, quartzitic gneiss, serpentinite and biotite schist (Fig. 5*b*; Ordóñez-Calderón *et al.*, 2009). The amphibolite is mainly basaltic with a transitional to tholeiitic affinity, and less andesitic in geochemical composition (Ordóñez-Calderón *et al.*, 2009). Trace-element petrogenetic studies suggest that the greenstone belt was deposited in a similar oceanic supra-subduction zone setting as the Ivisaartoq greenstone belt (Ordóñez-Calderón *et al.*, 2009; Polat *et al.*, 2011).

Tre Brødre terrane and Simiútat supracrustal group

The Tre Brødre terrane forms a ~5 km wide thrust sheet that is situated between the Færingehavn and Tasiusarsuaq terranes (Fig. 5*b*; Nutman and Friend, 2007). The Tre Brødre terrane consists of the ~2829 ± 11 Ma to 2817 ± 9 Ma Ikkattoq orthogneiss, which has a granodioritic composition with minor quartz diorite (Friend *et al.*, 2009). Geochemically, the Ikkattoq orthogneiss resembles modern volcanic arc granites (Friend *et al.*, 2009). In addition, amphibolite, ~2820 Ma felsic schist and ultramafic rocks form lenses in the orthogneiss and a metamorphosed gabbro-anorthosite complex forms sheets or larger enclaves within the orthogneiss (Chadwick and Coe, 1983; Dziggel *et al.*, 2014). Locally, graded-banding in less-deformed units of the complex and a transition from coarse-grained, cumulate-like to finer-grained, banded, sheared rocks is observed, suggesting upwards younging (Owens and Dymek, 1997). The mineralogy is dominated by plagioclase, which locally forms megacrysts, hornblende and minor opaque minerals (Chadwick and Coe, 1983; Owens and Dymek, 1997).

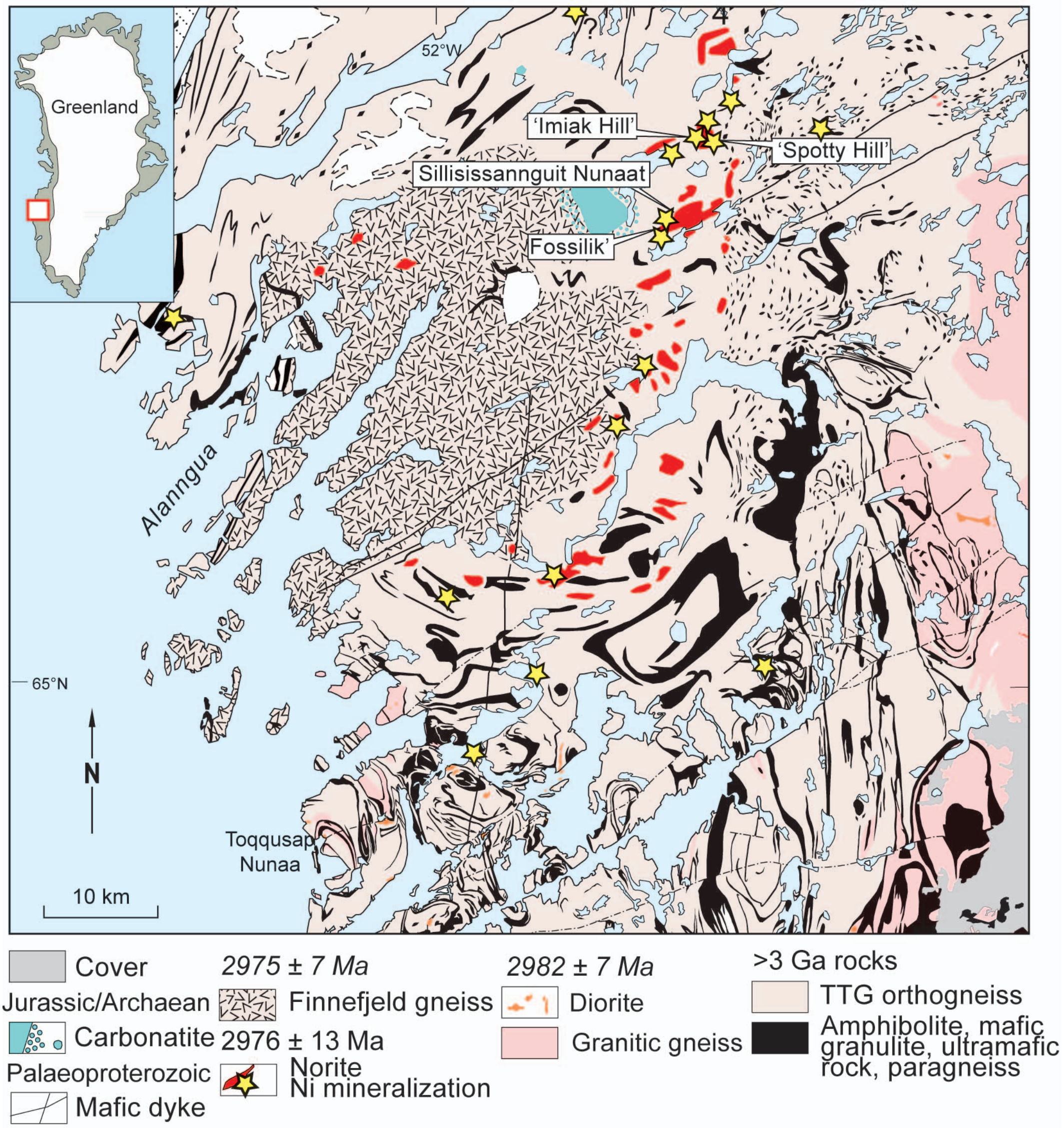


FIG. 6. Geological map of the Maniitsoq area showing the Ni occurrences hosted in various intrusions of the norite belt (modified after Garde *et al.*, 2013).

The type locality for the Simiútat supracrustal group is on the Simiutat and Qilanngaarsuit islands located south of Nuuk (Fig. 5*b*; Dziggel *et al.*, 2014). The sequence includes ultramafic rocks, basaltic amphibolite and aluminous cordierite-orthoamphibole gneiss that originated from ~2840 Ma volcanic protoliths (Friend *et al.*, 1996). Greenstone belts to the north of the islands have similar ages and possibly belong to the same sequence that extends from the Qarliit Nunaat fault, which forms the boundary between the Færingehavn and Tre Brødre terranes to the north and west. The greenstone belts consisting of the Simiútat supracrustal group represent tectonic klippes on Eoarchaean rocks of the Færingehavn terrane (Nutman and Friend, 2007). The Storø greenstone belt may represent the northernmost exponent of the Simiútat supracrustal group

(Fig. 5*b*). It formed between ~2840 and 2700 Ma and consists of amphibolite, garnet-biotite gneiss, quartzite, garnet gneiss, BIF and lenses of meta-ultramafic rocks (Nutman *et al.*, 2007*b*; Scherstén *et al.*, 2012; van Gool *et al.*, 2007). The amphibolite is tholeiitic and has the geochemical signature similar to modern island-arc tectonic settings (Ordóñez-Calderón *et al.*, 2011; Szilas and Garde, 2013). The garnet-biotite gneiss contains ⩽2840 Ma zircons interpreted as detrital in origin and suggesting that it represents a meta-sedimentary rock (Scherstén *et al.*, 2012; Szilas and Garde, 2013). The garnet gneiss is developed at the contact between amphibolite and garnet-biotite gneiss and is interpreted as a result of pre-metamorphic alteration of probably mafic volcanic rocks based on an unusual whole-rock composition and petrogenetic and mass-balance modelling (Szilas and Garde, 2013).

Tasiusarsuaq terrane

The Tasiusarsuaq terrane extends from the undulating Qarliit Nunaat fault north and south of Ameralik to Frederikshåb Isblink in the south (Fig. 5*b*). It consists of TTG-like orthogneiss with zircon U-Pb ages of ~2920−2820 Ma and youngs generally to the north (Compton, 1978; Crowley, 2002; Friend and Nutman, 2001; Kokfelt *et al.*, 2011; Kolb *et al.*, 2012; McGregor *et al.*, 1991; Nutman and Friend, 2007; Nutman *et al.*, 2004; Næraa and Scherstén, 2008; Schjøtte *et al.*, 1989). Amphibolite and mafic granulite with minor meta-sedimentary and meta-ultramafic rocks form small lenses and belts in the north (Chadwick and Coe, 1983; Kolb *et al.*, 2012; Friend *et al.*, 1996). The mafic and ultramafic rocks locally show pillow structures and have a MORB-like trace-element signature (Szilas *et al.*, 2012*b*). In the area north of Fiskenæsset, the 2795 +11/−7 Ma Ilivertalik granite forms *lit-par-lit* sheets of porphyritic monzogranite in a ~20 km wide belt (Fig. 5*b*; Pidgeon and Kalsbeek, 1978).

The Sermilik area includes the several hundred metres thick and eastward-trending Sermilik greenstone belt (Fig. 5*b*; Chadwick and Coe, 1983; Pidgeon and Kalsbeek, 1978), which consists of mafic granulite that is intercalated with minor layers of aluminous felsic schist (Kolb *et al.*, 2013*a*). The Grædefjord greenstone belt to the south contains amphibolite, leucoamphibolite and ultramafic rocks (Fig. 5*b*). Leucoamphibolite is fine-to-medium grained and locally exhibits volcaniclastic structures. The geochemistry suggests that the leucoamphibolite and ultramafic rocks were emplaced in a supra-subduction tectonic setting (Szilas *et al.*, 2013*a*).

The ~2970 Ma Fiskenæsset complex represents a metamorphosed layered mafic-ultramafic igneous complex (Figs 5*b*; Ghisler, 1970; Huang *et al.*, 2012, 2014; Myers, 1985; Polat and Longstaffe, 2014; Polat *et al.*, 2009, 2012; Windley *et al.*, 1973). It consists of a layered gabbro, leucogabbro, ultramafic rock and anorthosite series that hosts chromitite horizons and Ni-PGE and Ti-V mineralization (Ghisler, 1970; Ghisler and Windley, 1967). The complex has well preserved primary structures such as igneous layering and cumulate texture as well as relict primary magmatic minerals, namely olivine, pyroxene, plagioclase, hornblende and chromite (Polat and Longstaffe, 2014). It is interpreted to have formed by intrusion of multiple tholeiitic sills into Mesoarchaean oceanic crust (Polat *et al.*, 2009). Whole-rock trace-element composition of the complex displays a trend from mid-ocean ridge basalt to island-arc basalt, which is interpreted as a transition in the magma source from Mesoarchaean depleted mantle to an intra-oceanic supra-subduction regime (Polat *et al.*, 2009). Later dykes have negative Nb anomalies suggestive of hydrous subarc mantle peridotite, magmatic arc or supra-subduction zone ophiolite as their magma source (Polat *et al.*, 2012). Whole-rock stable oxygen isotope composition of various rock types of the complex are mantle-like (Polat and Longstaffe, 2014). The Fiskenæsset layered mafic-ultramafic igneous complex is interpreted to have formed in a Phanerozoic-like plate tectonic process in an island arc setting similar to Alaskan type layered mafic-ultramafic igneous complexes (Polat and Longstaffe, 2014; Polat *et al.*, 2009).

The Ikkattup Nunaa supracrustal group comprises rocks of the Bjørnesund, Ravns Storø and Perserajoorsuaq greenstone belts (Fig. 5*b*; Keulen *et al.*, 2014; Szilas *et al.*, 2012*a*). They are <10 km wide and <50 km long east- to northeast-trending belts, consisting of amphibolite with local calc-silicate rocks of volcanic and volcaniclastic origin, aluminous schist and lenses of ultramafic rocks. Layered anorthositic and gabbroic rocks north of Bjørensund are attributed to the Fiskenæsset complex (Myers, 1985). The ~3000 Ma amphibolites have a tholeiitic and calc-alkaline geochemistry with trace-element patterns and isotopic signature that resemble modern island arcs (Szilas *et al.*, 2012*a*).

Thrym complex

The Thrym complex forms a 200 km long strip along the southeastern coast of Greenland (Figs 5*c*,*d*; Bagas *et al.*, 2013). The oldest units (~2865–2800 Ma) consist of bands of mafic granulite-ultramafic rocks and bands of mafic granulite-paragneiss, which are up to 1 km wide and several tens of kilometres long (Kolb *et al.*, 2013*b*). These rocks are also present as relict, angular to rounded, cm- to m-scale xenoliths in orthogneiss. Based on their mineralogy and fabric, several generations of orthogneiss are distinguished in the field. Orthopyroxene-bearing, well-foliated orthogneiss forms the main type and porphyritic granitic rocks are present locally and have a less-deformed appearance. Most of the orthogneiss has a granodioritic to quartz monzodioritic composition with rare monzogranitic, tonalitic, monzonitic and quartz dioritic protoliths (Bagas *et al.*, 2013; Kolb *et al.*, 2013*b*). The protoliths were emplaced between ~2865 and 2800 Ma (Kolb *et al.*, 2013*b*). Metamorphic rims on zircons have ages of ~2800–2780 Ma, indicating high-grade metamorphism during the Timmiarmiut orogeny in the late Mesoarchaean (Kolb *et al.*, 2013*b*).

Southern blocks

The area south of the Tasiusarsuaq terrane in western Greenland is divided into four blocks based on differences in metamorphic grade (McGregor and Friend, 1997; Friend and Nutman, 2001; Windley and Garde, 2009). These are: (1) the largely granulite facies Sioraq block; (2) the amphibolite facies Paamiut block; (3) the Neria block or nappe that was largely retrogressed from the granulite facies; and (4) the low-grade metamorphic Sermiligaarsuk block comprising the volcano-sedimentary Tartoq group (Fig. 5*e*).

The Sioraq block underlies the Tasiusarsuaq terrane and is characterized by TTG and, locally, dioritic gneiss (Fig. 5*e*). The emplacement age for the orthogneiss protoliths varies between ~2950 and 2840 Ma (Kokfelt *et al.*, 2011; Friend and Nutman, 2001). Amphibolite, meta-ultramafic rocks and biotite-garnet-sillimanite gneiss form narrow belts in the orthogneiss (McGregor and Friend, 1997; Friend and Nutman, 2001; Windley and Garde, 2009).

The Paamiut block underlies the Sioraq block in the north and is made up of ~2920–2850 Ma biotite-bearing TTG gneiss (Kokfelt *et al.*, 2011; Friend and Nutman, 2001). Up to 1.5 km thick greenstone belts are characterized by the ⩾2930 Ma Kvanefjord amphibolite (Fig. 5*e*; Escher, 1971; Klausen *et al.*, 2011). The stratigraphy is complex and consists of amphibolite, komatiite, biotite-hornblende schist, ultramafic rocks and aluminous gneiss (Escher, 1971; Klausen *et al.*, 2011; Kolb, 2011). Primary volcanic and volcaniclastic structures are well-preserved and the geochemical signature resembles a modern tectonic setting in an evolving oceanic to island-arc environment (Klausen *et al.*, 2011; Kolb, 2011).

The Neria block or nappe overlies the Paamiut block and is dominated by ~2980–2870 Ma tonalitic and dioritic orthogneiss (Fig. 5*e*; McGregor and Friend, 1997; Friend and Nutman, 2001; Nutman and Kalsbeek, 1994; Windley and Garde, 2009). Lenses of metamorphosed mafic rocks and leucogabbro-melanogabbro-anorthosite rocks are common (McGregor and Friend, 1997; Windley and Garde, 2009).

The Sermiligaarsuk block underlies the Neria block and consists of ⩽3000 Ma TTG gneiss and several greenstone belts of the Tartoq group (Fig. 5*e*; Nutman *et al.*, 2004; Windley, 2009). The ~3190 Ma Tartoq group consists of amphibolite, hornblende-chlorite schist, chlorite schist, chlorite-ankerite schist and minor meta-conglomerate, quartzite, mica schist, quartz-muscovite gneiss, BIF, serpentinite and talc-schist (Higgins and Bondesen, 1966; Kisters *et al.*, 2012; Szilas *et al.*, 2013*b*). The mafic rocks are tholeiitic and have trace-element characteristics similar to magmas generated in modern arc tectonic settings; thus, they may represent remnants of a Mesoarchaean oceanic crust that formed in a suprasubduction zone geodynamic setting (Szilas *et al.*, 2013*b*).

Paamiut Event

The southern blocks of the craton in western Greenland are relatively poorly studied in terms of their tectonometamorphic evolution and timing of events. Sporadic data from metamorphic zircon overgrowths yield similar ages in the Paamiut and Neria blocks, indicating a metamorphic and tectonic event at ~2850–2830 Ma (Friend and Nutman, 2001; Nutman and Kalsbeek, 1994; Nutman *et al.*, 2004). Metamorphism in the Paamiut block did not exceed amphibolite facies

(Escher, 1971; Kolb, 2011; Kolb *et al.*, 2013*a*; McGregor and Friend, 1997). Rocks of the Neria block show widespread retrogression in the amphibolite facies after granulite facies peak metamorphism (McGregor and Friend, 1997). Early folds with a northeast–southwest trending axial trace were formed in the Paamiut and Neria blocks (Fig. 5*e*; Kolb, 2011; McGregor and Friend, 1997). The Paamiut and Sermiligaarsuk blocks are characterized by thrust belts of unknown age that are likely to be relatively young and are described in the section on the Neoarchaean Tasiusarsuaq orogeny (Kisters *et al.*, 2012; Kolb, 2011; Kolb *et al.*, 2013*a*).

