DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2013/50

Geological mapping and tectonostratigraphy of mineralised mafic bands of the Timmiarmiut region of South-East Greenland

South-East Greenland Mineral Endowment Task Project, SEGMENT 2009-2014

Brendan D. Lally

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

G E U S

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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GEUS

Introduction

In 2010, the Geological Survey of Denmark and Greenland (GEUS) and the Centre for Exploration Targeting, University of Western Australia (CET-UWA) agreed on scientific collaboration on projects in Greenland and mineral systems for Ni and Au mineralisation. In the following, two students and one professional geologist from Australia took part in the South-East Greenland Mineral Endowment Task expedition, SEGMENT 2011, in order to establish research collaboration and starting two Bachelor of Science in Geology projects. These were designed around Ni-sulphide mineralisation in several locations hosted by lower crustal ultramafic and mafic rocks. The Centre for Exploration Targeting established a research project ”Experimental determination of metal sources and transport mechanisms in the deep lithosphere”, in which the research in South-East Greenland was embedded. This multi-scale integrated study is designed to integrate experimental work with tests through the measurement of rock samples collected from key localities where the deep lithosphere is exposed, i.e. South-East Greenland.

This volume contains the Bachelor of Science in Geology Thesis by Brendan D. Lally, which represents the third collaborative bachelor project between GEUS and CET-UWA. Brendan mapped during the SEGMENT 2012 expedition breccias that are developed at various lithological contacts, but mainly at the contact between mafic granulite and felsic orthogneisses. His main objectives were the characterisation of the breccias as deformed rocks and host of hydrothermal alteration as well as establishing a model for breccia formation related to the regional tectonometamorphic and magmatic evolution. He was able to identify two general types of breccia: (1) heterolithic breccia with a massive sulphide matrix; and (2) heterolithic breccia with a fine-grained biotite matrix. The breccias were formed relatively late in the tectonometamorphic evolution in the retrograde stage from peak granulite facies either late during the Skjoldungen orogeny or during the Singertat stage. Mineral assemblages indicate a hydrothermal overprint in the amphibolite facies to the upper greenschist facies. Hydrothermal biotite in the breccia matrix was replaced by sulphides indicating an evolution of the fluids during the hydrothermal stage. The breccias potentially formed by brittle deformation in normally ductile crustal levels and represented pathways for the hydrothermal fluids.

Thus, they represent a mid-crustal zone of fluid transfer, which to date is not known to be related to larger scale hydrothermal mineralisation of e.g. gold.

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Abstract

Bands of mafic granulite with local ultramafic and possible meta-sedimentary rocks represent an exposure of the proto-lower crust in the Timmiarmiut region of the Thrym Complex. The mafic bands were intruded by the precursors to an extensive migmatite unit and numerous suites of granitic melts. The Timmiarmiut region has undergone a complex structural and metamorphic history with four Archean deformation events and at least three Proterozoic to Phanerozoic events. The earliest recognised event is the Timmiarmiut orogeny (D_T), characterised by isoclinal folding, which resulted in a foliation in the mafic bands and the migmatite. Peak granulite metamorphism occurred pre- to syn-D_T and lasted until the end of the Skjoldungen orogeny causing partial melting of mafic granulite and formation of the migmatitic texture. A NE-SW compressional regime termed the Skjoldungen orogeny resulted in isoclinal folding of the earlier foliation and formed a pervasive axial planar foliation traceable across the whole Thrym Complex. The Singertât stage brought about E-W compression and the major control on the present orientation of the mafic bands in the Timmiarmiut region. It is characterised by open to close folds and conjugate northwest trending dextral and northeast trending sinistral shear zones. These shear zones are associated with a retrogression in metamorphic facies to upper amphibolite, lower greenschist which is not seen in other areas. Locally, pyrrhotite, pyrite, chalcopyrite and ilmenite have precipitated along these shear zones and formed matrix-supported breccia. The final Archean deformation stage is coined D_4 and gently folds the rocks in an E-W direction.

Introduction

Problem identification

The aims of this study are to complete the first detailed mapping and documentation of rocks containing sulfides in the Timmiarmiut region along with a discussion on the structural evolution of the area. A reconnaissance study of the Timmiarmiut region of the Thrym Complex in the southeastern part of Greenland was conducted in 2011. The project was part of the South-East Greenland Mineral Endowment Task (SEGMENT) by the Geological Survey of Denmark and Greenland (GEUS) and the Centre for Exploration Targeting (CET) at The University of Western Australia (UWA). The project focused on what are locally called 'rusty' horizons representing possible sulfide bearing horizons that potentially characterise mineralised zones. Samples of the sulfides were collected for this study, although detailed geochemical analysis will be completed by GEUS in the future.

Aims and objectives

The aims and objectives of the study are summarised in the following two points:

1. Detailed mapping of the Timmiarmiut region along the southeastern coast of Greenland between 62°20`N and 62°40`N, focusing on mafic bands that locally contain sulfides. The mapping was conducted partly using 3D photogrammetry and direct mapping of outcrop in the field, together with the collection and synthesis of lithological and structural data.

2. Establishing a tectono-stratigraphic scheme that will include the sulfide occurrences and a structural model for the evolution of the mineralisation and its host rocks. This was achieved through petrography and geochemistry of samples collected in 2011 and new structural and stratigraphic profiles taken in the field during the 2012 expedition.

Field expedition of 2012

The 2012 field season to South-East Greenland took place from the 26th of July to the 3rd of September. As GEUS headquarters are located in Denmark, it was necessary to be present in Copenhagen beforehand, from the 21st of June, to plan out fieldwork and logistics, complete safety courses and conduct petrography and geochemical analysis on previously collected samples. Travelling to South-East Greenland required flying from Denmark to Iceland and from there to Kulusuk and finally Kassortoq in Greenland. The base camp for the expedition was the MV Fox, a former long-line fishing vessel from the Faroe Islands which was stationed near Skjoldungen (Figs. 1, 2).

The field area for this project is located in the Timmiarmiut region (Figs. 1, 2). The Timmiarmiut region, like much of South-East Greenland, is made up of steep-sided mountains, cut by wide fjords which varied from 300 to 1000m in width that needed to be crossed by helicopter. Most of the target areas were accessible by foot and were visited in the field. However, fieldwork was initially delayed due to bad weather conditions that prohibited helicopter flight for five days. The first 4 weeks of the field season were spent at various camps in the Timmiarmiut region gathering structural and lithological data. The last week of the field season was spent some 200 km north around Thor Land (Fig. 2), where the findings of the earlier part of the reconnaissance in Timmiarmiut were tested.

Once in the field, the expedition separated into small teams of between two and four geoscientists that conducted differing and complimentary work in various parts of the Archean Thrym Complex. Camp moves and supply drops were conducted via the helicopter, which was the main mode of transport and support to all members in the field.