Mineral deposits and mineralization

The Maniitsoq Ni Project

The Maniitsoq structure (Berthelsen, 1960; Garde, 1991; Garde *et al.*, 2012*a*) is situated in southern West Greenland, in the north-central part of the North Atlantic Craton (Figs 5*a* and 6). Within the structure, numerous mafic intrusions can typically be described as steeply to vertically dipping pipe- and sheet-like bodies emplaced within Mesoarchaean orthogneiss and greenstone belt equivalents. The intrusions consist largely of variable proportions of orthopyroxene and andesine with medium- to coarse-grained granular textures and localized rhythmic magmatic layering (Secher, 1983). The bulk composition of the intrusions displays a broadly uniform trace-element distribution pattern with high Mg, Cr and Ni contents (Garde, 1991; Garde *et al.*, 2012*a*).

In the southern part of the Maniitsoq structure, a series of lower-crustal mafic intrusions locally contain Ni-Cu sulfides. Mineralization associated with these intrusions, which are collectively known as the Norite belt (Nielsen, 1976; Secher, 1983), was discovered in the early 1960s by the mining and exploration company Kryolitselskabet Øresund A/S (Fig. 6). More recently, Cominco Ltd., Falconbridge Ltd. and NunaMinerals A/S did reconnaissance work in the area and in 2011 the availability of improved airborne geophysical exploration tools prompted the Canadian company North American Nickel Inc. (NAN) to resume exploration. The known extent of the Norite belt is shown in Fig. 6, but at least a few additional, unmapped bodies are known to occur east and west of the main belt.

The significant Ni occurrences discovered to date are spatially and genetically associated with the mafic intrusions (Fig. 6). The mineralized lenses commonly comprise heavily disseminated to near massive sulfide, commonly with abundant 0.2–5.0 cm subangular-to-subrounded inclusions of norite, forming breccia-like textures. In most cases, strongly mineralized zones containing matrix to massive horizons are surrounded by a broad halo of weaker, disseminated mineralization. The mineralized lenses rarely exceed 25 m in length (Secher, 1983) and contain a typical magmatic sulfide assemblage including pyrrhotite-pentlandite-chalcopyrite-pyrite, with accessory magnetite and ilmenite (Nielsen, 1976). Typical Ni contents of the mineralized lenses vary between 1 and 2 wt.% over several metres, with additional 0.1–0.6 wt.% Cu, 0.01–0.07 wt.% Co and very low PGE abundances, generally <0.2 ppm Pt and Pd, and Au in the ppb range, although Pd-dominated PGE-enrichment at ppm levels occurs sporadically (North American Nickel, 2014; Secher, 2001).

The main geological features of the mafic intrusions and their associated sulfide mineralization indicate that they were formed in highly dynamic systems such as open-end conduits, where magma flux was enhanced and the attainment of sulfide-supersaturation was favoured. These features include the occurrence of rocks crystallized from high-temperature ultramafic liquids, geochemical evidence of significant crustal contamination (e.g. elevated lithophile incompatible trace elements), the large Ni tenor in the sulfides and the widespread presence of inclusion-bearing, breccia-like rock types, that reflect the dynamic emplacement conditions of these intrusions (Garde *et al.*, 2012*a*). However, the lithospheric architecture and geodynamic environment, in which these intrusions were emplaced is presently unclear.

Garde *et al.* (2012*a*) put forward the working hypothesis that the emplacement of the mafic intrusions of the Norite belt is a direct consequence of the formation of a large crater created by the impact of an extraterrestrial bolide at ~3.0 Ga. According to this model, the Maniitsoq structure may constitute the deeply eroded, lower-crustal remains of such an impact. In this scenario, the structure would comprise a 35 km × 50 km-sized core of heterolitic breccia containing blocks and locally finely welded fragments of country rocks (mainly Finnefjeld orthogneiss and amphibolite), surrounded by a peripheral, annular, less damaged zone with a diameter of >200 km (Fig. 6; Garde, 2010; Garde *et al.*, 2012*a*). Intense hydrothermal alteration and related, fluid-induced, partial melting have affected the entire structure (Garde, 2010; Garde *et al.*, 2012*a*). While the possibility of impact-induced mantle melting associated with giant impacts has previously been discussed in the literature (Jones *et al.*, 2002), the strong spatial and genetic association between the Maniitsoq impact crater and the emplacement of mantle-derived melts within the Norite belt represents the first possible documented case (Garde *et al.*, 2012*a*). It is important to emphasize that unlike the 1.85 Ga Sudbury impact structure in Canada, where a group of world-class Ni-Cu deposits formed at the base of a differentiated impact melt sheet (Eckstrand and Hulbert, 2007), at Maniitsoq the Ni-Cu mineralization is hosted in mafic intrusions, which supposedly formed when localized mantle melting occurred in response to the shock associated with the Maniitsoq impact. However, mantle-derived mafic intrusions that locally contain Ni-Cu sulfide mineralization are known to occur in a wide range of geodynamic settings (e.g. Voisey's Bay, Nebo-Babel, Jinchuan), both within and along the boundaries of cratons (Begg *et al.*, 2010), and without any documented link to impact structures. In addition, available geochronological data indicate that the intrusive bodies of the Norite belt may have been emplaced at 2976 ± 13 Ma (Garde *et al.*, 2000), which would be considerably younger than the 'impact' age of ~3.0 Ga. Hence, the proposed impact and the widespread emplacement of mafic magmas may not be linked necessarily and the genesis of Ni-Cu mineralization at Maniitsoq remains to be evaluated.

The Fiskenæsset complex Ni-PGE-Cr-Ti-V mineralization

The ~2970 Ma Fiskenæsset complex represents a metamorphosed layered mafic-ultramafic igneous complex (Ghisler, 1970; Huang *et al.*, 2012, 2014; Myers, 1985; Polat and Longstaffe, 2014; Polat *et al.*, 2009, 2012; Windley *et al.*, 1973). The complex has a strike length of >200 km and covers ~5000 km^2 between the coast and inland ice to the east (Figs 5*b* and 7*a*). Following the work of Myers (1985), the stratigraphy of the Fiskenæsset complex consists of a layered succession from the bottom up comprising a lower gabbro unit (~50 m) followed by an ultramafic unit (~40 m) with mineral-graded dunite, peridotite and hornblendite (Fig. 7*b*). Above, there are a lower leucogabbro unit (~50 m) with minor ultramafic layers and a middle gabbro unit (~50 m) with layers of anorthosite, ultramafic rocks and peridotite (hornblende-orthopyroxene-spinel; Fig. 8*a*). Above these units follow an upper leucogabbro

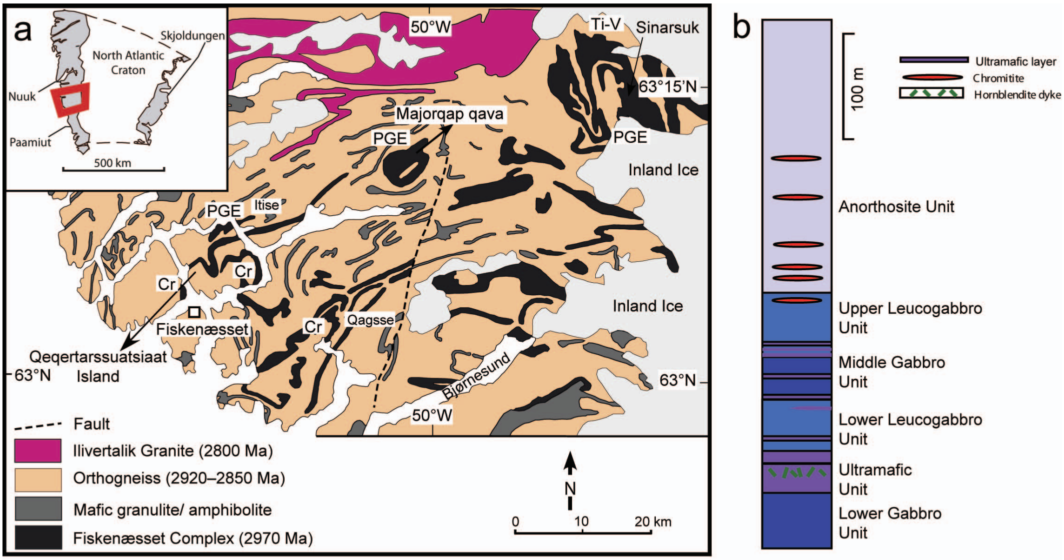


FIG. 7. (*a*) Geological map of the Fiskenæsset complex (modified after Myers, 1976*b*; Polat *et al.*, 2009). (*b*) Simplified stratigraphy of the Fiskenæsset complex (modified after Myers, 1985; Polat *et al.*, 2009).

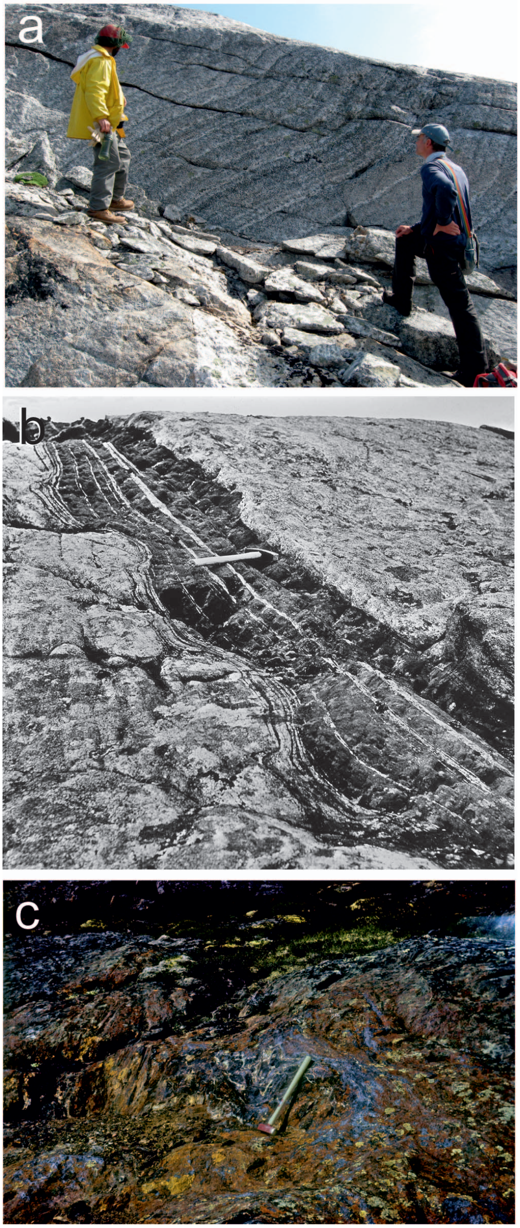


FIG. 8. (*a*) Photograph of layering in metamorphosed leucogabbro from Itise. (*b*) Characteristic chromite band in anorthosite from the Qagsse area. (*c*) Weathered sulfide-rich rock of the Fiskenæsset complex. For locations see Fig. 7.

unit (~60 m) with abundant chromitite bands, an anorthosite unit (~250 m) with massive chromitite and finally the upper gabbro unit (~50 m).

The Fiskenæsset complex is highly prospective for a series of mineralized environments, including chromitite horizons, Ni-PGE sulfide mineralization and Ti-V oxide mineralization (Ghisler, 1970; Ghisler and Windley, 1967). The complex has been deformed repeatedly and metamorphosed in amphibolite facies and, locally, granulite facies. We describe below the known mineralized occurrences associated with the emplacement and crystallization of the Fiskenæsset layered intrusion in the context of the knowledge acquired during exploration carried out in the last three decades, and in light of the large body of literature now available on mineral systems associated with layered intrusions.

Ghisler and Windley (1967) and subsequently Ghisler (1970) were the first to describe the chromitites from the Fiskenæsset complex. Unlike occurrences in other layered intrusions, where chromitite seams are generally associated with the lowermost ultramafic layers, potentially economic chromitite seams in the Fiskenæsset complex are concentrated in the upper part of the intrusion, where leucogabbro and anorthosite are more common (Ghisler, 1970). In the anorthosite unit, up to six stratigraphic levels of chromitite horizons can be found. Single layers are 0.5–10 cm thick, alternating with anorthosite layers of similar thickness (Rollinson *et al.*, 2010). Locally, the width of the chromitite horizons ranges from 50 cm to 3 m (Fig. 8*b*), and widths of up to 20 m are recorded in some localities, possibly due to thickening of the stratigraphy associated with isoclinal folding or magmatic slumping at the time of emplacement (Ghisler, 1970; Appel, 1992).

According to Appel (1992), in the Fiskenæsset area there are two types of chromitite: hornblende chromitite and augen chromitite. The hornblende chromitite is characterized by a most unusual mineral assemblage: highly calcic plagioclase, iron-rich aluminous chromite, hydromagmatic amphibole and biotite. In the layers, chromite grains are generally subhedral-to-euhedral in shape, commonly with straight grain boundaries, and have diameters of 100 μm to 2 mm. The layers are generally 1 cm thick, but much thicker layers of up to 1 m have been documented (Appel, 1992). The augen chromitite consists of <2 cm large plagioclase augen in a matrix of chromite and hornblende, and augen chromitite horizons are usually <1 m wide, but greater thicknesses of up to 20 m have been documented (Appel, 1992).

In the hornblende chromitite type, chromite constitutes up to 60 vol.% of the layer, whereas in the augen type the proportion is less at ~50 vol.% (Appel, 1992). Rutile, ilmenite and sulfides occur as accessory minerals in both chromitite types (Appel, 1992).

Recently, exploration activities were mostly carried out in the Qeqertarssuatsiaat area (Fig. 7), where in addition to scattered PGE mineralization associated with peridotite, bronzitite, pyroxenite and hornblendite (Fig. 8*c*), the main economic target is a near-continuous, shallow-dipping chromite body averaging 2 m in width (<20 m wide locally) traceable for 3.0–3.5 km along strike with an inferred resource estimate of eight million tons of chromite (21st North, 2013). The lens averages 42 wt.% chromite, with a Cr_2O_3 content of ~32 wt.% and a Fe/Cr ratio of 0.8. The Fiskenæsset complex as a whole is estimated to contain at least 100 Mt of chromite ore to a depth of 100 m (Ghisler, 1976).

At Sinarsuk, a series of vanadium-bearing, titaniferous, magnetite-ilmenite-rich predominantly gabbroic rocks occur in the middle gabbro stratigraphic unit (Fig. 7; following the classification of Myers, 1985). The mineralized rocks follow the general layering of the anorthosite complex and are expressed as a pronounced northwest-trending anomaly on aeromagnetic maps. The concordance between the Ti-V mineralized gabbro and the layering of the complex as well as internal gradual lithological changes indicate a primary origin for the oxide-rich layers. The Ti-V mineralized package is up to 250 m wide and can be traced on the surface for >13 km (Østergaard, 2013). It mainly comprises disseminated- grading into semi-massive- to massive-oxide layers at the base of the sequence (Østergaard, 2013). Multiple repeated sections of semi-massive to massive oxide bands are <1 m thick and occur within a well-developed layered leucogabbro.

Orthomagmatic Ni-Cu-PGE sulfide mineralization is associated commonly with layered complexes worldwide. In the Fiskenæsset complex, the highest PGE grades occur within sulfide-bearing ultramafic units (Fig. 8*c*), but are restricted to certain stratigraphic levels and in specific areas within the complex; i.e., the Ghisler reef in the Qeqertarssuatsiaat area (Fig. 7; Appel, 1993; Appel *et al.*, 2011). However, at present there is no clear understanding of the key processes that formed the known PGE mineralization. In the 1970s, Platinomino A/S searched for Ni-Cu-PGE reef-type deposits after the discovery of an ~1 m wide bronzitite layer with discrete chromite banding containing minor nickel-sulfides with highest grades up to 3.5 g/t PGE. In 1991 and 2008–2009, GEUS investigated the Qeqertarssuatsiaat area and found the ~5 m wide Ghisler reef with up to 2.0 ppm Pt+Pd+Au, which can be traced over ~5 km (Appel, 1993; Appel *et al.*, 2011). The PGE+Au are hosted in froodite ($PdBi_2$), sobolevskite (Pt,PdBi), insizwaite ($PtBi_2$), maslovite (PtTeBi), michenerite (Pd,PtTeBi), keithconnite (Pd_{1-x}Te,Bi), electrum and other alloys and sulfosalts (Appel *et al.*, 2011). Present knowledge indicates that PGEs are concentrated in hornblendite in the upper part of the middle gabbro unit overlying the upper leucogabbro unit (Appel, 1993; Appel *et al.*, 2011).

Sparse data on PGE trends in other parts of the stratigraphy, including variable PGE ratios and overall abrupt variations in concentrations, possibly indicate processes such as magma replenishment and/or localized sulfide saturation. Considering the size of the Fiskenæsset complex, the relative remoteness of the area, the limited exploration and the fact that PGE mineralization occurs commonly in extremely narrow reefs, it is considered likely that PGE mineralization occurs at several levels within the Fiskenæsset stratigraphy, as observed in other layered mafic intrusions (e.g. Stillwater, Bushveld). The potential also exists for the occurrence of other types of orthomagmatic mineralization, including conduit-hosted systems genetically and spatially associated with the larger intrusion and containing Ni-Cu sulfides.