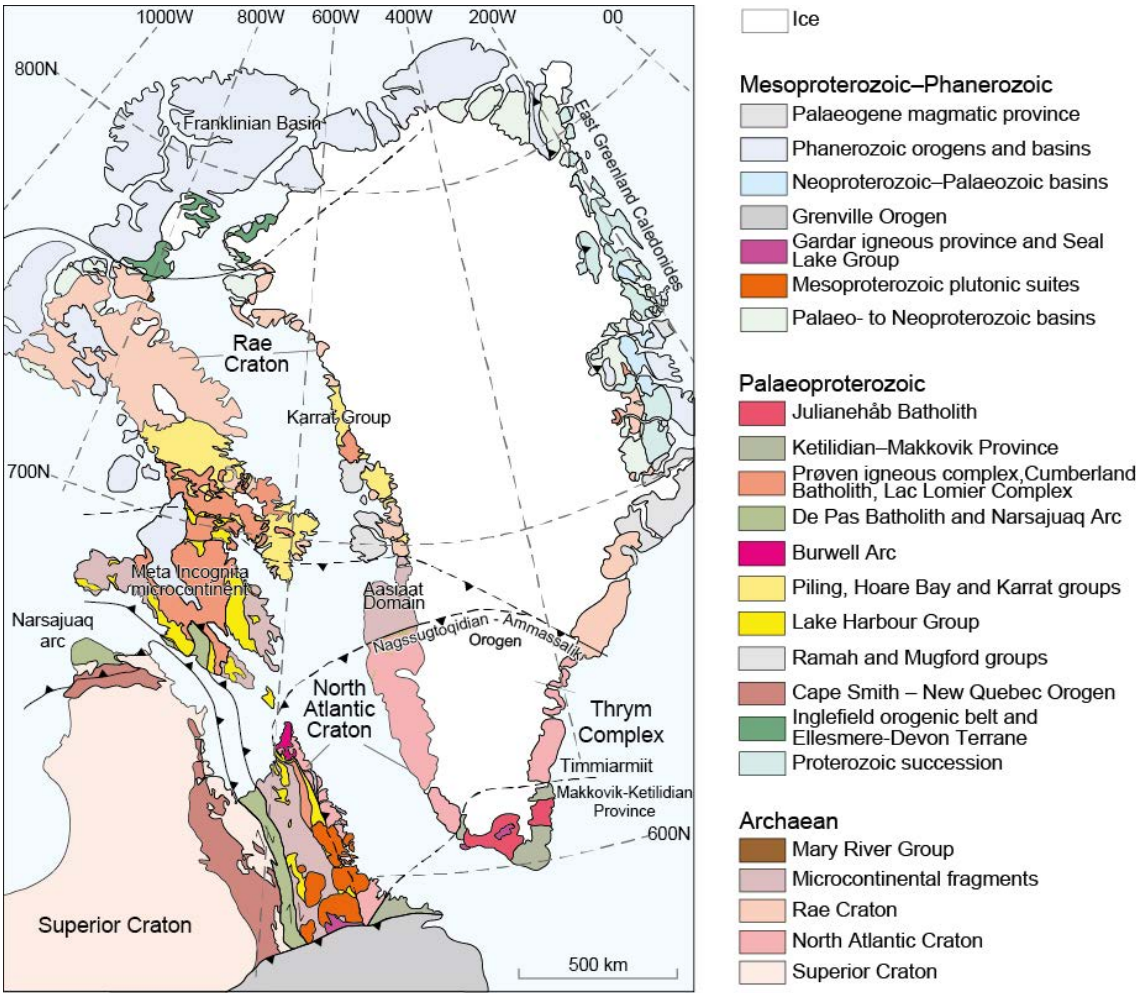

Fig. 1. Schematic geological map of Greenland in relation to the east coast of Canada. The North Atlantic Craton (NAC) of South-East Greenland (Thrym Complex) is linked with outcrop in southwestern Greenland and the Labrador coast of east Canada. The grey rectangular box highlights the Thrym Complex and is shown in more detail in Figure 2. Modified from (St-Onge *et al.*, 2009).

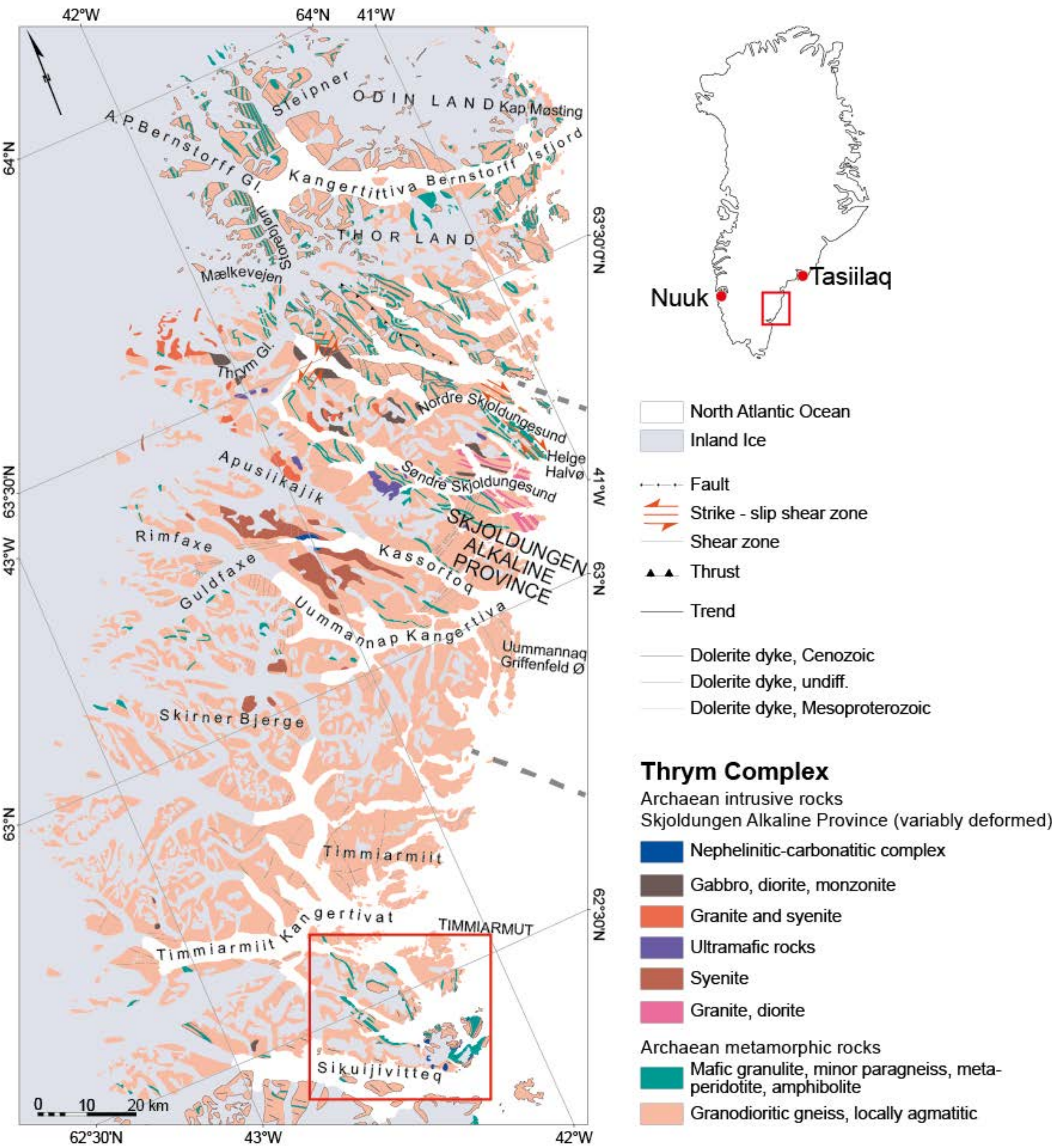

Fig. 2. Schematic geological map of the Thrym Complex showing the different lithologies present. The red box indicates the extent of the mapping and fieldwork completed for the 2012 expedition (modified after (Kolb *et al.*, 2013).

Geological background

Previous work

The exploration and documentation of geology in South-East Greenland has been very limited, and geological studies in the last 50 years have been completed by Government

Geological Surveys (discussed below). This limited work is due to the severe climate, rugged terrain, and isolation of the region, which render many potential areas of fieldwork inaccessible for much of the year and also to the nature of the rock outcrops. In fact, many of the field exposures are confined to steep sided cliff faces, which are covered in snow for much of the year and cut by wide fjords, making fieldwork challenging and requiring boat and helicopter support during the restricted summer months between July and September.

Early exploration of South-East Greenland was conducted by boat-based reconnaissance mapping in the late 1960s by the Geological Survey of Greenland (GGU), now GEUS, which was conducted primarily for the completion of the 1:2,500,000 scale geological map of Greenland (Andrews *et al.*, 1973). These early expeditions were used to create a preliminary geological framework for the Precambrian of the area (Bridgwater and Gormsen, 1969).

Follow up reconnaissance mapping was completed by ship in the late 1970s and early 1980s and again by helicopter in the late 1980s, which resulted in the compilation of a 1:500,000 scale geological map.

SEGMENT was formed by GEUS in 2009 in order to define potential scientific projects for the future and to target areas of economic interest (Stensgaard *et al.*, 2010; Kolb *et al.*, 2013). The fieldwork focused on the Thrym Complex, namely the area between Timmiarmiit Kangetivat and Bernstorff Isfjord (Fig. 2; Stensgaard *et al.*, 2010). Up until this point there had been minimal studies on mineralisation in the area, but with the identification of anomalous sulfide occurrences there are bound to be more detailed studies in the future.

Honours projects by John Owen and Steve Rennick from UWA in 2011 completed some of the preliminary projects that were identified by SEGMENT and focused on Ni mineralisation in the mafic and ultramafic units between Graah Fjord and Bernstorff Isfjord in the Skjoldungen region (Fig. 2) and detailed mapping and the structural evolution of these same areas. This honours project provides a complimentary study in the southern most region of the Thrym Complex with detailed mapping and tectono-stratigraphic analysis of the Timmiarmiut region. The project will allow for a better correlation between the geology of these two different parts of the Thrym Complex and help form a regional understanding of the geology of South-East Greenland.

Regional geology

Thrym Complex

The Thrym Complex of South-East Greenland (62° – 67°N) is bounded to the north by the Proterozoic Nagssugtoqidian-Ammassalik Orogen and south by the Ketilidian Orogen (Figs. 1, 2; Garde *et al.*, 2002; Kolb *et al.*, 2013). The complex represents the outcrop of the North Atlantic Craton (NAC) in South-East Greenland. The craton extends to the west to southwestern Greenland and on the Labrador coast of Canada, and to the east the Lewisian Complex of Scotland (Fig. 1; Bridgwater *et al.*, 1973; Bagas *et al.*, 2013).