The Amikoq PGE mineralization

Fragments of layered mafic-ultramafic rocks occur in orthogneiss of the Akia terrane in the Fiskefjord area (Fig. 5*b*). The Amikoq layered mafic-ultramafic complex is formed by a continuous chain of fragments that is up to 150 m thick in a doubly folded unit with a north–south extent of ~30 km (Armitage, 2009; Nilsson *et al.*, 2010). It is generally in tectonic contact with orthogneiss at the base and amphibolite at the top, although locally intrusive relationships are preserved in particular in the hanging wall of the complex. The complex lithology is dominated by leuconorite that is interlayered with coarse-grained pyroxenite, peridotite and dunite with local chromitite seams (Armitage, 2009; Nilsson *et al.*, 2010). Zircons from coarse-grained pyroxenite yield a laser ablation sector field inductively coupled

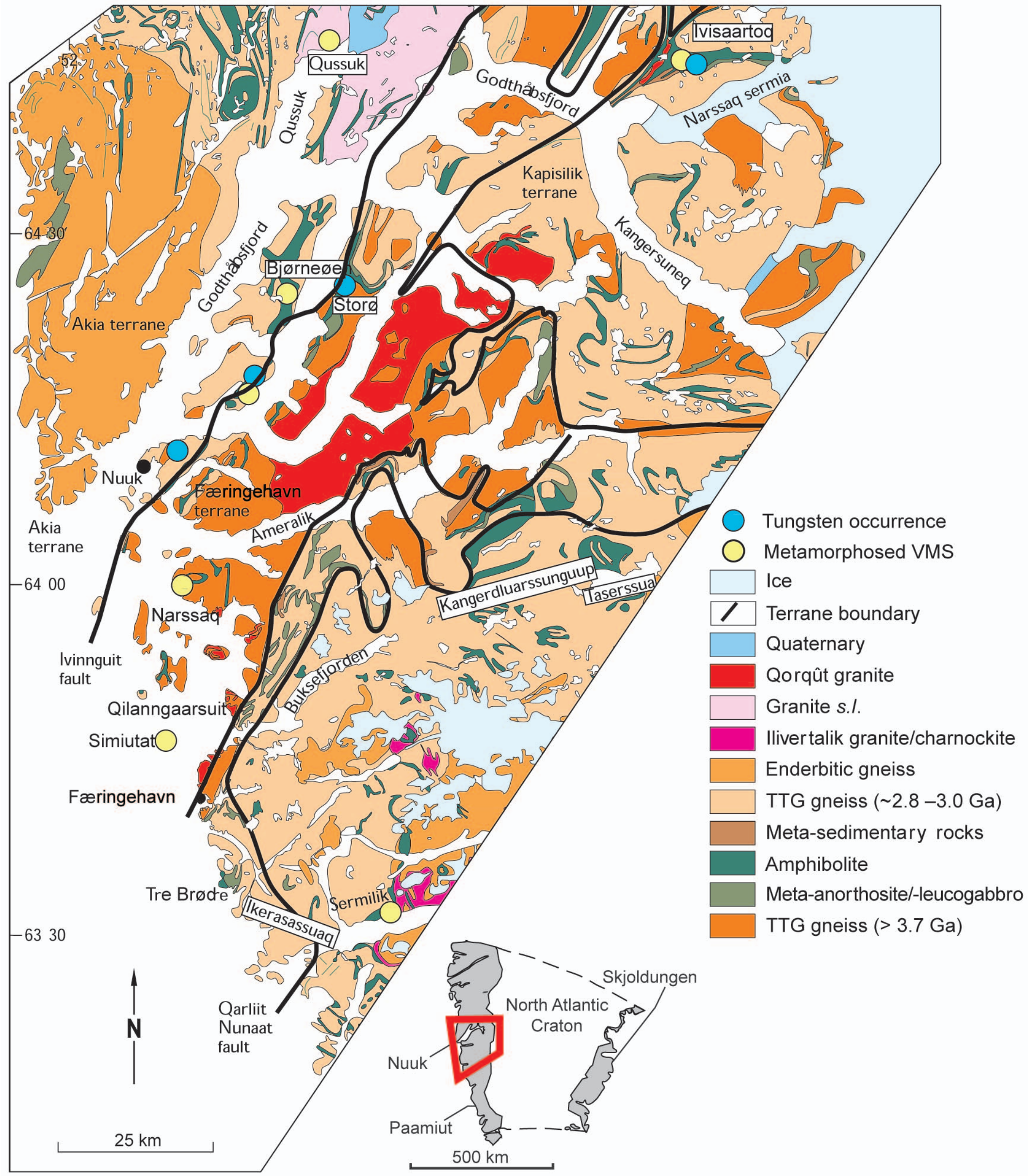


FIG. 9. Geological map of the Nuuk area in southern West Greenland showing the various tungsten and metamorphosed VMS occurrences (modified after Allaart, 1982).

plasma mass spectrometry Pb-Pb age of 2990 ± 3 Ma interpreted as either representing the emplacement age or the metamorphic overprint (Nilsson *et al.*, 2010).

PGE mineralization is hosted in a 2–4 m thick reef at the base of the leuconorite that has been explored by scree and channel sampling and diamond drilling for 2.5 km, but the overall fold geometry and extent of mineralization has not been investigated by NunaMinerals A/S and Impala Platinum Holdings Ltd (Armitage, 2009). The Pt+Pd grades range between 0.4–1.0 ppm

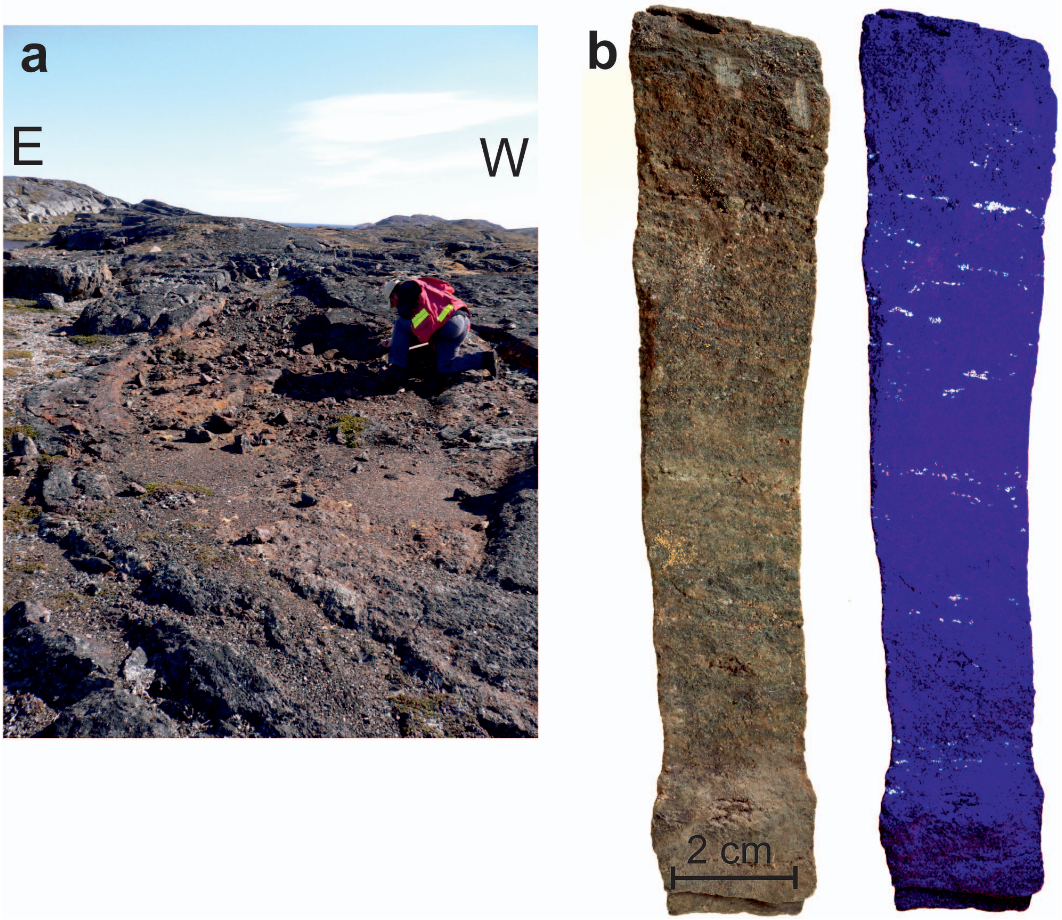


FIG. 10. (*a*) Typical metre-scale lensoid outcrop of massive to semi-massive sulfide mineralization on Simiutat. (*b*) Characteristic disseminated scheelite mineralization in banded amphibolite from the Godthåbsfjord area in normal (left) and ultraviolet light (right).

with a maximum at 1256 ppb Pt+Pd (Armitage, 2009). Another <0.5 m thick and ~500 m long PGE reef occurs at the base of coarse-grained pyroxenite and has high-Rh anomalies (Armitage, 2009). The genesis of the mineralization is not investigated in detail, but geochemistry suggests partial redistribution of PGE and Au during metamorphism and deformation (Armitage, 2009).

Metamorphosed VMS occurrences

Several small occurrences of massive to semi-massive sulfide hosted in greenstone belts are known in the Godthåbsfjord area and north of Sermilik (Fig. 9). The Ivisaartoq greenstone belt hosts minor gold mineralization in <50 cm wide massive to semi-massive pyrite layers that occur in zones several tens of metres wide in amphibolite, and can be traced >1 km along strike (Appel, 1988*a*). On Bjørneøen, Pb-Zn-Cu-sulfide mineralization is hosted as stringers in two, 8 m wide foliation-parallel bands in amphibolite. Pyrite, pyrrhotite and chalcopyrite form disseminated mineralization of 5–10 vol.% sulfides in quartz-garnet micaschist. Combined Pb-Zn-Cu contents are very small at <0.2 wt.% (Stendal, 2011). South of Nuuk, polymetallic Cu-Ag-Pb-Bi±W-Sn-Zn sulfide mineralization occurs mainly on Simiutat island (Appel, 1988*a*). The mineralization forms narrow horizons of a few metres width and several hundreds of metres strike length (Fig. 10*a*). It is composed of magnetite, pyrite, pyrrhotite, chalcopyrite, molybdenite, sphalerite and gahnite. Maximum values for selected metals are 9.0 wt.% Pb, 1.1 wt.% Zn, 0.2 wt.% Cu, 0.12 wt.% Sn, 924 ppm Bi and 19 ppm Ag (Appel, 1988*a*; Kolb *et al.*, 2009). The sulfide mineralization is surrounded by paragneiss and amphibolite that have an unusual mineral assemblage of garnet-quartz-biotite-tourmaline-cordierite-sillimanite-staurolite and garnet-anthophyllite-gedrite-tourmaline-hornblende-plagioclase, respectively (Appel, 1988*a*; Kolb *et al.*, 2009). This mineral assemblage in rocks surrounding sulfide mineralization is characteristic of metamorphosed alteration assemblages of VMS mineral systems in amphibolite-facies terranes (Hodges and Manojlovic, 1993). Although mineralization is restricted at the surface, a systematic exploration of the 3D geometry has never been carried out by drilling or geophysical methods.

Stratabound tungsten occurrences

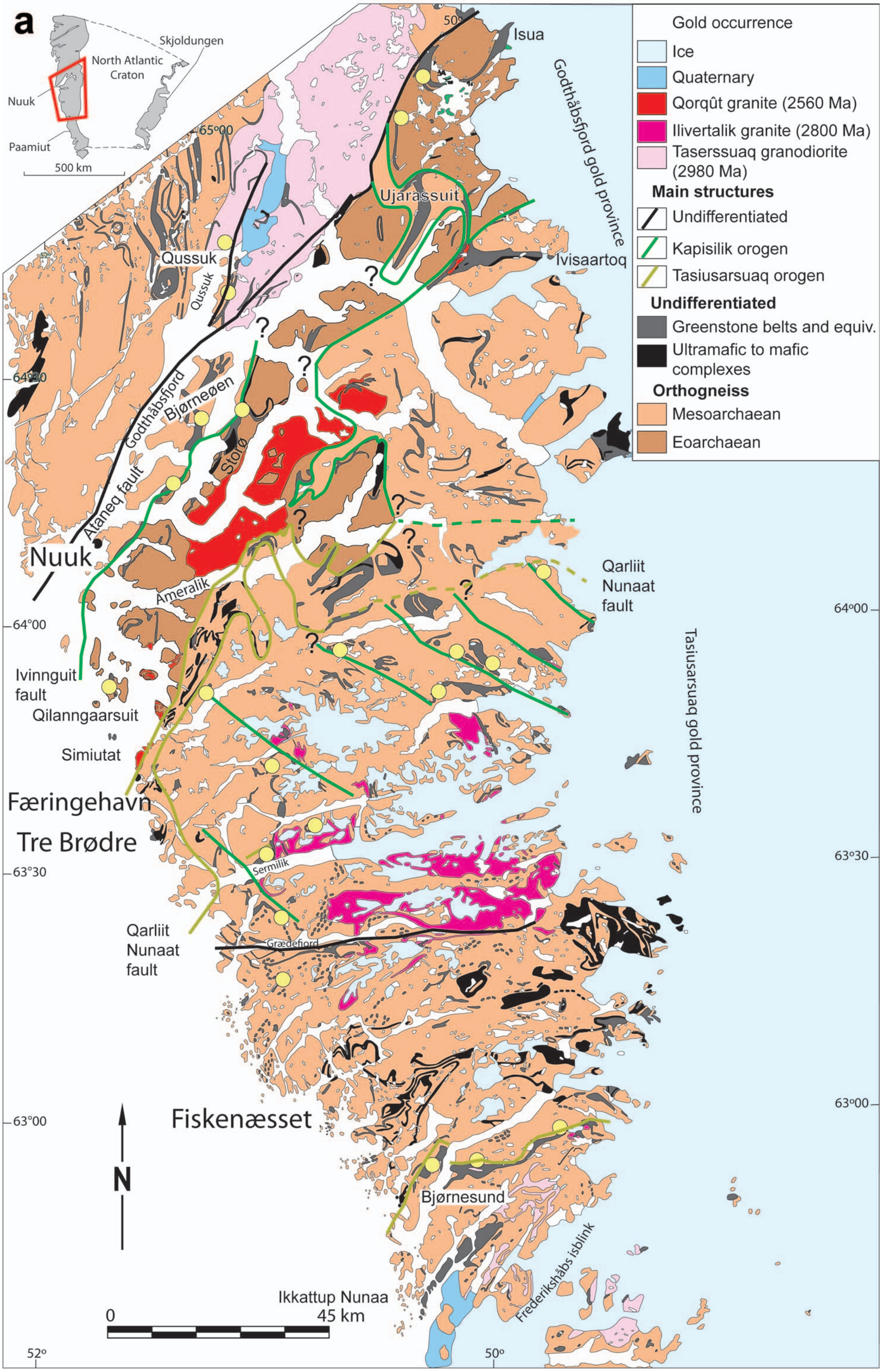
Scheelite is a common mineral in stream-sediment samples of the NAC in southern West Greenland, but was only identified in a larger extent in the Ivisaartoq greenstone belt, in three occurrences northeast of Nuuk and north of Sermilik (Fig. 9; Appel, 1986, 1990). Scheelite mineralization is disseminated in <10 m wide banded amphibolite with local porphyroblasts and in veins (Fig. 10*b*). In general, it is associated spatially with tourmaline and calc-silicate assemblages in the banded amphibolite (Appel, 1986, 1988*b*). Locally, tourmalinites contain <10 vol.% scheelite and form thin <1 m wide stratiform layers that can be followed several kilometres along strike (Appel, 1988b). On Bjørneøen the mineralization is weak, grading <0.2 wt.% W (Fig. 9; Stendal, 2011). The Ivisaartoq scheelite mineralization grading at ~0.45 wt.% W is found in stringers, in two ~3.5 and 10 km long horizons in ultramafic rocks and calc-silicate-rich amphibolite (Fig. 9; Appel, 1986, 1988*b*, 1990). The mineral assemblage is scheelite, tourmaline, magnetite, clinopyroxene, epidote, quartz, titanite and calcite (Appel, 1986, 1988*b*; Appel *et al.*, 2005). Locally, the mineralization is highly concentrated in boudin necks and overprints an early foliation (Appel *et al.*, 2005). The stratabound and continuous scheelite mineralization in amphibolite and the association with tourmalinites was used to argue for a submarine exhalative genesis of both scheelite and tourmaline, and local remobilization into veins and boudin necks during subsequent metamorphism and deformation (Appel, 1986, 1988*b*). However, the skarn-type mineral assemblage and the fact that the mineralization overprints an early deformation fabric suggest an epigenetic formation (Appel *et al.*, 2005). Abundant spatially associated pegmatite crosscuts the mineralization, and there is no association between other felsic intrusions and possible skarn W mineralization, suggesting that possible metamorphic hydrothermal activity was associated with the formation of the W mineralization at Ivisaartoq (Appel *et al.*, 2005).

Neoarchaean (2800–2500 Ma)

The Neoarchaean is mainly characterized by deformation and metamorphism of the Meso- to Eoarchaean terranes (Kolb *et al.*, 2012, 2013*b*; Nutman and Friend, 2007). Two larger granite complexes were emplaced in the region (Figs 5*b*,*e*): (1) the ~2560 Ma Qôrqut granite (Nutman *et al.*, 2010); and (2) granites north of Sermiligaarsuk (Kokfelt *et al.*, 2011).

Tasiusarsuaq orogen

The Tasiusarsuaq orogen extends from south of Nuuk to Frederikshåb isblink 400 km to the south, and possibly further, where a contemporaneous tectonometamorphic history is recorded in the Sioraq block (Figs 5*b*,*e* and 11). Crustal melts, leucosomes and metamorphic zircon overgrowths indicate peak metamorphism at ~2830–2800 Ma in the Tasiusarsuaq terrane and the Sioraq block and at ~2750 Ma in the Tre Brødre terrane (Crowley, 2002; Dziggel *et al.*, 2014; Kolb *et al.*, 2012; Friend and Nutman, 2001; Pidgeon and Kalsbeek, 1978). In the granulite-facies northern part of the Tasiusarsuaq terrane, *PT* conditions were ~850ºC and 7.5 kbar, followed by near-isobaric cooling to ~700ºC and 6.5–7.0 kbar (Dziggel *et al.*, 2012). Peak metamorphic conditions south of Sermilik occurred in amphibolite facies at 580–630ºC and 4–6 kbar in the Bjørnesund area (Schumacher *et al.*, 2011). The Sioraq block is a granulite-facies terrane (McGregor and Friend, 1997), and structures related to the early metamorphism here are only preserved in low-strain areas as relict foliation (Kolb *et al.*, 2012). The penetrative structures north of Sermilik are northwest-vergent fold-and-thrust structures (Kolb *et al.*, 2012). They formed during the ~2800–2700 Ma northwest-southeast shortening and near-isobaric cooling to


a
Skjoldungen
North Atlantic Craton
Nuuk
Paamiut
500 km
65°00
50°
Isua
Godthåbsfjord gold province
Ujarassuit
Ivisaartoq
Qussuk
Qussuk
64°30
Godthåbsfjord
Bjørneøen
Storø
Ataneq fault
Nuuk
Ameralik
64°00
Qarliit Nunaat fault
Tasiusarsuaq gold province
64°00
Ivinnguit fault
Qilanngaarsuit
Simiutat
Færingehavn
Tre Brødre
63°30
Sermilik
63°30
Qarliit Nunaat fault
Grædefiord
63°00
Fiskenæsset
63°00
N
Bjørnesund
Frederikshåbs isblink
Ikkattup Nunaa
0
45 km
52°
50°
Gold occurrence
Ice
Quaternary
Qorqût granite (2560 Ma)
Ilivertalik granite (2800 Ma)
Taserssuaq granodiorite (2980 Ma)
Main structures
Undifferentiated
Kapisilik orogen
Tasiusarsuaq orogen
Undifferentiated
Greenstone belts and equiv.
Ultramafic to mafic complexes
Orthogneiss
Mesoarchaean
Eoarchaean

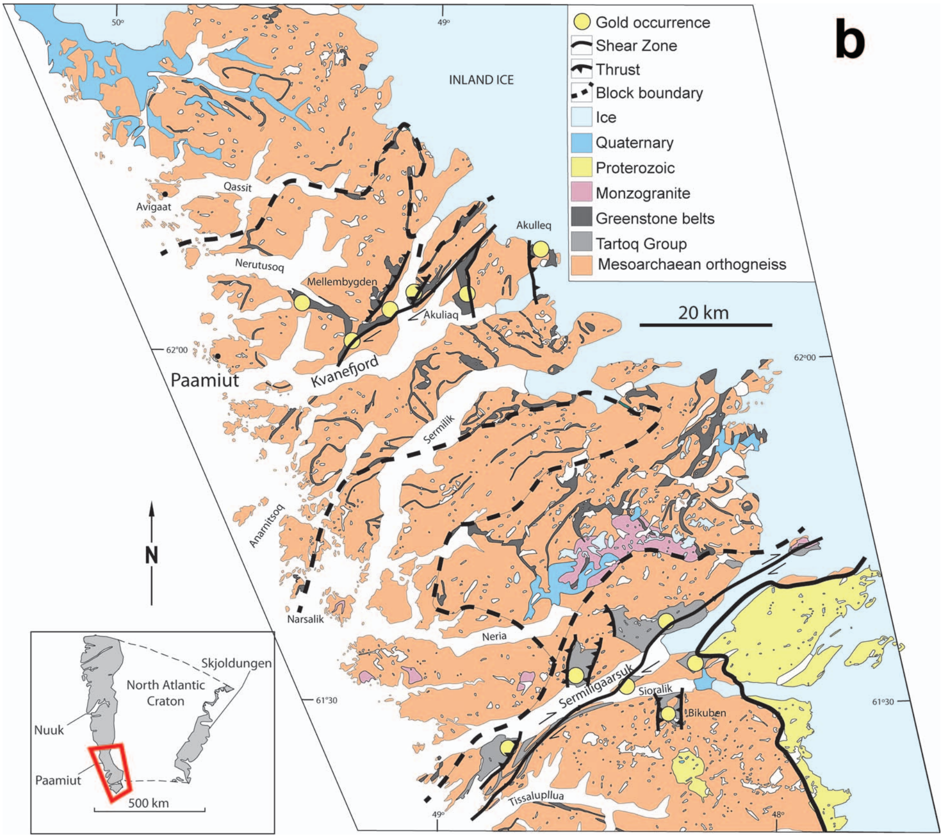


FIG. 11. Geological maps modified from Figs 5*b*,*e* showing the various orogenic gold occurrences and the major structures related to Neoarchaean orogeny (modified after: Kolb *et al.*, 2013*a*): (*a*) (*facing page*) the Godthåbsfjord and Tasiusarsuaq gold provinces in the Nuuk area; and (*b*) (*above*) the Paamiut and Tartoq gold provinces in South-West Greenland.

amphibolite-facies conditions (Dziggel *et al.*, 2012).

The *PT* conditions in the Tre Brødre terrane are estimated at 620–660ºC and 6 kbar, similar to retrogression in the Tasiusarsuaq terrane (Dziggel *et al.*, 2014). Several southeast-vergent back thrusts north of Sermilik locally host gold mineralization (Fig. 11*a*; Kolb *et al.*, 2010), while complex fold interference patterns characterize the structural grain south of Sermilik (Myers, 1985). The Bjørnesund and Ravns Storø greenstone belts are also characterized by northwest-vergent fold-and-thrust structures that probably formed relatively early in the orogen at ~2840 Ma or during a different tectonometamorphic event (Fig. 11*a*; Keulen *et al.*, 2011, 2014). Orogenic magmatism is represented by numerous pegmatites, granitic sheets, leucosomes and the larger ~2800 Ma Ilivertalik granite north of Fiskenæsset (Figs 5*b* and 11*a*; Kolb *et al.*, 2012; Pidgeon and Kalsbeek, 1978).

The detailed orogenic history of the Sioraq block and the Tasiusarsuaq terrane south of Sermilik is unconstrained, but the northern part of the Tre Brødre and Tasiusarsuaq terranes formed at an orogenic margin in a compressive regime (Dziggel *et al.*, 2014; Kolb *et al.*, 2012). After cessation of subduction-related magmatism at ~2800 Ma, the Tre Brødre and Tasiusarsuaq terranes underwent northwest-vergent compression under high-grade metamorphic conditions and near-isobaric cooling (Dziggel *et al.*, 2012; Kolb *et al.*, 2012). The deformation in the region is characterized by large-scale low-angle shear zones and related folds (Kolb *et al.*, 2012). High-pressure metamorphism and isothermal decompression culminated at ~2715–2700 Ma to the north in the Færingehavn terrane and Simiútat supracrustal group, following continent-continent collision between the Eoarchaean Færingehavn terrane and the Tre Brødre and Tasiusarsuaq terranes (Dziggel *et al.*, 2014; Nutman and Friend, 2007). Thrust sheets of the Simiútat supracrustal group extend as far as Storø northeast of Nuuk (Fig. 11*a*).

In the Paamiut and Sermiligaarsuk blocks, similar east- to southeast-vergent deformation postdates deposition of volcaniclastic rocks in the Tartôq group at 2842 ± 6 Ma (Nutman *et al.*, 2004), and predates Palaeoproterozoic mafic dykes (Kisters *et al.*, 2012; Kolb, 2011). Greenstone belt equivalents in the eastern parts of both blocks (Akulleq, Bikuben) show granulite-facies metamorphic assemblages and show early, complex, north-trending reverse shear zones and duplex structures including isoclinal folds, which record coaxial east- and west-vergent deformation during high-grade metamorphism (Figs 5*e* and 11*b*; Kisters *et al.*, 2012; Kolb, 2011). Peak *PT* conditions are estimated at >6–7 kbar and >800–850ºC (van Hinsberg *et al.*, 2010). The structures are interpreted to be related to burial of the greenstone sequences during east- to southeast-directed subduction (Kisters *et al.*, 2012). The retrograde exhumation took place along coaxial amphibolite and greenschist-facies shear zones and resulted in north-trending fold structures at various scales (Kisters *et al.*, 2012; Kolb, 2011). The overall geometry resembles an east-vergent fold-and-thrust belt geometry, stacking progressively lower-grade metamorphic rocks on top of higher-grade metamorphic units, interpreted as an Archaean accretionary complex (Kisters *et al.*, 2012; Kolb, 2011). These amphibolite and greenschist-facies structures host gold mineralization in the Paamiut and Tartoq gold provinces (Fig. 11*b*). The east-vergent stacking and lowest recorded metamorphic grades at 2–3 kbar and 350–450ºC in the westernmost Tartoq group are followed by greenschist-facies northeast–southwest extension (Kisters *et al.*, 2012; Kolb, 2011; van Hinsberg *et al.*, 2010). Pegmatites and granites of unknown age intruded the early compressional structures (Kisters *et al.*, 2012; Kolb, 2011).

Skjoldungen orogen

The ~2790–2680 Ma Skjoldungen orogen affected the dominantly Mesoarchaean rocks of the Thrym complex in southeastern Greenland (Fig. 5*d*; Kolb *et al.*, 2013*b*). The orogeny is accompanied by granulite facies peak metamorphism and complex calc-alkaline to alkaline and carbonatitic magmatism ~2750–2680 Ma (Andrews *et al.*, 1973; Blichert-Toft *et al.*, 1995; Kolb *et al.*, 2013*b*). Peak granulite-facies metamorphism at *PT* conditions of ~760ºC and 8 kbar caused widespread anatexis of orthogneiss, paragneiss and locally mafic granulite (Berger *et al.*, 2014; Kolb *et al.*, 2013*b*). The orogen was exhumed relatively fast to greenschist-facies levels at ~2700 Ma (Berger *et al.*, 2014). Deformation associated with the Skjoldungen orogeny (D_S) resulted in isoclinal folds of an early S_T foliation associated with the late Mesoarchaean Timmiarmiut orogeny (D_T) during northeast–southwest compression (Kolb *et al.*, 2013*b*). The axial planar S_{S1} foliation is the penetrative, locally mylonitic, southeast-trending fabric in the region. This regional fabric is folded during north–south compression into open to close folds and transposed into a discrete set of amphibolite-facies conjugate shear zones that define the S_{S2} foliation during the main pulse of alkaline magmatism (Fig. 5*d*; Kolb *et al.*, 2013*b*). Late orogenic north–south extension resulted in discrete greenschist-facies shear zones associated with carbonatitic magmatism during the Singertat Stage (D_R) of deformation (Kolb *et al.*, 2013*b*).

Orogenic magmatism started at ~2750 Ma with the emplacement of quartz-monzodioritic to syenitic and ultramafic intrusions that are commonly up to tens of metres wide and several hundred metres long, and form discontinuous boudins and lenses (Bagas *et al.*, 2013). The ~2720–2700 Ma alkaline rocks associated with D_{S2} deformation include hornblende-pyroxenite, hornblendite, hornblende-norite, diorite, leucogabbro, monzodiorite, monzonite and syenite (Blichert-Toft *et al.*, 1995; Kolb *et al.*, 2013*b*). The evolution of the Skjoldungen orogen mimics that of a Phanerozoic collisional orogen with early northeast-southwest compression and ~2750 Ma high-grade metamorphism followed by fast exhumation and retrogression in a stress field changed to more north-south compression at ~2700 Ma (Berger *et al.*, 2014). Orogen-normal extension was accompanied by alkaline-carbonate magmatism during the ~2680 Ma Singertat Stage of deformation (Kolb *et al.*, 2013*b*).

Kapisilik orogen

Evidence for Neoarchaean metamorphism is recorded by leucosomes in the Kapisilik terrane that indicate crustal melting and high-grade metamorphism at ~2600 Ma (Friend and Nutman, 2005*b*). A mylonite a few kilometres south of the Kapisilik terrane is dated at ~2650 Ma (Nutman and Friend, 2007). This together with mylonites of similar age in the Tasiusarsuaq terrane (Kolb *et al.*, 2012; Nutman and Friend, 2007) and Storø in the Færingehavn terrane (Nutman *et al.*, 2007*b*) defines the Kapisilik orogeny at ~2670–2580 Ma (Fig. 11*a*; Kolb *et al.*, 2013*a*). Metamorphic zircon rims and monazite in the Kapisilik terrane yield ages of ~2650–2580 Ma, when metamorphism possibly reached high-pressure granulite facies at ~2650 Ma east of Kapisillit, and only amphibolite facies in the north including the Ivisaartoq greenstone belt (Nutman and Friend, 2007).

The fold interference pattern in the terranes to the west and south of the Kapisilik terrane are largely a result of ~2670–2580 Ma deformation (Fig. 11*a*; Kolb *et al.*, 2012, 2013*a*). The northwest-trending fold axes and associated near-vertical northwest-trending transcurrent shear zones formed at amphibolite facies during east-west to northeast-southwest shortening (Kolb *et al.*, 2012). East-vergent reverse shear zones are developed locally, such as on Storø and in the Tasiusarsuaq terrane (Kolb *et al.*, 2012; Nutman *et al.*, 2007*b*). These structures host the important Neoarchaean hypozonal gold mineralization (Fig. 11*a*; Kolb *et al.*, 2013*a*). The structures in the orogenic foreland suggest westward imbrication of the Kapisilik terrane during the Kapisilik orogeny (Kolb *et al.*, 2013*a*).

Mineral deposits and mineralization

Neoarchaean gold provinces

Orogenic gold mineralization in Neoarchaean structures is widespread in western Greenland and is reviewed by Kolb *et al.* (2013*a*). Four gold provinces are distinguished based on their geographic distribution (Figs 11–12).

The Godthåbsfjord gold province includes the best-explored Archaean gold occurrences in Greenland known as the Storø and Qussuk prospects (Fig. 11*a*). The occurrences have been drilled, but no grade-tonnage data were released. Quartz veins and hypozonal hydrothermal alteration zones in shear zones or fold structures host these two prospects and five other occurrences in the province. The gold occurrences cluster on a regional scale around the ~2660–2600 Ma Ivinnguit-Storø-Ataneq fault system (Fig. 11*a*).

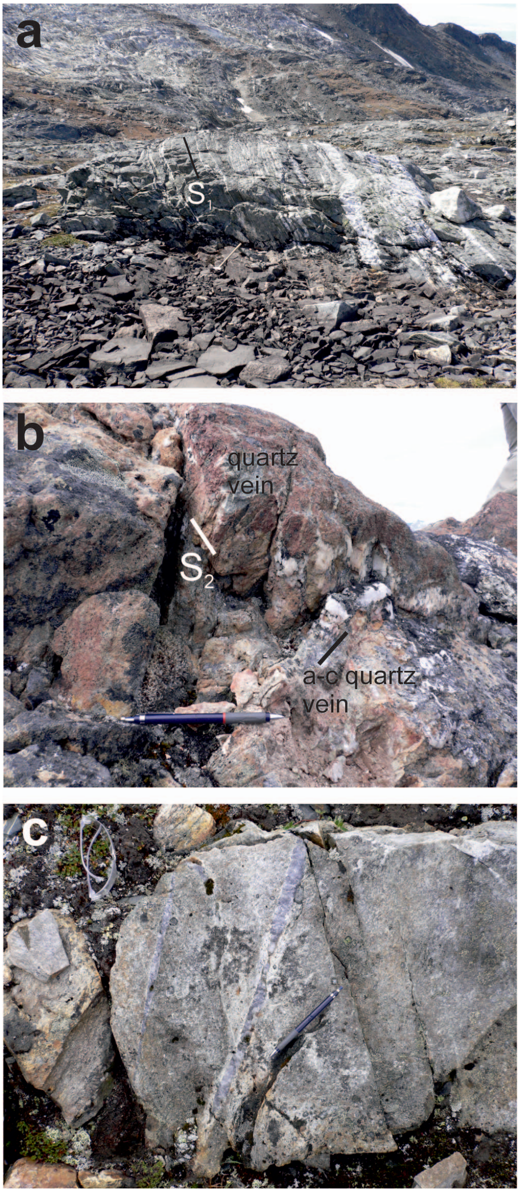


FIG. 12. (*a*) A number of S$_1$ foliation-parallel quartz veins forming a laminated vein system in the Mellembygden gold occurrence of the Paamiut gold province. (*b*) Intersection zone of two quartz veins (1) S$_2$–parallel and (2) in a–c orientation of F$_3$ folds showing intense hydrothermal alteration of the host rock in the Tasiusarsuaq gold province. (*c*) Small alteration halo around hydrothermal quartz veins in quartz-biotite schist of the Akuliaq gold prospect in the Paamiut gold province. Hydrothermal alteration is recognized by the white-coloured muscovite alteration of feldspar.

Gold mineralization at Storø is dated at ~2640 Ma by U-Pb zircon and Re-Os arsenopyrite techniques (Nutman *et al.*, 2007*b*; Scherstén *et al.*, 2012), and at Qilanngaarsuit it is bracketed between ~2715 and 2550 Ma based on hydrothermal replacement of ~2715 Ma metamorphic assemblages and a crosscutting relationship with ~2550 Ma pegmatite (Kolb *et al.*, 2013*a*). These pieces of evidence may point to a genetic relationship between tectonic activity and hydrothermal gold mineralization. Some authors suggest a syngenetic gold mineralization model for Storø and Qussuk based on imprecise geochronological data, folded auriferous quartz veins and pre-metamorphic alteration recorded by aluminous gneiss that locally contains gold mineralization (Garde *et al.*, 2012*b*; Knudsen *et al.*, 2007; Scherstén *et al.*, 2012). The typical hypozonal mineral assemblage of the gold province is, however, characterized by quartz, garnet, biotite, hornblende, pyrrhotite, chalcopyrite and gold, and it replaces peak metamorphic mineral assemblages in the host rocks, characteristic of an epigenetic and orogenic origin for the gold mineralization (Kolb *et al.*, 2013*a*).