The Thrym Complex is dominated by granodioritic orthogneiss with bands of amphibolitic to granulitic mafic and ultramafic rocks, which are up to 1 km in width and several tens of kilometres in length and small amounts of meta-sedimentary rocks (Fig. 2; Kolb *et al.*, 2013, Bagas *et al.*, 2013). A suite of late-tectonic alkaline intrusions form the Skjoldungen Alkaline Province (SAP), located in the Skjoldungen region (Fig. 2), are composed of hornblende-pyroxenite, hornblendite, hornblende-norite and diorite, leucogabbro, monzodiorite, monzonite, syenite, ijolite and carbonatite (Nielsen and Rosing, 1990; Nutman and Rosing, 1994; Blichert-Toft *et al.*, 1995).

Timmiarmiut region

The geology of the Timmiarmiut region shows both similarities and differences with the rest of the Thrym Complex (Fig. 3). The mafic and ultramafic rocks that are present extensively throughout the Skjoldungen region to the north are less abundant. A suite of ultramafic and alkaline rocks make up the Timmiarmiut Alkaline Province (TAP) of Kolb *et al.* (2013) and include metamorphosed granodiorite, monzodiorite and rare monzonite. Sequences identified as meta-sedimentary rocks are present in the Timmiarmiut region as well as in northern areas of the Thrym Complex and include garnet-sillimanite-quartz schists and biotite bearing gneisses (Chadwick and Walton, 1988).

Mafic and Ultramafic Rocks

The mafic and ultramafic rocks of the Timmiarmiut region form dismembered belts and disorientated fragments within granodioritic orthogneiss and are composed of gabbro, norite, dunite, hornblendite, and pyroxenite (Escher and Nielsen, 1983; Kolb *et al.*, 2013). They are interpreted as representing the oldest rocks in the area as the orthogneiss shows intrusive relationships with the mafic granulite and ultramafic rocks.

Orthogneisses

Orthogneiss is the dominant rock type in the area. The protoliths for the orthogneiss are granodiorite with lesser monzodiorite and rare monzonite (Kolb *et al.*, 2013; Bagas *et al.*, 2013). Migmatitic orthogneiss is common in the Timmiarmiut region. The orthogneiss shows relict intrusive relationships to an early basement of mafic amphibolites-granulites and has many similarities to the Frederikshåb district of southwestern Greenland (Andrews *et al.*, 1971).

Meta-sedimentary rocks

Successions interpreted as meta-sedimentary rocks are uncommon in the Timmiarmiut region and contain sillimanite-cordierite and garnet assemblages (Andrews *et al.*, 1971; Escher and Nielsen, 1983). They are reported from within the overall mafic dominated bands and their proposed sedimentary protoliths are based on their garnet and sillimanite content by (Escher and Nielsen, 1983), but this does not take into account retrogressed high-grade metamorphism and possible metasomatism that these rocks have been subjected to. Acknowledging this difficulty, these rocks are therein regarded cautiously as meta-sedimentary successions.

Metamorphism and deformation in the Timmiarmiut region

Peak metamorphism in the Timmiarmiut region, like in most of the Thrym Complex, is at granulite facies with local retrogression at upper amphibolite facies in shear zones (Escher and Nielsen, 1983; Bagas *et al.*, 2013).

Kolb *et al.* (2013) have identified at least seven deformation events in the Thrym Complex from the Archean to the present (Fig. 4). These include the Archean Timmiarmiut Orogeny (D_T), Skjoldungen Orogeny (D_S) and Singertât stage (D_R) and Proterozoic and Phanerozoic events. The Timmiarmiut Orogeny is characterised by a pronounced foliation (S_T) that is recorded in the mafic granulite, ultramafic rocks and the early orthogneiss. This foliation is folded during the Skjoldungen Orogeny into isoclinal folds (F_{S1}), which produce a regionally penetrative S_{S1} foliation. The Singertât stage produced tight folds and a conjugate set of shear zones with southeast-trending sinistral shear zones and northeast-trending dextral shear zones. The faults cross-cut all lithologies and formed under retrograde upper-amphibolite conditions. Paleo-, Meso- and Neo-Proterozoic dyke swarms have been distinguished throughout the Timmiarmiut region in association with brittle faulting (Fig. 4). Phanerozoic mafic dykes and faulting have also been identified (Fig. 4).

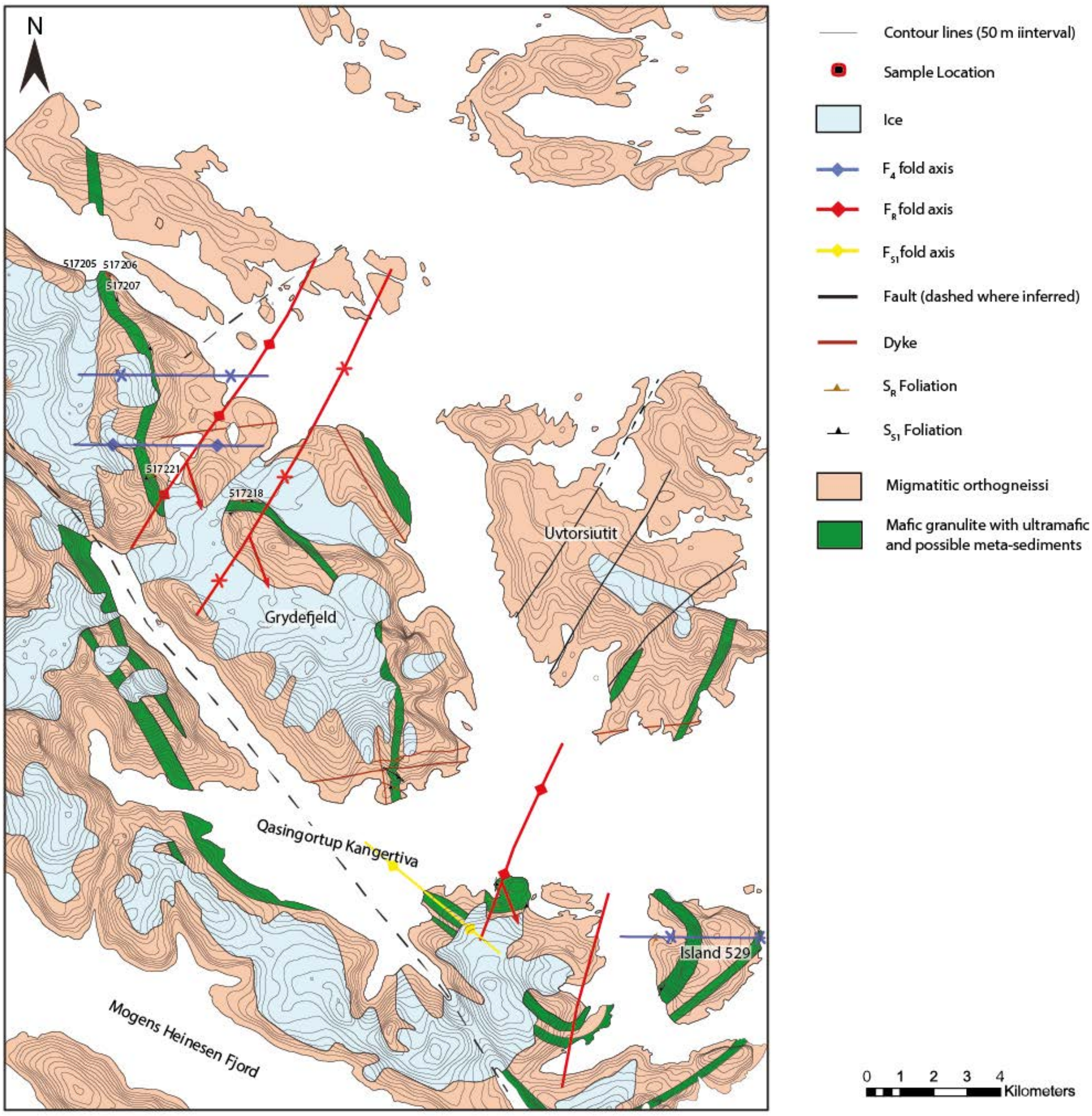

Fig. 3. Geological map of the Thrym Complex in the study area.