The Tasiusarsuaq gold province consists of hypozonal shear zone-hosted and fold-hosted gold occurrences of <0.5 g/t in the northern Tasiusarsuaq terrane (Figs 11*a* and 12*b*). The typical hypozonal mineral assemblage associated with quartz veins is quartz, biotite, hornblende, pyrrhotite, chalcopyrite and gold, and is similar to the Godthåbsfjord gold province. The mineralized shear zones are dated at ~2670–2610 Ma by metamorphic rims on zircon (Nutman and Friend, 2007) and syn-tectonic pegmatite (Kolb *et al.*, 2012), and overlap in age with gold mineralization in the Godthåbsfjord gold province. A common genetic model for orogenic gold mineralization in both provinces was developed, suggesting that hydrothermal mineralization is related to deformation caused by outboard accretion of the Kapisilik terrane during the Kapisilik orogeny (Kolb *et al.*, 2013*a*). The Ivinnguit-Storø-Ataneq fault system in the Godthåbsfjord gold province was reactivated focusing auriferous fluids, whereas in the Tasiusarsuaq gold province a set of parallel shear zones developed with no channelling of auriferous fluids, which explains the lower gold-grades in the hypozonal orogenic gold occurrences (Fig. 11*a*; Kolb *et al.*, 2013*a*). The Sermilik and Bjørnesund gold occurrences in the southern Tasiusarsuaq terrane are hosted by reverse shear zones related to the Tasiusarsuaq orogeny. Gold mineralization with grades of up to 6 g/t Au is present at Sermilik, where it is hosted by quartz veins with hypozonal quartz, biotite, garnet and pyrite alteration in systems that can be followed over several hundred metres along strike. A similar hypozonal alteration halo is developed at Bjørnesund around quartz veins containing <0.8 g/t Au in several occurrences along a ~10 km strike extent.

The Paamiut gold province is characterized by four occurrences with locally high gold grades of up to 12 g/t in vein sets several metres wide and with a strike length of hundreds of metres (Figs 12*a*,*c*). North-trending reverse and west-trending strike-slip shear zones in a regional east- to southeast-vergent deformation belt host auriferous quartz veins in the region (Fig. 11*b*). The mesozonal hydrothermal alteration assemblage consists of quartz, biotite, orthoamphibole, tourmaline, pyrrhotite, arsenopyrite and gold replacing peak metamorphic amphibolite facies assemblages. Akulleq is the easternmost occurrence, which is interesting from a geodynamic and mineral system point of view, because auriferous quartz veins are surrounded locally by cm-scale leucosomes, indicating prograde metamorphism that overprinted orogenic gold mineralization (Kolb *et al.*, 2013*a*).

The Tartoq gold province consists of six orogenic gold occurrences (Fig. 11*b*), two of which have been drilled sporadically for a VMS target (Petersen, 1992). Gold is, however, hosted in quartz veins and alteration zones in greenstones and BIF. The quartz veins are in <450 m wide reverse and strike-slip shear zones, which can be followed over several kilometres. The shear zones are related to the east- to southeast-vergent Neoarchaean accretionary complex of the Sermiligaarsuk and Paamiut blocks. The typical hydrothermal alteration assemblage is mesozonal, containing quartz, ankerite, muscovite, chlorite, pyrite, arsenopyrite and gold. A single hypozonal orogenic gold occurrence is restricted to the granulite-facies Bikuben belt (Kolb *et al.*, 2013*a*).

The Skjoldungen Ni-sulfide and magnetite occurrences

Mafic granulite and ultramafic rocks host pods and layers of Ni-Cu sulfide mineralization in the Thrym complex (Fig. 13; Owen, 2012). The types of mineralization recognized are: (1) interstitial to net-textured sulfides in peridotite; and (2) sulfide

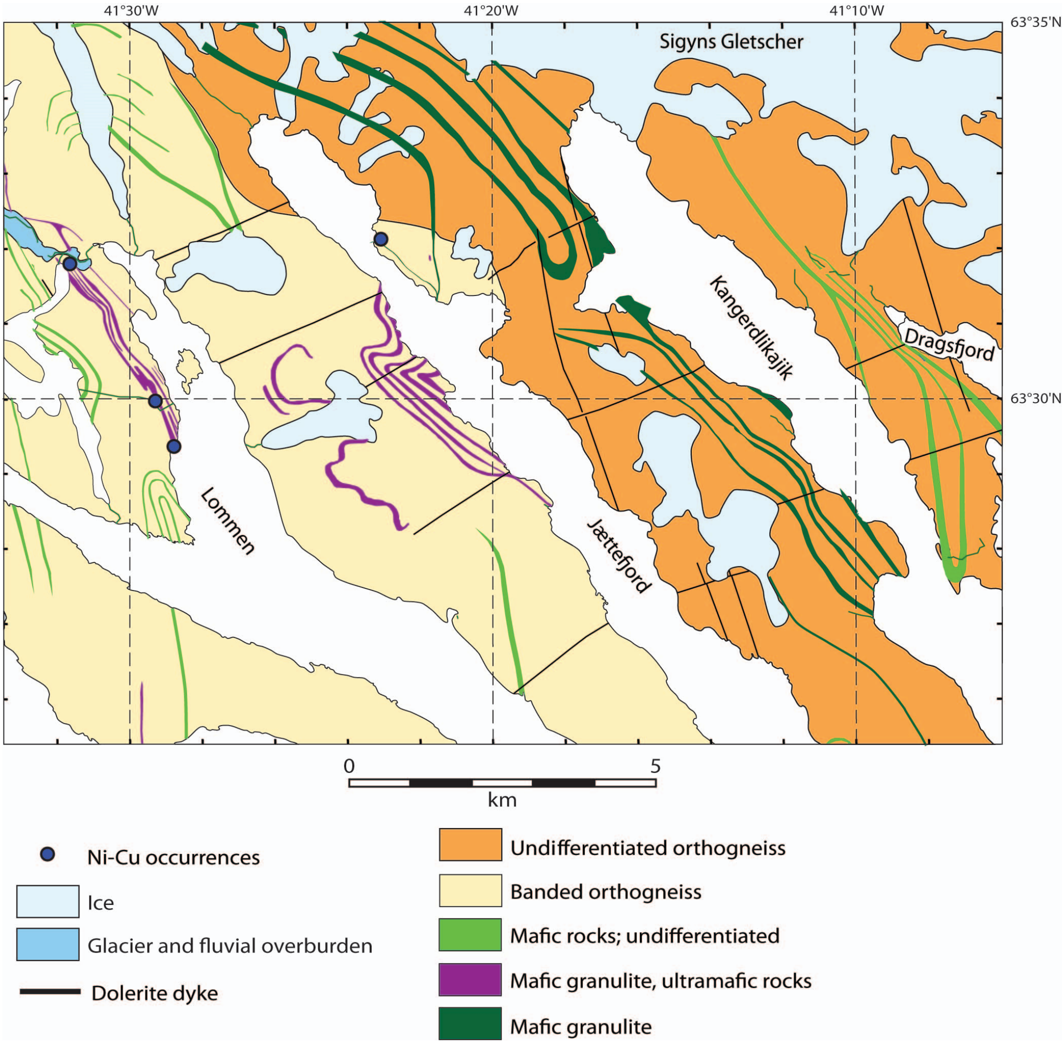


FIG. 13. Geological map of the Ni-sulfide occurrences associated with mafic granulite-ultramafic rock bands in the Thrym complex of south-east Greenland (modified after Owen, 2012).

mineralization and quartz alteration in 0.5 m wide D_{S2} shear zones of the Skjoldungen orogen. Interstitial to net-textured sulfide mineralization (<20 vol.%) is hosted by ~15 m thick irregular peridotite lenses and in ~4 m wide zones at the contact between peridotite and mafic granulite. The sulfides consist of pyrrhotite with minor pyrite, chalcopyrite and pentlandite. In numerous samples pentlandite occurs as lamellar exsolutions within pyrrhotite. Pyrite generally forms rounded grains edged by chalcopyrite. Mineralized samples assay up to 5180 ppm Ni and 2560 ppm Cu. The mineralized D_{S2} shear zones crop out semi-continuously for >20 km, trending east and dipping 52ºS. Sulfides in the second mineralization type cross-cut the silicate phases through jigsaw-fit fractures and are associated with quartz alteration. The shear zone-hosted mineralization is notably depleted in nickel with a maximum assay of 680 ppm Ni and 2280 ppm Cu. The metal source for this type of mineralization was probably the interstitial to net-textured sulfide mineralization in peridotite, which was remobilized during subsequent deformation.

Magnetite bands and veins are hosted by ~2700 Ma layered intrusions of the Thrym complex (Fig. 5*d*). An example is the Vend Om gabbro, which is a small 350 m × 450 m elliptical intrusion with <2 m wide bands of <35 vol.% magnetite and hercynite, hornblende and plagioclase (Klausen and Kokfelt, 2014). Several magnetite, ilmenite and spinel bands <0.2 m wide are present in the Njords Glacier gabbro (Klausen and Kokfelt, 2014). Narrow veins dominated by magnetite and apatite cross cut the magmatic layering of the Ruinnæsset complex (Klausen and Kokfelt, 2014). Although the mapped occurrences are small, it shows the mineral potential in the larger region.

Archaean geological evolution and genesis of mineral deposits

The history of the NAC started in the Eoarchaean with the formation of greenstones and emplacement of TTG, and subsequent deformation, metamorphism and the emplacement of monzogranite and layered mafic complexes at ~3650–3600 Ma (Nutman *et al.*, 2010; Næraa *et al.*, 2012). This evolution favoured the formation of the Isua iron deposit as a BIF in a marine hydrothermal setting, accumulating >1000 Mt Fe in the deposit (Fig. 14). Only

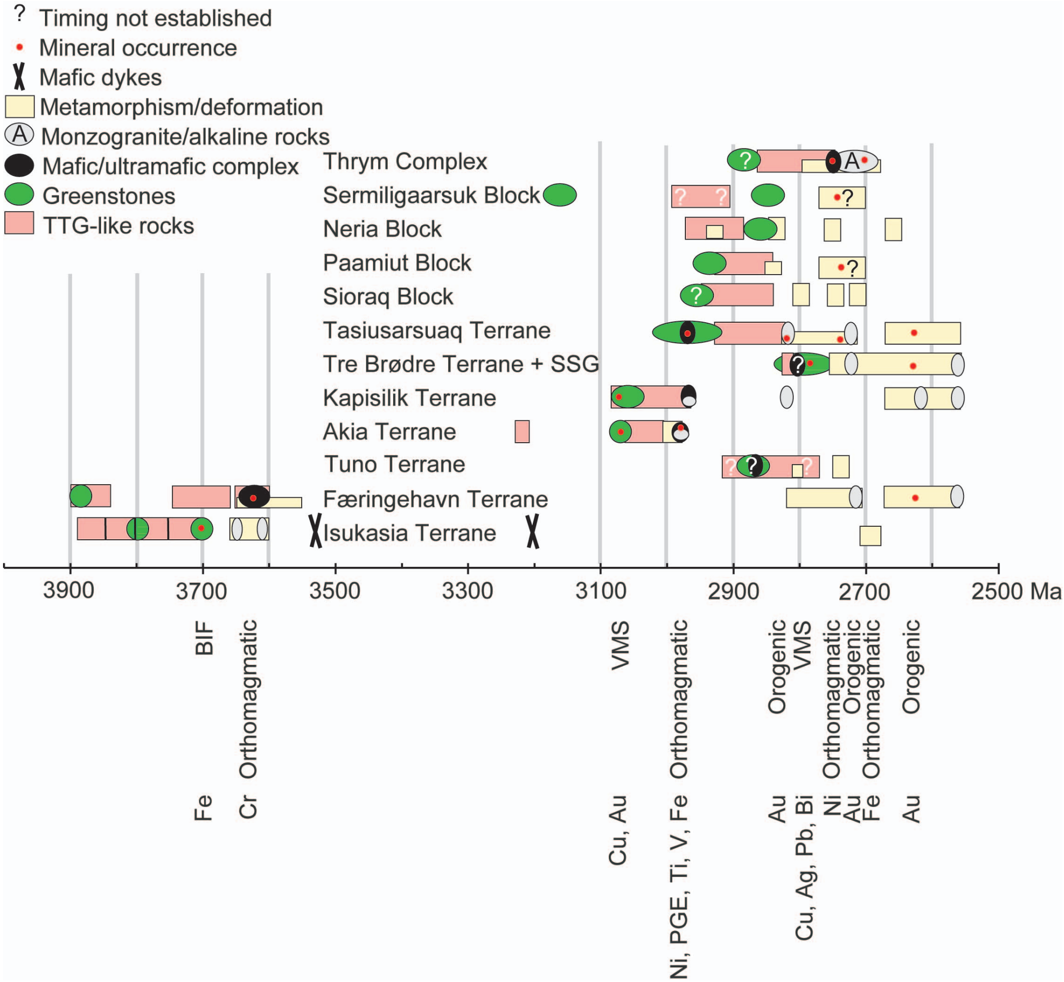


FIG. 14. Summary of the geological evolution of the NAC in Greenland. The timing of petrogenesis and its relationship to mineralization is shown schematically. See text for references to the age data and further explanation (SSG: Simiútat supracrustal group).

small Cr occurrences are related to the mafic magmatism during the orogenic stage at the end of the Eoarchaean evolution (Rollinson *et al.*, 2002). The Eoarchaean was followed by a >450 million year hiatus (Nutman *et al.*, 2010; Næraa *et al.*, 2012), interrupted only by minor TTG emplacement in the Akia terrane, mafic dykes and greenstone formation in an oceanic setting in the Sermiligaarsuk block (Fig. 14). The Eoarchaean terranes probably formed small continental blocks in an overall oceanic setting with a low potential for preservation. The formation of greenstones started again at ~3080 Ma in the Akia and Kapisilik terranes and subsequently also in the other terranes (Fig. 14; Garde, 2007*a*). The geochemical affinity of the greenstones is similar to modern arc settings, which was used to suggest plate tectonic models for the evolution of the Palaeo- to Mesoarchaean terranes (Garde, 2007*a*; Ordóñez-Calderón *et al.*, 2008; Polat *et al.*, 2007, 2008*a*,*b*). Locally, the greenstone belts host small, metamorphosed VMS deposits that could have formed in an arc setting. Greenstone formation was accompanied and followed by emplacement of TTG-like rocks.

Mafic intrusions in the Kapisilik and Akia terranes formed late in the orogenic stage of terrane evolution and, in the case of the orthomagmatic Ni-bearing Norite belt in the Akia terrane, may be related to bolide impact (Garde *et al.*, 2012*a*). The ~2970 Ma Fiskenæsset complex in the Tasiusarsuaq terrane was emplaced into amphibolite and is interpreted to be a syn- to slightly post-greenstone belt intrusion in a possible Alaskan-type island-arc setting (Fig. 14; Polat and Longstaffe, 2014). The complex hosts ~100 Mt Cr ore, promising PGE reefs and Ti-V mineralization in magnetite-ilmentite bands. The formation of greenstone belts and TTG is widespread in the NAC between ~2970 and 2820 Ma, and until ~2750 Ma in the Thrym complex of eastern Greenland, overprinted by widespread metamorphism and deformation in Neoarchaean orogens (Fig. 14; e.g. Bagas *et al.*, 2013; Dziggel *et al.*, 2014; Friend and Nutman, 1994, 2001; Garde, 2008; Garde *et al.*, 2000; Hollis *et al.*, 2006; Kolb *et al.* 2012, 2013*b*; Nutman and Friend, 2007). Most of the NAC underwent Neoarchaean upper amphibolite- to granulite-facies metamorphism, with exceptions in the amphibolite-facies Isukasia terrane, Tre Brødre terrane and Paamiut block, and the greenschist-facies Sermiligaarsuk block. High-grade metamorphism may explain some of the nearly exclusive preservation of bimodal suites of mafic and TTG-like rocks, where meta-sedimentary rocks could be lost through anatexis recorded by the unusual, non-TTG-like trace-element composition of granitic rocks (Bagas *et al.*, 2013; Kolb *et al.*, 2012, 2013*b*).

Hypozonal and mesozonal orogenic gold deposits formed mainly in two stages at ~2740 Ma and 2630 Ma in the Tasiusarsuaq and Kapisilik orogens (Fig. 14; Kolb *et al.*, 2013*a*). The Simiútat supracrustal group represents Neoarchaean flysch-like metasedimentary and metavolcanic rocks hosting small VMS occurrences that are metamorphosed and preserved in orogenic nappe structures in the Nuuk area. The final stages of the Skjoldungen orogen in eastern Greenland are characterized by a change from compression to transpression and extension, which is associated with ultramafic and alkaline magmatism (Bagas *et al.*, 2013; Kolb *et al.*, 2013*b*). The intrusions host small orthomagmatic occurrences of Ti-bearing oxides and Ni-sulfides. The emplacement of ~2560 Ma leucogranite concludes the Archaean history of the NAC; Palaeoproterozoic mafic dykes probably mark the break-up of the Archaean craton (Nilsson *et al.*, 2010; Nutman *et al.*, 2010).

Geological, geochemical and geophysical exploration signatures

The NAC of Greenland represents an area of relatively low-resolution geochemical and geophysical data sets and variable geological understanding. Almost all mineral exploration targets have been defined by prospecting for gossan or geochemical anomalies and not through an integrated geochemical-geophysical exploration approach. Thus, the NAC area is under-explored compared to Archaean terranes elsewhere in the world, as also shown by the small number of exploration licenses granted and the relatively low expenditure on exploration. Currently, the metallogeny of the NAC in Greenland is mainly defined by banded iron formation Fe, orthomagmatic Cr-Ni-PGE-Ti-V, orogenic Au, gemstone and Cu-Au-Ag-Pb-Bi deposits in metamorphosed VMS.