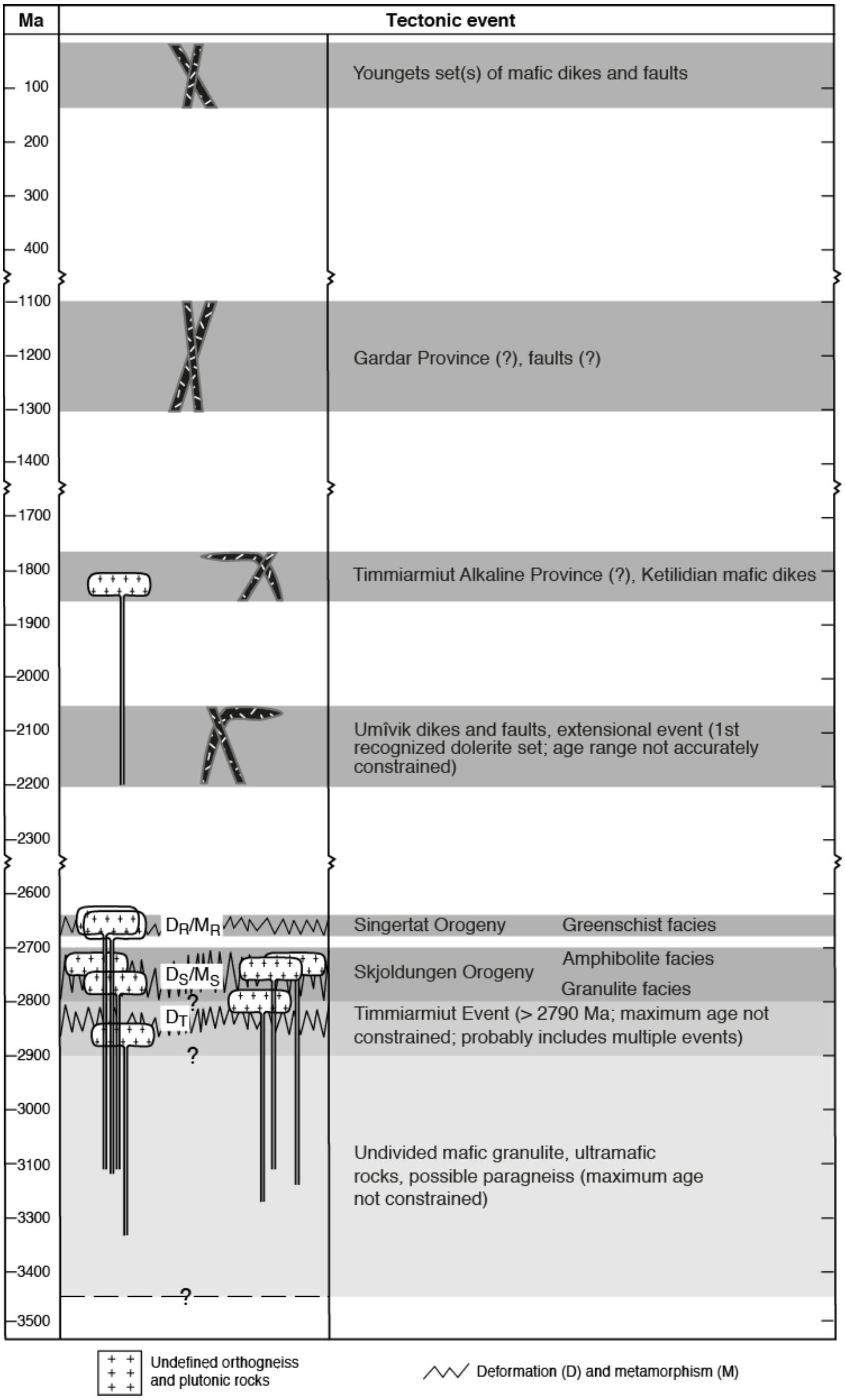

Fig. 4. Summary diagram of the structural, magmatic and tectono-metamorphic events for the Thrym Complex as proposed by Kolb *et al.* (2013).

Research methods

3D aerial photogrammetry

3D aerial photogrammetry is a form of remote sensing that enables geological features to be mapped prior to fieldwork and is also used for the planning of camps and work locations. The software used for the photogrammetry is SOCET SET, which is used in conjunction with the Planar SD2420W StereoMirror and the Planar SA2311W monitors. StereoMirror consists of two display units, oriented at 110° and mounted on a specifically designed stand. A passive “beam-splitter” (half-mirror) mirror is stationed between the two display units and bisects the angle made between them. The objective of the stereoscopic display is to present the left eye image to the left eye and the right eye image to the right eye. The human visual system merges the two images, which results in the perception of depth, the ‘3D’ image. Crossed-polarising glasses with polarising films mounted on the eye-pieces with their planes of polarisation at right angles to one another are worn so the user only sees the left eye image with the eyepiece that contains the 90° polariser and the right eye image with the eyepiece having the 0° polariser (PLANAR, 2012).

The orthogonal photographs used for the photogrammetry were taken during a previous reconnaissance program and were catalogued in order over the entire extent of the NAC of South-East Greenland.

It was possible to create a link between the SOCET software and GIS based software, ArcMap to digitalise points, lines and polygons and get direct spatial correlation between the aerial photos and their geographic position. This allowed the mapping of geological features directly from the 3D images.

Petrography

Petrography was conducted prior to fieldwork during June and July of 2012. Thin sections of samples collected in 2011 were cut and polished at Vancouver GeoTech Labs, and studied using a Zeiss Axioskop 40 microscope with an attached Zeiss AxioCam MRc5 camera at GEUS in Copenhagen. Transmitted polarised light microscopy was used for silicate assemblages whereas reflected polarised light microscopy was used for sulfide and oxide assemblages. Both types of microscopy could be done from the same microscope. The photomicrographs were taken in conjunction with the attached Zeiss AxioCam MRc5 camera and a software program called AxioVision that was connected to the camera and operated from a nearby computer.

Geochemistry

Whole-rock major and trace element geochemistry

Six samples (517205, 517206, 517207, 517208, 517218 and 517221) were gathered during the 2011 field expedition from the Timmiarmiut region and were sent to Activation Laboratories in Canada for both whole-rock and trace element geochemistry. The detection limits for the three analytical techniques used are presented in Table 1.

All of the samples sent to Activation Laboratories were tested for major and trace elements. The major elements were analysed by Fusion-Inductively Coupled Plasma (ICP) along with a few selected trace elements (Ba, Be, Sc, Sr, V, Y and Zr), while the majority of the trace elements were analysed by Fusion-Inductively Coupled Plasma Mass Spectrometry (ICP-MS). A sample size of 1g is digested in aqua regia and then diluted to a volume of 250 ml. International reference materials for the metals of interest are digested at the same time. These samples and standards are then analysed on a Thermo Jarrell Ash ENVIRO II simultaneous and sequential ICP or either a Varian Vista 735 ICP or a Thermo 6500 ICP. A Perkin Elmer SCIEX ELAN 6000, 6100 or 9000 ICP/MS is used for the trace elements.

Five of the six samples were analysed for Au, Pt and Pd using the 1C- research method of fire assay and ICP-MS (FA-MS). A sample of ~ 50g is mixed with fire assay fluxes (borax, soda ash, silica, and litharge) and Ag, which is used as a collector. The mixture is heated at 850°, 950° and finally 1060°C. Once the sample has cooled, the lead button is separated from the slag and cupelled at 950°C to recover the Ag (doré bead) and Au, Pt and Pd. The Ag doré bead is then digested in a hot (95°C) HNO_3 + HCl solution with a complexing agent to prevent the Au, Pt and Pd from adsorbing onto the test tube.

Upon cooling the sample solution for 2 hours, it is then analysed for Au, Pt and Pd using a Perkin Elmer Sciex ELAN 6000, 6100 or 9000 ICP-MS. With every 15 samples, a blank and digested sample is run and every 38 samples, a blank and a duplicate international standard are run. The ICP-MS is recalibrated every 45 samples (Activation Labratories, 2012).

Table 1. Detection limits and analytical methods used for (a) major elements and (b) trace element geochemistry. From (Activation Labratories, 2012).