Iron mineralization associated with BIF, and base and noble metal sulfide ore associated with large mafic-ultramafic intrusive complexes, have a large geological footprint. Therefore, future exploration will most likely focus on specific high-grade areas within bodies that have already been identified, as larger occurrences are unlikely to have been overlooked. Magnetite BIF is readily identifiable in the aeromagnetic data, whereas larger mafic intrusive complexes are associated generally with Ni-Cr-Ti anomalies in the stream sediment geochemical data.

Conversely, orogenic gold systems, conduit-hosted Ni-Cu-PGE sulfide mineralization and metamorphosed VMS occurrences have a much smaller geological footprint and represent much more challenging targets. Semi-massive to massive sulfide occurrences may be in the order of several tens of metres wide at surface; however, their 3D geometry is unknown and the geochemical footprint of nickel-sulfide systems is largely unconstrained (Le Vaillant *et al.*, 2015). These occurrences are easily overlooked in the field and in geochemical and geophysical data sets, but may represent interesting exploration targets. The maps of the NAC in Greenland are lacking in structural geological data, and major Archaean shear zones are not mapped, which makes the identification of potential orogenic gold occurrences associated with such structures difficult. The shear zones are generally not expressed by the low-resolution aeromagnetic data, which commonly enhance young structures and the presence of ubiquitous mafic dykes, thus masking the Archaean structures. The relatively small auriferous quartz veins and hydrothermal alteration zones in the scale of hundreds of metres are not usually recorded by anomalies in the stream sediment geochemistry data, because they easily lie outside the catchment areas. However, it has been possible to identify several new gold occurrences in the Tasiusarsuaq gold province, using a combination of 1:20,000 scale field maps from the GEUS archives and aeromagnetic, radiometric and stream-sediment geochemical data and fieldwork (Kolb *et al.*, 2013*a*). Recent predictive gold potential modelling using geological, geochemical and geophysical data identified not only the known occurrences, but also a few new interesting gold targets (Schlatter and Stensgaard, 2014; Stensgaard, 2013;).

The examples above show that even low-resolution data and a broad geological understanding can be used in integrated studies to locate mineral occurrences successfully. However, in order to generate a robust understanding of the metal endowment potential of the NAC in Greenland, it is necessary to apply a comprehensive mineral-system analysis (McCuaig *et al.*, 2010; Wyborn *et al.*, 1994) of the various terranes through an integrated and collective approach between government, research and industry. The mineral-system analysis approach allows the identification of prospective regions across multiple scales. It is based on the hypothesis that the genesis of sizeable mineralization requires a combination of scale-hierarchical temporally and spatially independent parameters and processes, operating from the scale of the mantle down to the scale of individual faults, intrusions and lithologies (Hronsky and Groves, 2008; McCuaig *et al.*, 2010). The application of such an approach in Greenland will identify key knowledge gaps and help to prioritize efforts towards a holistic predictive understanding of the prospectivity of the craton. The NAC of Greenland is similar to other well-endowed Archaean terranes but is underexplored, and is therefore likely to host numerous targets for greenfields exploration with high-risk, high-reward potential.

Conclusions

What did we learn?

In recent years, geological maps of the NAC from the 1960s and 1980s have been updated, mainly by mapping at various scales. Maps at a scale of 1:100,000 (but 1:500,000 for eastern Greenland) are published, and document the basic understanding of the geology of the NAC. Geochemical and geophysical data exist at a regional scale, with stream-sediment sample density of one per 20–40 km^2 and aeromagnetic data collected at 300 m altitude with a line-spacing of 500 m (Steenfelt, 2001; Thorning, 1984). Although the 1:500,000 scale geological map is seamless, the geological understanding varies between areas and processes are only well-understood locally. As an example, large amounts of geochronological data and robust geological models are available for the Nuuk area, but not for the Paamiut and Sermiligaarsuk areas (e.g. Dziggel *et al.*, 2014; Nutman and Friend, 2007; Næraa *et al.*, 2012). Our general understanding of the NAC in Greenland is therefore still defined by relatively low-resolution data sets and largely fragmented data in survey reports and field diaries. Several promising exploration targets have been defined in recent years, mainly representing Fe, Ni, PGE and Au projects, of which only the Isua iron and the Aappaluttoq ruby deposits are currently developed beyond the exploration stage. Most of the exploration targets were identified by prospecting or by studies of historical data from the GEUS archives, reflecting the relatively poor understanding of geological processes related to ore formation.

What are the key problems?

Besides the relatively low resolution of the available data, several geological problems can be identified that reflect the lack of understanding of the link between geological processes and mineral systems that could otherwise boost mineral exploration and enhance targeting. Better modern data are required, but also improved deposit models that reflect the geological features of the NAC, and the application of a mineral system analysis. The generally high metamorphic nature of the NAC requires a better understanding of hypozonal orogenic gold mineral systems and metamorphosed and deformed syngenetic mineralization, such as that in the Fiskenæsset complex or VMS occurrences. While an improved deposit model for hypozonal gold ores will aid targeting, understanding of the metamorphic and structural processes overprinting the ores is required for interpretation of remobilization and ore-body geometry; e.g. of discontinuous PGE reefs. Integrated geological investigations, including experimental work and computer modelling, will probably be required. Most importantly, the application of mineral system analysis in Greenland will identify key knowledge gaps and help to prioritize efforts towards a holistic predictive understanding of the prospectivity of the NAC, which has the economic potential of a largely under-explored Archaean craton, but also boasts an extensive 3D outcrop that allows geological models to be tested against geological facts. The NAC in Greenland can be explored by the newest methods developed during exploration of other cratons and serve as a show-case for an integrated and sustainable approach in the exploration and exploitation of its mineral wealth.

Acknowledgements

Fieldwork and follow-up research projects on the geology and metallogeny of the Greenlandic North Atlantic Craton were financed jointly by the Geological Survey of Denmark and Greenland (GEUS) and the Greenland Ministry of Mineral Resources (MMR; former Bureau of Minerals and Petroleum, BMP). D.M. Schlatter, P. Armitage and an anonymous reviewer are thanked for their helpful comments that improved the manuscript. JK would like to thank B.M. Stensgaard, A. Polat, A. Dziggel, A.F.M. Kisters and numerous colleagues at GEUS, MMR and in exploration companies for discussion of the various aspects of metallogeny in Greenland. J. Halskov is thanked for the help with the figures. MLF acknowledges support from the Australian Research Council through Linkage and the Future Fellowship Scheme (FT110100241). This is contribution 531 from the ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS).

References

21st North (2013) *The Fiskenæsset PGE prospect: unexplored PGE mineralisation within ultramafic rocks of the Fiskenæsset gabbro-anorthosite complex*. 21st North, Svendborg, Denmark [www.21stnorth.com].

Allaart, J.H. (1982) *Geological Map of Greenland: Frederikshåb Isblink - Søndre Strømfjord*. Geological Survey of Greenland, Copenhagen.

Allaart, J.H. and Jensen, S.B. (1979) Compilation of 1:500 000 reconnaissance mapping in the Precambrian of the Evighedsfjord - Søndre Strømfjord - Itivdleq region, southern West Greenland. *Rapport Grønlands Geologiske Undersøgelse*, **95**, 72–76.

Andrews, J.R., Bridgwater, D., Gormsen, K., Gulson, B., Keto, L. and Watterson, J. (1973) The Precambrian of south-east Greenland. Pp. 143–156 in: *The Precambrian of Scotland and Related Rocks of Greenland* (R.G. Park and J. Tarney, editors). University of Keele, Keele, UK.

Appel, P.W.U. (1980) On the Early Archaean Isua iron-formation, west Greenland. *Precambrian Research*, **11**, 73–87.

Appel, P.W.U. (1982) Strata-bound sulphides in the Early Archaean Isua supracrustal belt, West Greenland. Pp. 405–412 in: *Ore Genesis: The State of the Art* (G.C. Amstutz, A. El Goresy, G. Frenzel, C. Kluth, G. Moh, A. Wauschkuhn and R.A. Zimmermann, editors). Springer-Verlag, Berlin-Heidelberg.

Appel, P.W.U. (1986) Strata bound scheelite in the Archean Malene supracrustal belt, West Greenland. *Mineralium Deposita*, **21**, 207–215.

Appel, P.W.U. (1988*a*) On an Sn-W-bearing iron-formation in the Archaean Malene supracrustals, West Greenland. *Precambrian Research*, **39**, 131–137.

Appel, P.W.U. (1988*b*) Stratiform tourmalinites in the

Archaean tungsten province of West Greenland. *Mineralogy and Petrology*, **39**, 79–91.

Appel, P.W.U. (1990) *Tungsten mineralization in the Nuuk region, West Greenland*. Open File Series Grønlands Geologiske Undersøgelse 90/4. GEUS, Copenhagen, 25 pp.

Appel, P.W.U. (1992) *Chromite in the Fiskenæsset stratiform anorthosite complex, West Greenland*. Open File Series Grønlands Geologiske Undersøgelse 92/5. GEUS, Copenhagen. 14 pp.

Appel, P.W.U. (1993) *Gold and platinum-group element anomalies in the Fiskenæsset stratiform anorthosite complex, West Greenland*. Open File Series Grønlands Geologiske Undersøgelse 93/6. GEUS, Copenhagen, 24 pp.

Appel, P.W.U., Garde, A.A., Jørgensen, M.S., Moberg, E., Rasmussen, T.M., Schjøth, F. and Steenfelt, A. (2003) *Preliminary evaluation of the economic potential of the greenstone belts in the Nuuk region: general evaluation of compiled geophysical, geochemical and ore geological data*. Geological Survey of Denmark and Greenland Report 2003/94. GEUS, Copenhagen, 147 pp.

Appel, P.W.U., Coller, D., Coller, V., Heijlen, W., Moberg, E.D., Polat, A., Raith, J., Schjøth, F., Stendal, H. and Thomassen, B. (2005) *Is there a gold province in the Nuuk region? Report from field work carried out in 2004*. Geological Survey of Denmark and Greenland Report 2005/27. GEUS, Copenhagen, 79 pp.

Appel, P.W.U., Dahl, O., Kalvig, P. and Polat, A. (2011) *Discovery of new PGE mineralization in the Precambrian Fiskenaesset anorthosite complex, West Greenland*. Geological Survey of Denmark and Greenland Report 2011/3. GEUS, Copenhagen, 48 pp.

Armitage, P. (2009) *Exploration in the Amikoq sub-area of licence 2005/16 Fiskefjord, southern West Greenland*. NunaMinerals A/S, Nuuk, Greenland, pp. 180.

Bagas, L., Næraa, T., Kolb, J., Reno, B.L. and Fiorentini, M.L. (2013) Partial melting of the Archaean Thrym Complex of southeastern Greenland. *Lithos*, **160–161**, 164–182.

Ball, H.S. (1922) The mineral resources of Greenland. *Meddelelser om Grønland*, **63**, 1–60.

Barnes, S.J. and Fiorentini, M.L. (2012) Komatiite magmas and Ni sulfide deposits: a comparison of variably endowed Archean terranes. *Economic Geology*, **107**, 755–780.

Begg, G.C., Hronsky, J.M.A., Arndt, N.T., Griffin, W.L., O'Reilly, S. and Hayward, N. (2010) Lithospheric, cratonic, and geodynamic setting of Ni-Cu-PGE sulfide deposits. *Economic Geology*, **105**, 1057–1110.

Berger, A., Kokfelt, T.F. and Kolb, J. (2014) Exhumation rates in the Archean from pressure-time paths: example from the Skjoldungen Orogen (SE Greenland), *Precambrian Research*, **255**, 774–790.

Berthelsen, A. (1960). *Structural Studies in the Pre-Cambrian of Western Greenland. II. Geology of Tovqussap nunâ*. Meddelelser om Grønland, **123(1)**. Museum Tusculanum Press, University of Copenhagen, Copenhagen, 223 pp.

Blichert-Toft, J., Rosing, M.T., Lesher, C.E. and Chauvel, C. (1995) Geochemical constraints on the origin of the Late Archean Skjoldungen alkaline igneous province, SE Greenland, *Journal of Petrology*, **36**, 515–561.

Boak, J.L. and Dymek, R.F. (1982) Metamorphism of the ca. 3800 Ma supracrustal rocks at Isua, West Greenland: implications for early Archaean crustal evolution. *Earth and Planetary Science Letters*, **59**, 155–176.

Bridgwater, D., Watson, J. and Windley, B.F. (1973) The Archaean craton of the North Atlantic region. *Philosophical Transactions of the Royal Society London*, **273**, 493–512.

Chadwick, B. (1986) Malene stratigraphy and late Archaean structure: new data from Ivisârtoq, inner Godthåbsfjord, southern West Greenland. *Rapport Grønlands Geologiske Undersøgelse*, **130**, 74–85.

Chadwick, B. (1990) The stratigraphy of a sheet of supracrustal rocks within high-grade orthogneisses and its bearing on Late Archaean structure in southern West Greenland. *Journal of the Geological Society London*, **147**, 639–652.

Chadwick, B. and Coe, K. (1983) *Buksefjorden 63 V1 Nord descriptive text geological map of Greenland 1:100000. The regional geology of a segment of the Archaean block of southern West Greenland*. Grønlands Geologiske Undersøgelse, Copenhagen, pp. 70.

Chadwick, B. and Coe, K. (1988) *Geologisk kort over Grønland, 1:100000, Ivisârtoq 64 V2 Nord*, Geological Survey of Denmark and Greenland, Copenhagen.

Clout, J.M.F. and Simonson, B.M. (2005) Precambrian iron formations and iron formation-hosted iron ore deposits, *Economic Geology 100th Anniversary Volume*, 643–679.

Compton, P. (1978) Rare earth evidence for the origin of the Nûk gneisses Buksefjorden region, southern West Greenland. *Contributions to Mineralogy and Petrology*, **66**, 283–293.

Crowley, J.L. (2002) Testing the model of late Archean terrane accretion in southern West Greenland: a comparison of the timing of geological events across the Qarliit nunaat fault, Buksefjorden region. *Precambrian Research*, **116**, 57–79.

Crowley, J.L. (2003) U-Pb geochronology of 3810–3630 Ma granitoid rocks south of the Isua greenstone belt, southern West Greenland. *Precambrian Research*, **126**, 235–257.

Dubé, B. and Gosselin, P. (2007) Greenstone-hosted quartz-carbonate vein deposits. Pp. 49–73 in: *Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods* (W.D. Goodfellow, editor). Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5., St. John's, Canada.

Dziggel, A., Diener, J.F.A., Stoltz, N.B. and Kolb, J. (2012) The role of H_2O in the formation of garnet coronas during near isobaric cooling of mafic granulites: the Tasiusarsuaq terrane, southern West Greenland. *Journal of Metamorphic Geology*, **30**, 957–972.

Dziggel, A., Diener, J.F.A., Kolb, J. and Kokfelt, T. (2014) Metamorphic record of accretionary processes during the Neoarchaean: the Nuuk region, southern West Greenland. *Precambrian Research*, **242**, 22–38.

Eckstrand, O.R. and Hulbert, L.J. (2007) Magmatic nickel-copper-platinum group element deposits. Pp. 205–222 in: *Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods* (W.D. Goodfellow, editor). Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5., St. John's, Canada.

Escher, J.C. (1971) *The geology of Akuliaq with particular bearing on the origin and evolution of the supracrustal Kvanefjord belt, Frederikshåb area, South-West Greenland*. Unpublished thesis, University of Lausanne, Switzerland, 108 pp.

Escher, J.C. (1990) *Geological Map of Greenland: Sheet 14, Skjoldungen*. Geological Survey of Denmark and Greenland, Copenhagen.

Frei, R., Bridgwater, D., Rosing, M. and Stecher, O. (1999) Controversial Pb-Pb and Sm-Nd isotope results in the early Archean Isua (West Greenland) oxide iron formation: preservation of primary signatures versus secondary disturbances. *Geochimica et Cosmochimica Acta*, **63**, 473–488.

Friend, C.R.L. and Nutman, A.P. (1994) Two Archaean granulite-facies metamorphic events in the Nuuk-Maniitsoq region, southern West Greenland: correlation with the Saglek block, Labrador. *Journal of the Geological Society London*, **151**, 421–424.

Friend, C.R.L. and Nutman, A.P. (2001) U-Pb zircon study of tectonically bounded blocks of 2940–2840 Ma crust with different metamorphic histories, Paamiut region, South-West Greenland: implications for the tectonic assembly of the North Atlantic craton. *Precambrian Research*, **105**, 143–164.

Friend, C.R.L. and Nutman, A.P. (2005*a*) Complex 3670–3500 Ma orogenic episodes superimposed on juvenile crust accreted between 3850 and 3690 Ma, Itsaq Gneiss Complex, southern West Greenland. *The Journal of Geology*, **113**, 375–397.

Friend, C.R.L. and Nutman, A.P. (2005*b*) New pieces to the Archaean terrane jigsaw puzzle in the Nuuk region, southern West Greenland: steps in transforming a simple insight into a complex regional tectonothermal model, *Journal of the Geological Society London*, **162**, 147–162.

Friend, C.R.L., Nutman, A.P., Baadsgaard, H., Kinny, P.D. and McGregor, V.R. (1996) Timing of late Archaean terrane assembly, crustal thickening and granite emplacement in the Nuuk region, southern West Greenland. *Earth and Planetary Science Letters*, **142**, 353–365.

Friend, C.R.L., Nutman, A.P., Bennet, V.C. and Norman, M.D. (2008) Seawater-like trace element signatures (REE + Y) of Eoarchaean chemical sedimentary rocks from southern West Greenland, and their corruption during high-grade metamorphism. *Contributions to Mineralogy and Petrology*, **155**, 229–246.

Friend, C.R.L., Nutman, A.P., Baadsgaard, H. and Duke, M.J.M. (2009) The whole rock Sm–Nd 'age' for the 2825 Ma Ikkattoq gneisses (Greenland) is 800 Ma too young: Insights into Archaean TTG petrogenesis. *Chemical Geology*, **261**, 61–75.

Garde, A.A. (1991) Post-kinematic diorite intrusions in Archaean basement rocks around outer Fiskefjord, southern West Greenland. *Bulletin of the Geological Society of Denmark*, **39**, 167–177.

Garde, A.A. (1995) Accretion and evolution of an Archaean high-grade amphibolite-gneiss complex: the Fiskefjord area, southern West Greenland, *Precambrian '95: Tectonics and Metallogeny of Early/Mid Precambrian Orogenic Belts Montreal*. Abstract p. 252. Université du Quebec à Montréal, Canada.

Garde, A.A. (1997) Accretion and evolution of an Archaean high-grade grey gneiss-amphibolite complex: the Fiskefjord area, southern West Greenland. *Geology of Greenland Survey Bulletin*, **177**, 114.

Garde, A.A. (2007*a*) A mid-Archaean island arc complex in the eastern Akia terrane, Godthåbsfjord, southern West Greenland. *Journal of Geological Society London*, **164**, 565–579.

Garde, A.A. (2007*b*) *Sheet 1: South Greenland, Geological Map of Greenland.* Geological Survey of Denmark and Greenland, Copenhagen.

Garde, A.A. (2008) *Geochemistry of Mesoarchaean andesite rocks with epithermal gold mineralisation at Qussuk and Bjørneøen, southern West Greenland. Mineral resource assessement of the Archaean Craton (66° to 63°30′N) SW Greenland.*

Contribution no. 8, Geological Survey of Denmark and Greenland Report 2008/4. GEUS, Copenhagen, 52 pp.

Garde, A.A. (2010) The 2975 Ma Maniitsoq impact structure in West Greenland: the oldest and most deeply exposed meteorite crater on Earth. *Abstracts and Proceedings of the Geological Society of Norway*, **1**, 57–58.

Garde, A.A. and Marker, M. (2010) *Geological Map of Greenland, 1:500 000, Kangerlussuaq/Søndre Strømfjord – Nuussuaq, Sheet 3*. Geological Survey of Denmark and Greenland, Copenhagen.

Garde, A.A., Grocott, J. and McCaffrey, K.J.W. (1999) New insights on the north-eastern part of the Ketilidian orogen in South-East Greenland. *Geology of Greenland Survey Bulletin*, **183**, 23–33.

Garde, A.A., Friend, C.R.L., Nutman, A.P. and Marker, M. (2000) Rapid maturation and stabilisation of middle Archaean continental crust: the Akia terrane, southern West Greenland. *Bulletin of the Geological Society of Denmark*, **47**, 1–27.

Garde, A.A., Hamilton, M.A., Chadwick, B., Grocott, J. and McCaffrey, K.J.W. (2002) The Ketilidian orogen of South Greenland: geochronology, tectonics, magmatism, and fore-arc accretion during Palaeoproterozoic oblique convergence. *Canadian Journal of Earth Sciences*, **39**, 765–793.

Garde, A.A., McDonald, I., Dyck, B. and Keulen, N. (2012*a*) Searching for giant, ancient impact structures on Earth: the Mesoarchaean Maniitsoq structure, West Greenland. *Earth and Planetary Science Letters*, **337–338**, 197–210.

Garde, A.A., Whitehouse, M. and Christensen, R. (2012*b*) Mesoarchean epithermal gold mineralization preserved at upper amphibolite-facies grade, Qussuk, southern West Greenland. *Economic Geology*, **107**, 745–753.

Garde, A.A., Pattison, J., Kokfelt, T.F., McDonald, I. and Secher, K. (2013) The norite belt in the Mesoarchaean Maniitsoq structure, southern West Greenland: conduit-type Ni-Cu mineralisation in impact-triggered, mantle-derived intrusions, Review of Survey activities 2012. *Geological Survey of Denmark and Greenland Bulletin*, **28**, 45–48.

Garde, A.A., Dyck, B., Esbensen, K.H., Johansson, L. and Möller, C. (2014) The Finnefjeld domain, Maniitsoq structure, West Greenland: Differential rheological features and mechanical homogenisation in response to impacting? *Precambrian Research*, **255**, 791–808.

Ghisler, M. (1970) Pre-metamorphic folded chromite deposits of stratiform type in the early Precambrian of West Greenland. *Mineralium Deposita*, **5**, 223–236.

Ghisler, M. (1976) Composition and classification of chromites in the Fiskenæsset anorthosite complex. *Rapport Grønlands Geologiske Undersøgelse*, **73**, 61–66.

Ghisler, M. and Windley, B.F. (1967) The chromite deposits of the Fiskenæsset region, West Greenland, *Rapport Grønlands Geologiske Undersøgelse*, **12**, 39.

Goldfarb, R.J., Baker, T., Dubé, B., Groves, D.I., Hart, C.J.R. and Gosselin, P. (2005) Distribution, character, and genesis of gold deposits in metamorphic terranes. *Economic Geology 100th Anniversary Volume*, 407–450.

Government of Greenland (2013) *Report to Inatsiartut on Mineral Resource Activities in 2013*. Available from http://www.govmin.gl/about-bmp/publications.

Hagemann, S.G. and Cassidy, K.F. (2000) Archean orogenic lode gold deposits. Pp. 9–68 in: *Gold in 2000* (S.G. Hagemann and P.E. Brown, editors). Reviews in Economic Geology, **13**, Society of Economic Geologists, Littleton, Colordado, USA.

Hall, R.P. (1978) An occurrence of ironstone enclaves east of Sukkertoppen, southern West Greenland. *Rapport Grønlands Geologiske Undersøgelse*, **90**, 57–60.

Hayashi, M., Komiya, T., Nakamura, Y. and Maruyama, S. (2000) Archean regional metamorphism of the Isua supracrustal belt, southern West Greenland: implications for a driving force for Archean plate tectonics. *International Geology Review*, **42**, 1055–1115.

Henriksen, N., Higgins, A.K., Kalsbeek, F. and Pulvertaft, T.C.R. (2009) Greenland from Archaean to Quaternary. *Geological Survey of Denmark and Greenland Bulletin*, **18**, 126.

Higgins, A.K. and Bondesen, E. (1966) Supracrustals of pre-Ketilidian age (the Tartoq Group) and their relationships with Ketilidian supracrustals in the Ivigtut region, South-West Greenland. *Rapport Grønlands Geologiske Undersøgelse*, **8**, 21.

Hodges, D.J. and Manojlovic, P.M. (1993) Application of lithogeochemistry to exploration for deep VMS deposits in high grade metamorphic rocks. *Journal of Geochemical Exploration*, **48**, 201–224.

Hollis, J.A., Frei, D., van Gool, J.A.M., Garde, A.A. and Persson, M. (2006) Using zircon geochronology to resolve the Archaean geology of southern West Greenland. *Geological Survey of Denmark and Greenland Bulletin*, **10**, 49–52.

Horie, K., Nutman, A.P., Friend, C.R.L. and Hidaka, H. (2010) The complex age of orthogneiss protoliths exemplified by the Eoarchaean Itsaq Gneiss Complex (Greenland): SHRIMP and old rocks. *Precambrian Research*, **183**, 25–43.

Hronsky, J.M.A. and Groves, D.I. (2008) Science of targeting: definition, strategies, targeting and performance measurement. *Australian Journal of Earth Sciences*, **55**, 3–12.

Huang, H., Polat, A., Fryer, B.J., Appel, P.W.U. and Windley, B.F. (2012) Geochemistry of the Mesoarchean Fiskenæsset Complex at Majorqap qâva, SW Greenland: Evidence for two different magma compositions. *Chemical Geology*, **314–317**, 66–82.

Huang, H., Fryer, B.J., Polat, A. and Pan, Y. (2014) Amphibole, plagioclase and clinopyroxene geochemistry of the Archean Fiskenæsset Complex at Majorqap qâva, southwestern Greenland: Implications for Archean petrogenetic and geodynamic processes. *Precambrian Research*, **247**, 64–91.

Jones, A.P., Price, G.D., Price, N.J., De Carli, P.S. and Clegg, R.A. (2002) Impact induced melting and the development of large igneous provinces. *Earth and Planetary Science Letters*, **202**, 551–561.

Kamber, B.S. and Moorbath, S. (1998) Initial Pb of the Amitsoq gneiss revisited: implication for the timing of early Archaean crustal evolution in West Greenland. *Chemical Geology*, **150**, 19–41.

Keulen, N., Schumacher, J.C. and Kokfelt, T.F. (2011) *Notes on established structural profiles related to the 1:100000 digital geological map of southern West and South-West Greenland, 61º30′ – 64ºN*. Danmarks og Grønlands Geologiske Undersøgelse Rapport, 2011/13. GEUS, Copenhagen, 68 pp.

Keulen, N., Schumacher, J.C., Næraa, T., Kokfelt, T.F., Scherstén, A., Szilas, K., van Hinsberg, V.J., Schlatter, D.M. and Windley, B.F. (2014) Meso- and Neoarchaean geological history of the Bjørnesund and Ravns Storø supracrustal belts, southern West Greenland: Settings for gold enrichment and corundum formation. *Precambrian Research*, **254**, 36–58.

Kisters, A.F.M., van Hinsberg, V.J. and Szilas, K. (2012) Geology of an Archaean accretionary complex – The structural record of burial and return flow in the Tartoq Group of South West Greenland. *Precambrian Research*, **220–221**, 107–122.

Klausen, M.B., Kokfelt, T.F., Keulen, N., Berger, A. and Schumacher, J.C. (2011) Tholeiitic 'komatiite'-basalt and calc-alkaline andesite-dacite succession in the Archaean Kvanefjord area (South-West Greenland): a composite oceanic and volcanic arc suite? *Geophysical Research Abstracts*, **13**, EGU2011–10661.

Klausen, M.B. and Kokfelt, T. (2014) *Field report from the 2011 field season on the Skjoldungen Alkaline Province, South-East Greenland.* Geological Survey of Denmark and Greenland Report 2014/81. GEUS, Copenhagen, 85 pp.

Knudsen, C., van Gool, J.A.M., Østergaard, C., Hollis, J.A., Rink-Jørgensen, M., Persson, M. and Szilas, K. (2007) Gold-hosting supracrustal rocks on Storø, southern West Greenland: lithologies and geological environment. *Geological Survey of Denmark and Greenland Bulletin*, **13**, 41–44.

Kokfelt, T., Keulen, N., Næraa, T., Scherstén, A. and Heijboer, T. (2011) New zircon U/Pb age data from the Archaean craton, South-West and southern West Greenland (61º30'N – 64º00'N). *Geophysical Research Abstracts*, **13**, EGU2011–14038.

Kolb, J. (2011) *Controls of hydrothermal quartz vein mineralisation and wall rock alteration in the Paamiut and Tartoq areas, South-West Greenland*. Geological Survey of Denmark and Greenland Report 2011/114. GEUS, Copenhagen, 176 pp.

Kolb, J. (2014) Structure of the Palaeoproterozoic Nagssugtoqidian Orogen, South-East Greenland: model for the tectonic evolution. *Precambrian Research*, **255**, 809–822.

Kolb, J., Stensgaard, B.M., Schlatter, D.M. and Dziggel, A. (2009) *Controls of hydrothermal quartz vein mineralisation and wall rock alteration between Ameralik and Sermilik, southern West Greenland*. Danmarks og Grønlands Geologiske Undersøgelse Rapport, 2009/25. GEUS, Copenhagen, 76 pp.

Kolb, J., Dziggel, A., Koppelberg, M., Stoltz, N.B., Kisters, A.F.M. and Bergen, A. (2010) *Controls of hydrothermal quartz vein mineralisation and wall rock alteration between Sermilik and Grædefjord, southern West Greenland*. Danmarks og Grønlands Geologiske Undersøgelse Rapport, 2010/47. GEUS Copenhagen, 73 pp.

Kolb, J., Kokfelt, T. and Dziggel, A. (2012) Deformation history of an Archaean terrane at mid-crustal level: the Tasiusarsuaq terrane of southern West Greenland. *Precambrian Research*, **212–213**, 34–56.

Kolb, J., Dziggel, A. and Schlatter, D.M. (2013*a*) Gold occurrences of the Archean North Atlantic craton, southwestern Greenland: a comprehensive genetic model. *Ore Geology Reviews*, **54**, 29–58.

Kolb, J., Thrane, K. and Bagas, L. (2013*b*) Field relationship of high-grade Neo- to Mesoarchaean rocks of South-East Greenland: Tectono-metamorphic and magmatic evolution. *Gondwana Research*, **23**, 471–491.

Le Vaillant, M., Barnes, S.J., Miller, J., McCuaig, T.C., Mucilli, P. and Fiorentini, M.L. (2015) A hydrothermal Ni-As-PGE geochemical halo around the Miitel nickel sulfide deposit, Yilgarn Craton, Western Australia. *Economic Geology*, **110**, 505–530.

London Mining Plc (2014) *Greenland Bankable Feasibility Study*. Isua Iron Ore Project, London Mining.

Lydon, J.W. (2007) An overview of the economic and geological contexts of Canada's major mineral deposit types. Pp. 3–48 in: *Mineral Deposits of Canada: a Synthesis of Major Deposit-types, District*

Metallogeny, the Evolution of Geological Provinces, and Exploration Methods (W.D. Goodfellow, editor). Geological Association of Canada, Mineral Deposits Division, Special Publication, **No. 5**. GAC, St. John's, Canada.

McCuaig, T.C., Beresford, S. and Hronsky, J.M.A. (2010) Translating the mineral systems approach into an effective exploration targeting system. *Ore Geology Reviews*, **38**, 128–138.

McGregor, V.R. and Friend, C.R.L. (1997) Field recognition of rocks totally retrogressed from granulite facies: an example from Archaean rocks in the Paamiut region, South-West Greenland. *Precambrian Research*, **86**, 59–70.

McGregor, V.R. and Mason, B. (1977) Petrogenesis and geochemistry of metabasaltic and metasedimentary enclaves in the Amîtsoq gneisses, West Greenland. *American Mineralogist*, **62**, 887–904.

McGregor, V.R., Friend, C.R.L. and Nutman, A.P. (1991) The late Archaean mobile belt through Godthåbsfjord, southern West Greenland: a continent-continent collision zone? *Bulletin of the Geological Society of Denmark*, **39**, 179–197.

Myers, J.S. (1976*a*) The Early Precambrian Gneiss Complex of Greenland. Pp. 165–176 in: *The Early History of the Earth* (B.F. Windley, editor). Wiley. London.

Myers, J.S. (1976*b*) Channel deposits of peridotite, gabbro and chromitite from turbidity currents in the stratiform Fiskenaesset anorthosite complex, southwest Greenland. *Lithos*, **9**, 281–291.

Myers, J.S. (1985) Stratigraphy and structure of the Fiskenæsset Complex, southern West Greenland. *Bulletin Grønlands Geologiske Undersøgelse*, **150**, 72.

Myers, J.S. and Crowley, J.L. (2000) Vestiges of life in the oldest Greenland rocks? A review of early Archean geology in the Godthabsfjord region, and reappraisal of field evidence for >3850 Ma life on Akilia. *Precambrian Research*, **103**, 101–124.

Nielsen, B.L. (1973) *A survey of the economic geology of Greenland (exclusive fossil fuels)*, Geological Survey of Greenland Report 56. GEUS, Copenhagen, 45 pp.

Nielsen, B.L. (1976) Economic minerals. Pp. 460–487 in: *Geology of Greenland* (A. Escher and W.S. Watt, editors). The Geological Survey of Greenland. Copenhagen.

Nilsson, M.K.M., Söderlund, U., Ernst, R.E., Hamilton, M.A., Scherstén, A. and Armitage, P.E.B. (2010) Precise U–Pb baddeleyite ages of mafic dykes and intrusions in southern West Greenland and implications for a possible reconstruction with the Superior craton. *Precambrian Research*, **183**, 399–415.

North American Nickel (2014) *Maniitsoq Overview*. http://www.northamericannickel.com/English/projects/greenland/maniitsoq/default.aspx.

Nutman, A.P. and Friend, C.R.L. (2007) Adjacent terranes with ca. 2715 and 2650 Ma high-pressure metamorphic assemblages in the Nuuk region of the North Atlantic Craton, southern West Greenland: Complexities of Neoarchaean collisional orogeny. *Precambrian Research*, **155**, 159–203.

Nutman, A.P. and Friend, C.R.L. (2009) New 1:20,000 scale geological maps, synthesis and history of investigation of the Isua supracrustal belt and adjacent orthogneisses, southern West Greenland: A glimpse of Eoarchaean crust formation and orogeny. *Precambrian Research*, **172**, 189–211.

Nutman, A.P. and Kalsbeek, F. (1994) A minimum age of 2944 ± 7 Ma for the Tartoq Group, South-West Greenland. *Rapport Grønlands Geologiske Undersøgelse*, **161**, 35–38.

Nutman, A.P., McGregor, V.R., Friend, C.R.L., Bennett, V.C. and Kinny, P.D. (1996) The Itsaq Gneiss Complex of southern West Greenland; the world's most extensive record of early crustal evolution (3900–3600 Ma). *Precambrian Research*, **78**, 1–39.

Nutman, A.P., Mojzsis, S.J. and Friend, C.R.L. (1997) Recognition of ⩾3850 Ma water-lain sediments in West Greenland and their significance for the early Archaean Earth. *Geochimica et Cosmochimica Acta*, **61**, 2475–2484.

Nutman, A.P., Bennett, V.C., Friend, C.R.L. and Norman, M.D. (1999) Meta-igneous (non-gneissic) tonalites and quartz-diorites from an extensive ca. 3800 Ma terrain south of the Isua supracrustal belt, southern West Greenland: constraints on early crust formation. *Contributions to Mineralogy and Petrology*, **137**, 364–388.