Element	*Unit*	*Detection limit*	*Analytical method*	*Element*	*Unit*	*Detection limit*	*Analytical method*
SiO_2	%	0.01	FUS-ICP	Ho	ppm	0.01	FUS-MS
Al_2O_3	%	0.01	FUS-ICP	In	ppm	0.1	FUS-MS
Fe_2O_3(t)	%	0.01	FUS-ICP	La	ppm	0.05	FUS-MS
MnO	%	0.001	FUS-ICP	Lu	ppm	0.002	FUS-MS
MgO	%	0.01	FUS-ICP	Mo	ppm	2	FUS-MS
CaO	%	0.01	FUS-ICP	Nb	ppm	0.2	FUS-MS
Na_2O	%	0.01	FUS-ICP	Nd	ppm	0.05	FUS-MS
K_2O	%	0.01	FUS-ICP	Ni	ppm	20	FUS-MS
TiO_2	%	0.001	FUS-ICP	Pb	ppm	5	FUS-MS
P_2O_5	%	0.01	FUS-ICP	Pd	ppb	0.1	FA-MS
LOI	%	0.01	FUS-ICP	Pr	ppm	0.01	FUS-MS
				Pt	ppb	0.1	FA-MS
Ag	ppm	0.5	FUS-MS	Rb	ppm	1	FUS-MS
As	ppm	5	FUS-MS	Sb	ppm	0.2	FUS-MS
Au	ppm	1	FA-MS	Sc	ppm	1	FUS-MS
Ba	ppm		FUS-ICP	Sm	ppm	0.01	FUS-MS
Be	ppm	1	FUS-ICP	Sn	ppm	1	FUS-MS
Bi	ppm	0.1	FUS-MS	Sr	ppm		FUS-ICP
Ce	ppm	0.05	FUS-MS	Ta	ppm	0.01	FUS-MS
Co	ppm	1	FUS-MS	Tb	ppm	0.01	FUS-MS

Cr	ppm	20	FUS-MS	Th	ppm	0.05	FUS-MS
Cs	ppm	0.1	FUS-MS	Ti	ppm	0.05	FUS-MS
Cu	ppm	10	FUS-MS	Tm	ppm	0.005	FUS-MS
Dy	ppm	0.01	FUS-MS	U	ppm	0.01	FUS-MS
Er	ppm	0.01	FUS-MS	V	ppm		FUS-ICP
Eu	ppm	0.005	FUS-MS	W	ppm	0.5	FUS-MS
Ga	ppm	1	FUS-MS	Y	ppm	0.5	FUS-MS
Gd	ppm	0.01	FUS-MS	Yb	ppm	0.01	FUS-MS
Ge	ppm	0.5	FUS-MS	Zn	ppm	30	FUS-MS
Hf	ppm	0.1	FUS-MS	Zr	ppm	1	FUS-MS

Energy-Dispersive X-ray Spectroscopy

Energy-dispersive X-ray spectroscopy (EDS) was carried out on a Phillips XL40 Scanning Electron Microscope (SEM) at GEUS in Copenhagen. The polished sections were first carbon coated with a Polaran Range CC7650 Carbon Coater before being placed into the SEM. EDS was utilised to identify some of the minerals that were observed in thin section, rather than as an extensive analysis of the samples. The results from the EDS are integrated into the results section.

Results

Fieldwork in the Timmiarmiut region predominantly focused on bands of mafic granulite that can be traced for kilometres along strike and their relationship with the surrounding rocks (Figs. 2, 3). Breccia and mylonite of various relative generations are commonly developed along lithological contacts between mafic granulite and migmatite and also at the contact between mafic granulite and later granitic intrusions. The breccia and mylonite locally host sulfide occurrences and are a focus of this project. Detailed thin section petrography of the sulfide-bearing breccia was completed on samples that had been acquired during the 2011 field work to the Timmiarmiut region. There are 12 thin sections from six different mineralised samples in the Grydefjeld region (for sample location see Fig. 3). Specifically, the aim of the petrography is to characterise the host rocks, mineral assemblage and mineralisation style of the breccia. These thin section results are integrated with detailed outcrop, hand specimen and structural analysis from the field to form the basis of this project and are documented below.

Geological mapping is the major component of this project and combines 3D photogrammetry, the field relationships along with the structural control from measurements taken in the field, to produce a geological map (Fig. 3). The geological map was produced in ArcGIS and Adobe Illustrator. The rock units that make up the geological map in Figure 3 are discussed in detail in the following section.

Host rocks

Mafic granulite

Mafic granulite is dark grey to black and usually contains veins of leucosome (Fig. 5a) and associated melanosome. The granulite contains ~ 1 mm to sub-mm scale grains that show typical granoblastic texture with 120° sutured grain boundaries and is foliated.

The mafic granulite is typically composed of plagioclase, pyroxene and locally hornblende, biotite and quartz, which suggest that the protolith is a gabbroic or basaltic rock. The leucosomes predominantly contain plagioclase and are generally surrounded by peritectic pyroxene and garnet. In some areas, namely around island 529 (see Fig. 3 for location), the mafic granulite has similar mineralogy although a slightly coarser grainsize.

The mafic granulite forms both laterally continuous and dismembered bands that can be followed for kilometres within the Timmiarmiut region (Figs. 2, 3, 5b). The mafic granulite contains felsic leucosomes that are parallel to foliation and the overall orientation of the mafic bands. Numerous sheets of granitic material have intruded into the mafic granulite and are both parallel to the foliation and cross-cut the foliation (Fig. 5c-e). The mafic granulite bands are generally found in strongly sheared areas and in contact with a number of different lithological units. The contacts are usually sheared and brecciated (Fig. 5f), but in some cases primary igneous contacts can be observed. Some of these brecciated locations have a rusty weathering appearance (Fig. 5b) and locally contain pyrite and pyrrhotite. Some of the interpreted contacts between the mafic granulite and the migmatite are intruded by granites, which mask the original contact.

Ultramafic rocks

At least three different types of ultramafic rock are present and include hornblendite, pyroxenite and peridotite. The hornblendite is a medium- to coarse-grained, black to very dark grey rock ~ 90% hornblende and minor amounts of pyroxene (Fig. 6a). The pyroxenite is metallic green in colour due to the dominance of clinopyroxene. Peridotite has a bluish-green appearance and contains olivine, two pyroxenes and local hornblende. Locally, calcite veining is present in the ultramafic rocks (Fig. 6b).

The ultramafic rocks form discrete lenses or boudins within the mafic granulite and migmatite and have sharp contacts (Fig. 6c). They generally have a distinct reddish-brown weathering that has a rough, almost limestone feel. One location that was visited during fieldwork near the locally named ‘green anomaly’ that is characterised by a vegetative cover had a very high distribution of ultramafic lenses that are 10-15 m thick.

Meta-sedimentary rocks

Possible meta-sedimentary rocks have a red to brown colour and vary in grainsize. Locally they have a rusty appearance due to the weathering of sulfides. They typically contain garnet, biotite, sillimanite and are here referred to as garnet-biotite-sillimanite schists (Fig. 6d). The garnet is up to 20mm in diameter and often displays ‘snowball’ textures indicative of growth during shearing. The biotite and sillimanite are elongate and foliated which gives the rock its schistose appearance.

Meta-sedimentary rocks are locally found as discontinuous lenses or bands within the mafic granulite. At some locations, the meta-sedimentary rocks form 5 to 10 cm thick alternating bands with the mafic granulite over a distance of a few metres, and the contact with the mafic granulite is generally brecciated. They usually have a rusty weathering colour.

Migmatite

The migmatite generally has a light grey/brown colour with strongly banded melano- and leucosomes (Fig. 6e). The composition is quartz, plagioclase, hornblende, and biotite and locally magnetite.

Migmatite forms the most extensive lithological unit in the Timmiarmiut region and represents the earliest orthogneiss recognized in the area (Fig. 3). It displays relict intrusive contacts with the adjacent mafic granulite, along with containing fragments of mafic granulite and ultramafic rocks suggesting that the protoliths for the migmatite are younger than the precursors to the mafic granulite and the ultramafic rocks. The migmatite is strongly banded and highly deformed.

Orthogneiss

The orthogneiss has a light grey to cream colour and is strongly foliated. It is compositionally quite similar to the migmatite, with plagioclase and quartz the dominant minerals and accessory hornblende, biotite and magnetite. However, it is generally texturally homogenous compared to the strongly banded migmatite and it is this textural difference and also intrusive contacts between the two that enables differentiation. The protolith of the orthogneiss also intrudes into the mafic granulite and is itself cut by various granites.

Granitic rocks

Late leucogranite, cordierite-bearing granite and pegmatitic granite intrude the mafic granulite and migmatite and were found at numerous locations.

The leucogranite is fine-grained (average grainsize ~ 1 mm) and contains quartz, plagioclase and biotite. The cordierite-bearing granite is coarse-grained (average 10-12 mm) and contains quartz, plagioclase and cordierite. However, the Cordierite is locally up to 50-100 mm (Fig. 6f). The pegmatitic granite is found in southern Timmiarmiut and also in the south Grydefjeld region (Fig.3 for location). It contains coarse-grained quartz, plagioclase and biotite.

The granitic intrusions usually form sheets and sill-like bodies that are sub-parallel to the foliation (Fig. 5e). They all show intrusive contacts and cross-cut the mafic granulite, the migmatite and the orthogneiss. Some of the granitic intrusions may possess a weak foliation. Some of the granites are folded by deformation events that affect the mafic granulite and the migmatite, which further indicates the relative timing of emplacement.

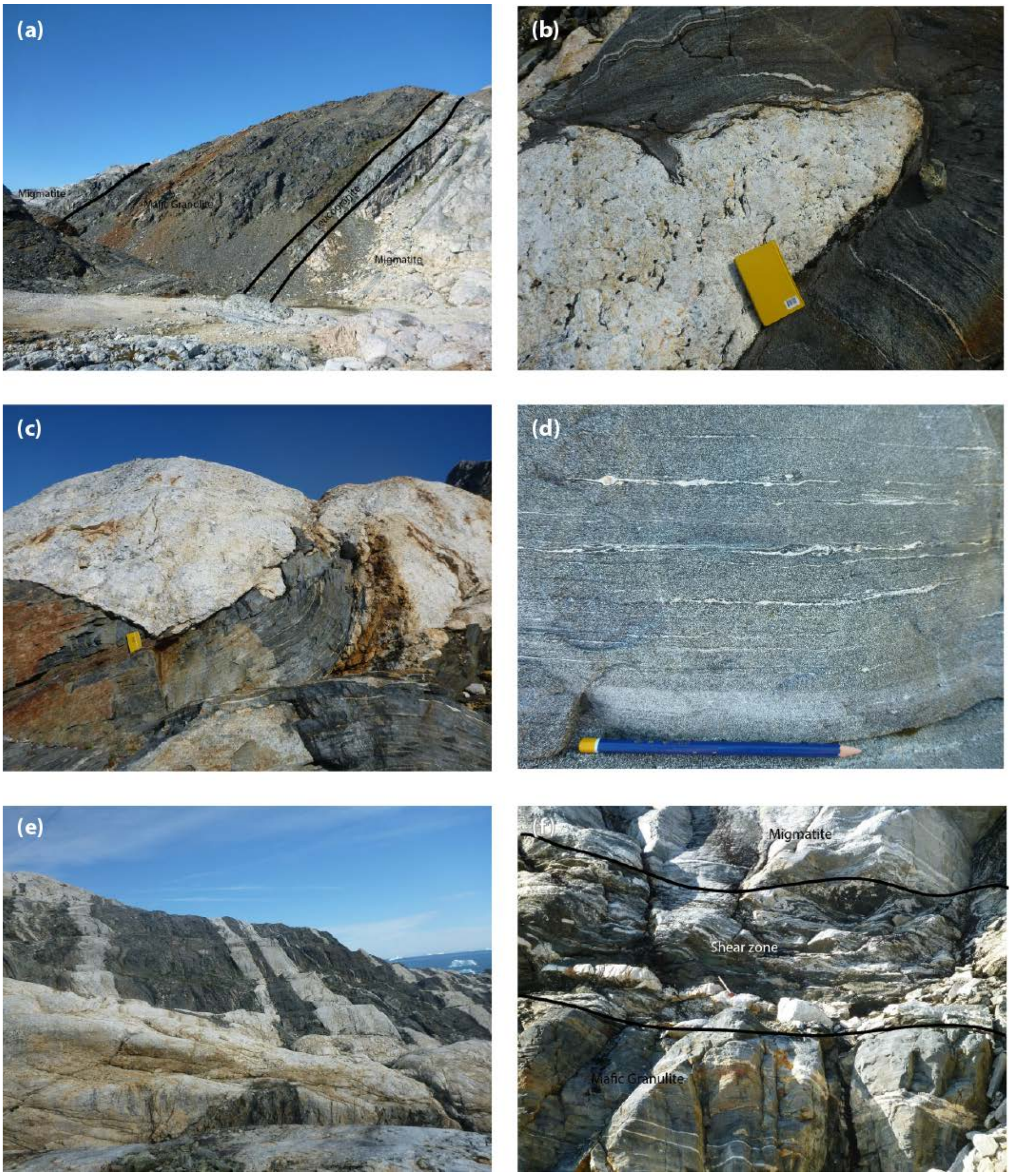

Fig. 5. Photographs of mafic granulites: (a) mafic granulites with felsic leucosomes; (b) field relationships between mafic granulite, orthogneiss and leucogranite parallel to S_2 foliation; (c) pegmatitic granite intruding mafic granulite; (d) cordierite granite intruding into the mafic granulite; (e) bands of

pegmatitic granite running parallel to S_2 foliation within the mafic granulite; and (f) sheared and locally mylonitic contact between mafic granulite and migmatite.

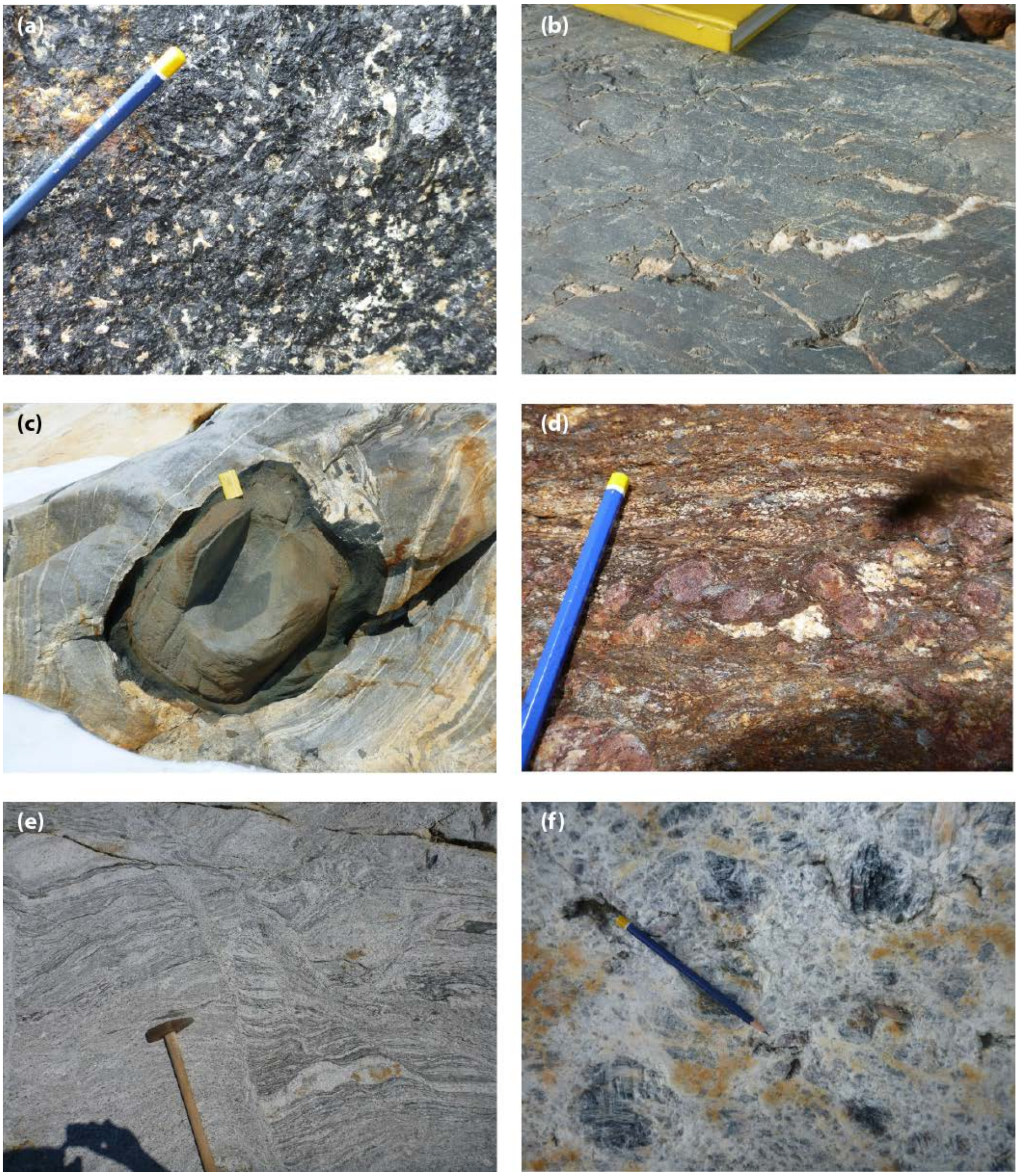

Fig. 6. Photographs showing various field rock relationships: (a) and (b) ultramafic rock with thin (1-2 mm to 10 mm) calcite veins; (c) ultramafic lens entrained within migmatite; (d) garnet-biotite-sillimanite schist; (e) strongly deformed migmatite; and (f) Coarse grains of cordierite (up to 100 mm) within cordierite-bearing granite.