Nutman, A.P., Bennett, V.C., Friend, C.R.L. and McGregor, V.R. (2000) The early Archaean Itsaq Gneiss Complex of southern West Greenland: the importance of field observations in interpreting age and isotopic constraints for early terrestrial evolution. *Geochimica et Cosmochimica Acta*, **64**, 3035–3060.

Nutman, A.P., McGregor, V.R., Shiraishi, K., Friend, C.R.L., Bennett, V.C. and Kinny, P.D. (2002) ⩾3850 Ma BIF and mafic inclusions in the early Archaean Itsaq Gneiss Complex around Akilia, southern West Greenland? The difficulties of precise dating of zircon-free protoliths in migmatites. *Precambrian Research*, **117**, 185–224.

Nutman, A.P., Friend, C.R.L., Barker, S.L.L. and McGregor, V.R. (2004) Inventory and assessment of Palaeoarchaean gneiss terrains and detrital zircons in southern West Greenland. *Precambrian Research*, **135**, 281–314.

Nutman, A.P., Bennett, V., Friend, C., Horie, K. and Hidaka, H. (2007*a*) ~3,850 Ma tonalites in the Nuuk region, Greenland: geochemistry and their reworking within an Eoarchaean gneiss complex. *Contributions to Mineralogy and Petrology*, **154**, 385–408.

Nutman, A.P., Christiansen, O. and Friend, C.R.L. (2007*b*) 2635 Ma amphibolite facies gold mineralisation near a terrane boundary (suture?) on Storo, Nuuk region, southern West Greenland. *Precambrian Research*, **159**, 19–32.

Nutman, A.P., Kalsbeek, F. and Friend, C.R.L. (2008) The Nagssugtoqidian Orogen in South-East Greenland: evidence for Paleoproterozoic collision and plate assembly. *American Journal of Science*, **308**, 529–572.

Nutman, A.P., Friend, C.R.L. and Hiess, J. (2010) Setting of the ~2560 Ma Qôrqut granite complex in the Archean crustal evolution of southern West Greenland. *American Journal of Science*, **310**, 1081–1114.

Næraa, T. and Scherstén, A. (2008) New zircon ages from the Tasiusarsuaq terrane, southern West Greenland. *Geological Survey of Denmark and Greenland Bulletin*, **15**, 73–76.

Næraa, T., Scherstén, A., Rosing, M.T., Kemp, A.I.S., Hoffmann, J.E., Kokfelt, T.F. and Whitehouse, M.J. (2012) Hafnium isotope evidence for a transition in the dynamics of continental growth 3.2 Gyr ago. *Nature*, **485**, 627–631.

Næraa, T., Kokfelt, T.F. and Thrane, K. (2014) Zircon geochronology of the Skjoldungen region, SE Greenland. *31st Nordic Geological Winter Meeting, Lund, Sweden*. Geological Society of Sweden, Abstract volume, p. 92.

Ordóñez-Calderón, J.C., Polat, A., Fryer, B.J., Gagnon, J.E., Raith, J.G. and Appel, P.W.U. (2008) Evidence for HFSE and REE mobility during calc-silicate metasomatism, Mesoarchean (~3075 Ma) Ivisaartoq greenstone belt, southern West Greenland. *Precambrian Research*, **161**, 317–340.

Ordóñez-Calderón, J.C., Polat, A., Fryer, B., Appel, P.W.U., van Gool, J.A.M., Dilek, Y. and Gagnon, J.E. (2009) Geochemistry and geodynamic origin of Mesoarchean oceanic crust in the Ujarassuit and Ivisaartoq greenstone belts, SW Greenland. *Lithos*, **113**, 133–157.

Ordóñez-Calderón, J.C., Polat, A., Fryer, B.J. and Gagnon, J.E. (2011) Field and geochemical characteristics of Mesoarchean to Neoarchean volcanic rocks in the Storø greenstone belt, SW Greenland: evidence for accretion of intra-oceanic volcanic arcs. *Precambrian Research*, **184**, 24–42.

Østergaard, C. (2013) *Greenland Gold Resources – 2012 Field Work Pinnersut (Fiskenæsset)*. 21st North, Svendborg, Denmark [www.21stnorth.com].

Owen, J. (2012) *Characterisation of the nickel sulphide mineralisation between Graah Fjord and Bernstorff Isfjord, South-East Greenland*. Geological Survey of Denmark and Greenland Report 2012/66. GEUS, Copenhagen, 107 pp.

Owens, B.E. and Dymek, R.F. (1997) Comparative petrology of Archaean anorthosites in amphibolite and granulite facies terranes, SW Greenland. *Contributions to Mineralogy and Petrology*, **128**, 371–384.

Petersen, J.S. (1992) *Kujataa: Field Report – 1992. Nuuluk-Iterlak Gold and Massive Sulfide Project, Taartoq Archaean Greenstone Belt, SW Greenland*. Internal Report, **55**, NunaOil A/S, Greenland.

Pidgeon, R.T. and Kalsbeek, F. (1978) Dating of igneous and metamorphic events in the Fiskenaesset region of southern West Greenland. *Canadian Journal of Earth Sciences*, **15**, 2021–2025.

Polat, A. and Hofmann, A.W. (2003) Alteration and geochemical patterns in the 3.7–3.8 Ga Isua greenstone belt, West Greenland. *Precambrian Research*, **126**, 197–218.

Polat, A. and Longstaffe, F.J. (2014) A juvenile oceanic island arc origin for the Archean (ca. 2.97 Ga) Fiskenæsset anorthosite complex, southwestern Greenland: evidence from oxygen isotopes. *Earth and Planetary Science Letters*, **396**, 252–266.

Polat, A., Appel, P.W.U., Frei, R., Pan, Y., Dilek, Y., Ordóñez-Calderón, J.C., Fryer, B., Hollis, J.A. and Raith, J.G. (2007) Field and geochemical characteristics of the Mesoarchean (~3075 Ma) Ivisaartoq greenstone belt, southern West Greenland: evidence for seafloor hydrothermal alteration in supra-subduction oceanic crust. *Gondwana Research*, **11**, 69–91.

Polat, A., Frei, R., Appel, P.W.U., Dilek, Y., Fryer, B., Ordonez-Calderon, J.C. and Yang, Z. (2008*a*) The origin and compositions of Mesoarchean oceanic crust: evidence from the 3075 Ma Ivisaartoq greenstone belt, SW Greenland. *Lithos*, **100**, 293–321.

Polat, A., Frei, R., Appel, P.W.U., Fryer, B., Dilek, Y. and Ordóñez-Calderón, J.C. (2008*b*) An overview of the lithological and geochemical characteristics of the Mesoarchean (ca. 3075 Ma) Ivisaartoq greenstone belt, southern West Greenland. Pp. 51–76. in: *When Did Plate Tectonics Begin on Planet Earth?* (K.C. Condie and V. Pease, editors). Geological Society of America Special Paper, **440**. The Geological Society of America, Boulder, Colorado, USA.

Polat, A., Appel, P.W.U., Fryer, B., Windley, B.F., Frei, R., Samson, I.M. and Huang, H. (2009) Trace element systematics of the Neoarchean Fiskenæsset anorthosite complex and associated meta-volcanic rocks, SW Greenland: Evidence for a magmatic arc origin. *Precambrian Research*, **175**, 87–115.

Polat, A., Appel, P.W.U. and Fryer, B.J. (2011) An overview of the geochemistry of Eoarchean to Mesoarchean ultramafic to mafic volcanic rocks, SW Greenland: implications for mantle depletion and petrogenetic processes at subduction zones in the early Earth. *Gondwana Research*, **20**, 255–283.

Polat, A., Fryer, B.J., Samson, I.M., Weisener, C., Appel, P.W.U., Frei, R. and Windley, B.F. (2012) Geochemistry of ultramafic rocks and hornblendite veins in the Fiskenæsset layered anorthosite complex, SW Greenland: Evidence for hydrous upper mantle in the Archean. *Precambrian Research*, **214–215**, 124–153.

Rasmussen, T.M. and van Gool, J.A.M. (2000) Aeromagnetic survey in southern West Greenland: project Aeromag 1999. *Geological Survey of Denmark and Greenland Bulletin*, **186**, 73–77.

Rasmussen, T.M., Thorning, L., Stemp, R.W., Jørgensen, M.S. and Schjøth, F. (2001) *AEM Greenland 1994–1998 – summary report*. Geological Survey of Denmark and Greenland Report 2001/58. GEUS, Copenhagen, 46 pp.

Reimold, W.U., Gibson, R.L. and Koeberl, C. (2013) Comment on "Searching for giant, ancient impact structures on Earth: The Mesoarchaean Maniitsoq structure, West Greenland" by Garde *et al.* [*Earth Planet. Sci. Lett*. **337–338** (2012) 197–210]. *Earth and Planetary Science Letters*, **369–370**, 333–335.

Riciputi, L.R., Valley, J.W. and McGregor, V.R. (1990) Conditions of Archean granulite metamorphism in the Godthab-Fiskenaesset region, southern West Greenland. *Journal of Metamorphic Geology*, **8**, 171–190.

Robert, F. and Poulsen, K.H. (1997) World-class Archaean gold deposits in Canada: an overview. *Australian Journal of Earth Sciences*, **44**, 329–351.

Rollinson, H.R., Appel, P.W.U. and Frei, R. (2002) A metamorphosed, Early Archaean chromitite from West Greenland: Implications for the genesis of Archaean anorthositic chromitites. *Journal of Petrology*, **43**, 2143–2170.

Rollinson, H.R., Reid, C. and Windley, B.F. (2010) Chromitites from the Fiskenæsset anorthositic complex, West Greenland: clues to late Archaean mantle processes. Pp. 197–212 in: *The Evolving Continents: Understanding Processes of Continental Growth* (T.M. Kusky, M.-G. Zhai and W. Xiao, editors). Geological Society of London Special Publications, **338**, London.

Rosing, M.T., Nutman, A.P. and Lofqvist, L. (2001) A new fragment of the early earth crust: the Aasivik terrane of West Greenland. *Precambrian Research*, **105**, 115–128.

Scherstén, A. and Garde, A.A. (2013) Complete hydrothermal re-equilibration of zircon in the Maniitsoq structure, West Greenland: A 3001 Ma minimum age of impact? *Meteoritics & Planetary Science*, **48**, 1472–1498.

Scherstén, A., Szilas, K., Creaser, R.A., Næraa, T., van Gool, J.A.M. and Østergaard, C. (2012) Re-Os and U-Pb constraints on gold mineralisation events in the Meso- to Neoarchaean Storø greenstone belt, Storø, southern West Greenland. *Precambrian Research*, **200–203**, 149–162.

Schjøtte, L., Compston, W. and Bridgwater, D. (1989) U-Pb single-zircon age for the Tinissaq gneiss of southern West Greenland: a controversy resolved. *Chemical Geology*, **79**, 21–30.

Schlatter, D.M. and Stensgaard, B.M. (2014) Combined exploration and multivariate techniques to detect the Bjørnesund West gold occurrence, southern West Greenland. *Geological Survey of Denmark and Greenland Bulletin*, **31**, 67–70.

Schumacher, J.C., van Hinsberg, V.J. and Keulen, N. (2011) *Metamorphism in supracrustal and ultramafic rocks in southern West and South-West Greenland 64 – 61.5ºN*. Geological Survey of Denmark and Greenland Report 2011/6, GEUS, Copenhagen, 30 pp.

Secher, K. (1983) Noritic rocks and associated nickel-copper-sulphide occurrences in Sukkertoppen district, central West Greenland. *Rapport Grønlands Geologiske Undersøgelse*, **115**, 30–34.

Secher, K. (2001) *The Pd+Pt dispersion in noritic and undifferentiated mafic rocks of the Archaean craton east of Maniitsoq, southern West Greenland*. Geological Survey of Denmark and Greenland Report 2001/123. GEUS, Copenhagen, 22 pp.

St-Onge, M.R., van Gool, J.A.M., Garde, A.A. and Scott, D.J. (2009) Correlation of Archaean and Palaeoproterozoic units between northeastern Canada and western Greenland: Constraining the pre-collisional upper plate accretionary history of the Trans-Hudson orogen. Pp. 193–235 in: *Earth Accretionary Systems in Space and Time* (P.A. Cawood and A. Kröner, editors). Geological Society of London Special Publications, **318**, London.

Steenfelt, A. (2001) *Geochemical atlas of Greenland – West and South Greenland*. Danmarks og Grønlands Geologiske Undersøgelse Rapport, 2001/46. GEUS, Copenhagen, 39 pp.

Stendal, H. (2011) *Geology and mineral resources of the Archaean craton (66º–63º30'N), southern West Greenland*. Geological Survey of Denmark and Greenland Report 2011/57. GEUS, Copenhagen, 45 pp.

Stensgaard, B.M. (2013) *Predictive gold potential in entire southern West Greenland assessed by geological experience, artificial neural network and self-organizing maps analysis*. Geological Survey of Denmark and Greenland Report 2013/15. GEUS, Copenhagen, 88 pp.

Szilas, K. and Garde, A.A. (2013) Mesoarchaean aluminous rocks at Storø, southern West

Greenland: new age data and evidence of premetamorphic seafloor weathering of basalts. *Chemical Geology*, **354**, 124–138.

Szilas, K., Hoffmann, J.E., Scherstén, A., Rosing, M.T., Windley, B.F., Kokfelt, T.F., Keulen, N., van Hinsberg, V.J., Næraa, T., Frei, R. and Münker, C. (2012*a*) Complex calc-alkaline volcanism recorded in Mesoarchaean supracrustal belts north of Frederikshåb Isblink, southern West Greenland: Implications for subduction zone processes in the early Earth. *Precambrian Research*, **208–211**, 90–123.

Szilas, K., Næraa, T., Scherstén, A., Stendal, H., Frei, R., van Hinsberg, V.J., Kokfelt, T. and Rosing, M.T. (2012*b*) Origin of Mesoarchaean arc-related rocks with boninite/komatiite affinities from southern West Greenland. *Lithos*, **144–145**, 24–39.

Szilas, K., Hoffmann, J.E., Scherstén, A., Kokfelt, T.F. and Münker, C. (2013*a*) Archaean andesite petrogenesis: Insights from the Grædefjord Supracrustal Belt, southern West Greenland. *Precambrian Research*, **236**, 1–15.

Szilas, K., Van Hinsberg, V.J., Kisters, A.F.M., Hoffmann, J.E., Windley, B.F., Kokfelt, T.F., Scherstén, A., Frei, R., Rosing, M.T. and Münker, C. (2013*b*) Remnants of arc-related Mesoarchaean oceanic crust in the Tartoq Group of SW Greenland. *Gondwana Research*, **23**, 436–451.

Thorning, L. (1984) Aeromagnetic maps of parts of southern and central West Greenland: acquision, compilation and general analysis of data. *Rapport Grønlands Geologiske Undersøgelse*, **122**, 36.

Tukiainen, T., Rasmussen, T.M., Secher, K. and Steenfelt, A. (2003) *Restored digital airborne radiometric data from surveys flown in 1975 and 1976 by GGU between 63º and 69ºN, West Greenland*. Geological Survey of Denmark and Greenland Report 2003/37. GEUS, Copenhagen, 9 pp.

Tukiainen, T. and Thorning, L. (2005) Detection of kimberlitic rocks in West Greenland using airborne hyperspectral data: the HyperGreen 2002 project. *Geological Survey of Denmark and Greenland Bulletin*, **7**, 69–72.

van Gool, J.A.M., Connelly, J.N., Marker, M. and Mengel, F.C. (2002) The Nagssugtoqidian Orogen of West Greenland: tectonic evolution and regional correlations from a West Greenland perspective. *Canadian Journal of Earth Sciences*, **39**, 665–686.

van Gool, J.A.M., Scherstén, A., Østergaard, C. and Næraa, T. (2007) *Geological setting of the Storø gold prospect, Godthåbsfjord region, southern West Greenland; Results of detailed mapping, structural analysis, geochronology and geochemistry*. Geological Survey of Denmark and Greenland Report 2007/83. GEUS, Copenhagen, 158 pp.

van Hinsberg, V.J., Szilas, K. and Kisters, A.F.M. (2010) *The Tartoq group, SW Greenland: Mineralogy, textures and a preliminary metamorphic to hydrothermal history*. Geological Survey of Denmark and Greenland Report 2010/120. GEUS, Copenhagen, 40 pp.

Whitehouse, M.J., Kamber, B.S. and Moorbath, S. (1999) Age significance of U-Th-Pb zircon data from early Archaean rocks of west Greenland – a reassessment based on combined ion-microprobe and imaging studies. *Chemical Geology*, **160**, 201–224.

Windley, B.F. (2009) Shear zones and suture on tectonic boundaries in the Grædefjord region. P. 29 in: *Annual Workshop on the Geology of Southern West Greenland Related to Field Work* (J. Kolb and T. Kokfelt, editors). Abstract Volume I, 2009/21. Geological Survey of Denmark and Greenland Report, Copenhagen.

Windley, B.F. and Garde, A.A. (2009) Arc-generated blocks with crustal sections in the North Atlantic craton of West Greenland: crustal growth in the Archean with modern analogues. *Earth-Science Reviews*, **93**, 1–30.

Windley, B.F., Herd, R.K. and Bowden, A.A. (1973) The Fiskenæsset complex, West Greenland Part I A preliminary study of the stratigraphy, petrology, and whole rock chemistry from Qeqertarssuatsiaq. *Meddelelser om Grønland*, **196**, 80.

Wyborn, L.A.I., Heinrich, C.A. and Jaques, A.L. (1994) Australian Proterozoic mineral systems: essential ingredients and mappable criteria. *Australian Institute for Minerals and Metallogeny Annual Conference*, 109–115.