Mineralisation

Breccia-hosted mineralisation

As previously mentioned, sulfide mineralisation was found locally within breccia located along the contacts between mafic granulite and migmatite and granitic intrusions. The vast majority of mineralisation is found in matrix-supported breccia, which comprises multiple different types of rock fragments and mineral fragments (Figs. 7, 8). Figure 3 shows the location of breccia-hosted mineralised samples at the contact between mafic granulite and migmatite.

Rock fragments

The breccia contains many different rock fragments consisting of the mineral assemblages granoblastic plagioclase, recrystallised quartz, plagioclase(-biotite), granoblastic orthopyroxene, clinopyroxene(-recrystallised quartz) and clinopyroxene, hornblende, recrystallised quartz. The size and shape of these fragments varies from 1.5 to 40 mm across and are typically well-rounded to angular with dissolution textures (Figs. 7, 8a). The relative proportion of these fragments differs greatly throughout the breccia zones, with the dominant fragments being the recrystallised quartz and plagioclase(-biotite). Some of the rock fragments have been strongly fractured and are subsequently infilled by sulfides (Fig. 8a). The fractures usually make a 'jigsaw' pattern and are 0.1 to 0.4 mm in thickness. Foliation is locally evident within some rock fragments and is defined by the recrystallised quartz and biotite (Fig. 7b). There are generally two types of recrystallised quartz found in the rock fragments: one type that is in equilibrium with adjacent minerals (Fig. 7d) and the other type where mineral grains are entrained within it (Fig. 7c).

Mineral Fragments

The other types of fragments that are found in the breccia are mineral fragments. Individual grains of plagioclase, hornblende, orthopyroxene, clinopyroxene and biotite can be seen supported in the sulfide matrix and are semi-angular to well-rounded. They vary in size from 0.05 to 4 mm, however, on average they are around 1mm. Plagioclase is consistently altered to white mica (muscovite/sericite). EDS analysis of samples is used to identify and confirm some of the minerals within samples. Plagioclase with a composition of labradorite is seen in Sample 517221 and 517205. Clinopyroxene with a composition of pigeonite is seen in Sample 517206 and diopside in Sample 517205. The EDS was never meant to be a thorough analysis of the samples and therefore the results do not necessarily represent the composition of all plagioclase and clinopyroxene present in the rocks. Locally, zoisite and epidote are found replacing plagioclase and hornblende. The mineral fragments, like the rock fragments have been fractured (Fig. 7d), usually along cleavage planes. Poikiloblastic texture is a common feature displayed by mineral fragments in the breccia, especially in amphibole and plagioclase. Many of the mineral fragments have a rim of fine grained biotite and chlorite or recrystallised quartz.

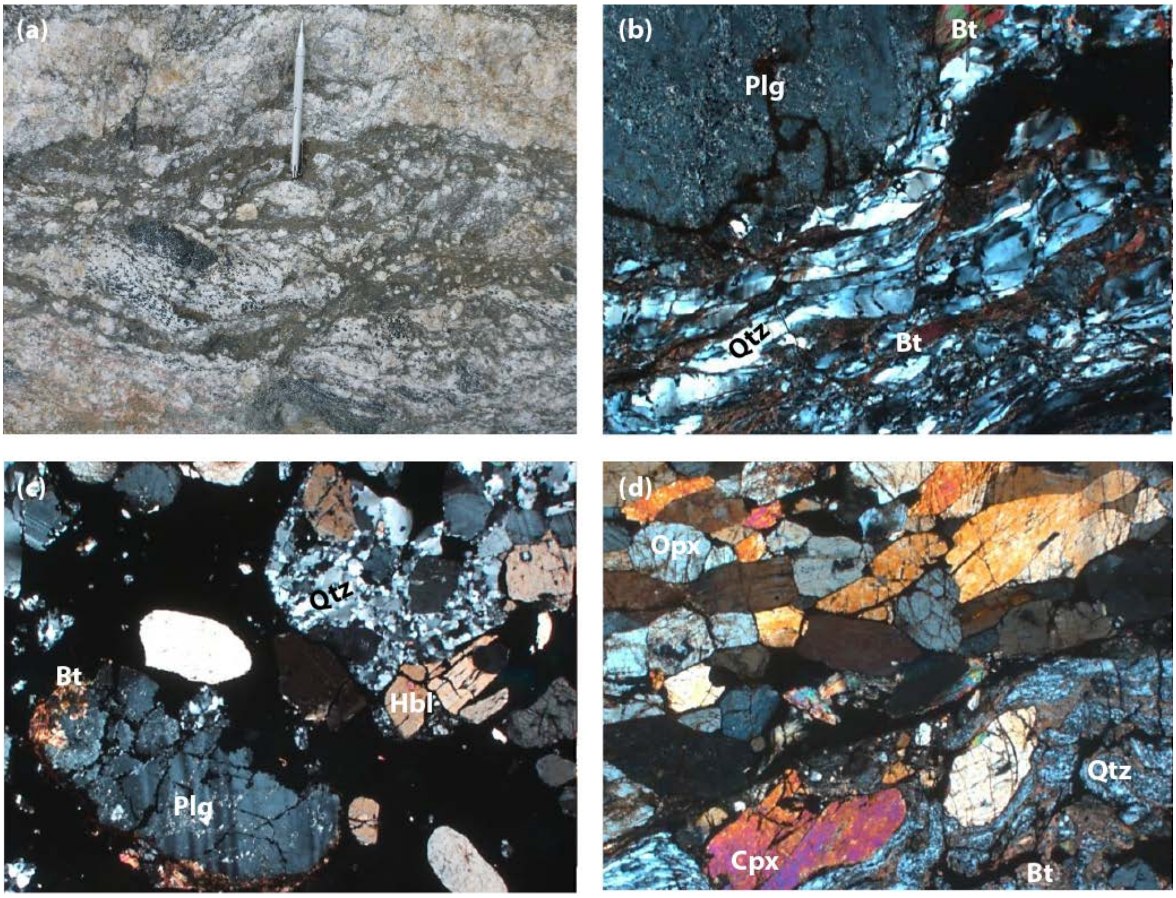

Fig. 7. Breccia: (a) outcrop photo of brecciated contact between the migmatite and a granite with rock fragments comprising the two lithologies; (b) photomicrograph of sample 517207 showing foliated quartz and biotite in the bottom half in contact with a fractured plagioclase grain; (c) photomicrograph of sample 517206-2 showing a plagioclase mineral fragment with a biotite rim in the bottom left corner and recrystallised quartz and hornblende rock fragment in the top right; and (d) photomicrograph of sample 517221-3 showing a granoblastic pyroxene fragment in the top half adjacent to a recrystallised quartz

fragment. For detailed thin section descriptions see Fig. 3. Abbreviations: Bt = biotite, Cpx = clinopyroxene, Hbl = hornblende, Opx = orthopyroxene, Plg = plagioclase and Qtz = quartz.

Matrix

The matrix accounts for around half of the rocks studied and is predominantly made up of massive sulfides, namely pyrrhotite with lesser amounts (up to 5 %) of chalcopyrite and pyrite (Fig. 8). Locally, 5 to 10 µm wide grains of ilmenite are also present. However, the matrix in the non-mineralised breccia consists of biotite. Relict biotite rims are still visible in some of the mineralised samples (Fig. 7c). The µm-scale biotite rims could be the remnants of this earlier alteration that has been replaced progressively by pyrrhotite and minor pyrite and chalcopyrite. Along with biotite, there appears to be quartz alteration. The chalcopyrite and pyrite form in close proximity to contacts between the pyrrhotite and silicate grains (Fig 8b). The chalcopyrite usually forms blebs and forms in small voids in the pyrrhotite. The pyrite generally forms euhedral grains that are a characteristic feature of pyrite (Fig. 8c). Locally, fine-grained pyrite replaces pyrrhotite along grain boundaries as seen in Figure 8d.

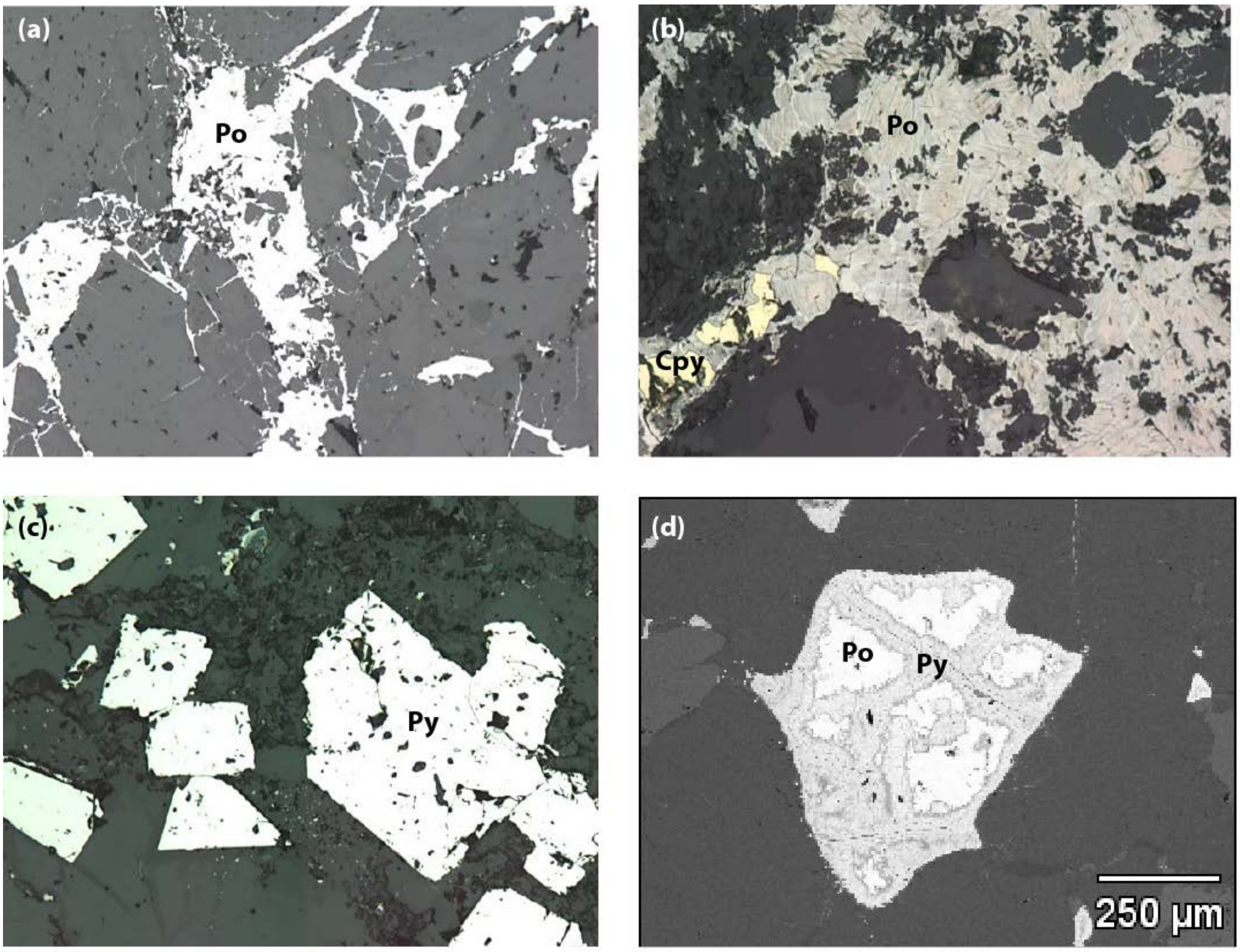

Fig. 8. Photomicrographs and SEM images: (a) photomicrograph of sample 517221-3 showing the strongly 'jigsaw' fractured fragments and the in fill by pyrrhotite (10x zoom); (b) photomicrograph of sample 517221-1 showing chalcopyrite forming near the contacts between pyrrhotite and rock fragments (20x zoom); (c) photomicrograph of sample 517207 showing euhedral pyrite grains (10x zoom); and (d) SEM image of fine grained pyrite replacing pyrrhotite along grain boundaries. Abbreviations: po = pyrrhotite, cpy = chalcopyrite, py = pyrite.

Structural evolution

The structural evolution of the Timmiarmiut region is analysed as part of this project. There are four main Archean deformation events that are recognisable in the study area and are further referred to as D_T, D_{S1}, D_R and D_4 which is the classification scheme proposed by Kolb *et al.* (2013). This is done to provide consistency with previous work done in the area. As previously stated, the last 10 days of the field season were spent further north around Thor Land (Fig. 2) where structural analysis was also conducted as a comparison and to see if the deformation scheme developed applies regionally. Fabric assigned to the deformation events D_T through to D_R were present in the north and showed some remarkable similarities with the Timmiarmiut region located ~ 200 km to the south. Stereographic projection of foliations and lineations (Fig. 9) were utilised to characterise and better understand the style of folding and shearing in these different deformational events and to piece together a structural evolution for the whole of the Thrym Complex. Data from Thor land is plotted and analysed on a separate stereonet to easily distinguish between the two areas (Fig. 9e).

Timmiarmiut Orogeny (D_T)

D_T is the earliest deformation and is also the hardest to recognise in the field as it is only recognised in the hinge of isoclinal F_{S1} folds in the mafic granulite and the migmatite. F_T folds are very rarely preserved and where recognised are isoclinally folded with a pervasive S_T foliation. In most cases, S_T is parallel to the second (S_{S1}) foliation that generally trends northwest, except where it is folded by later folds. Furthermore, in the northern Thrym Complex, S_T was established in the migmatite and it was seen to be cross-cut by an orthogneiss that lacked the same S_T foliation.

Skjoldungen Orogeny (D_{S1})

Structures assigned to the second deformation event (D_{S1}) are the easiest recognisable fabrics in the field and include a regionally penetrative axial planar (S_{S1}) foliation associated with isoclinal (F_{S1}) folds (Fig. 10a, c). These isoclinal folds fold the earlier S_T foliation, which is in most cases parallel with S_{S1} and plunge gently to moderately towards the south (Fig. 9b). The mafic bands studied in this project define and follow the regional-scale S_{S1} foliation (Fig. 3), which generally trends northwest in the study area, but has a large variation because it is folded by later F_R and F_4 folds (Fig. 9c). In contrast, the S_{S1} foliation trends northwest in the areas around Thor Land, which is due to the later F_R folding (Fig. 10e). D_{S1} is also characterised by sinistral shearing (Z_{S1}; Fig. 10f).

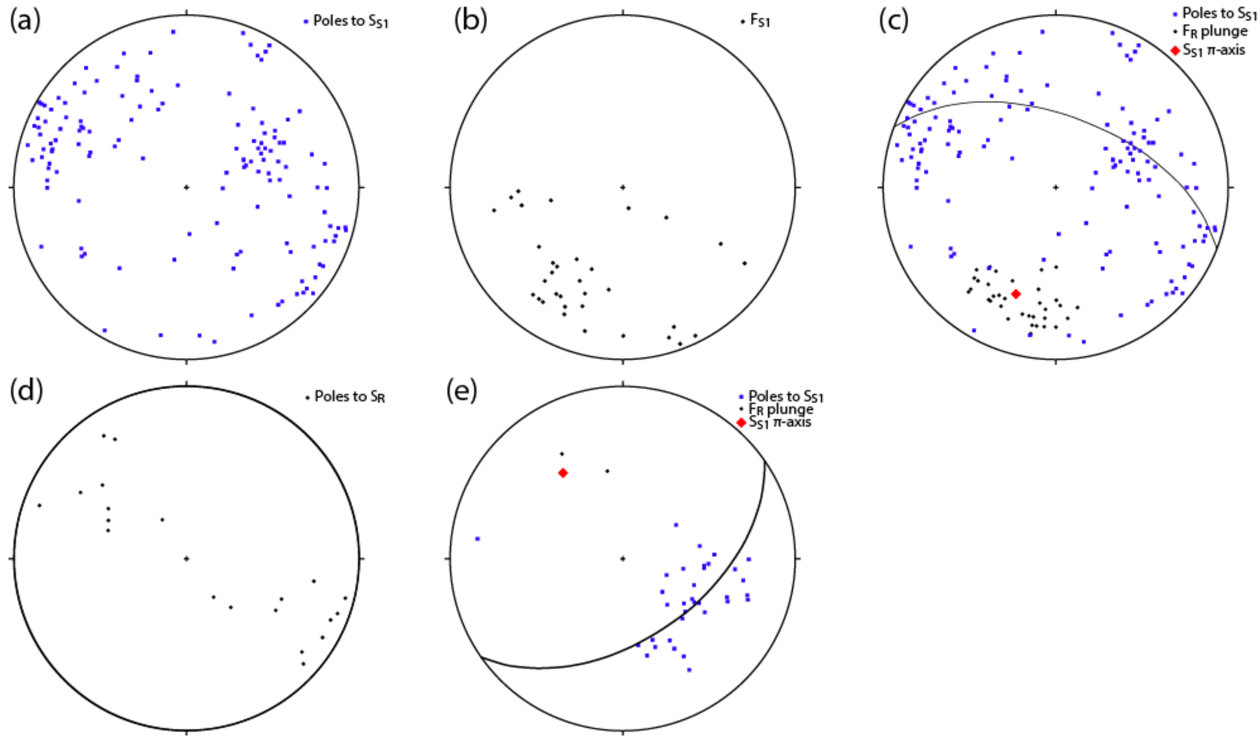

Fig. 9. Lower hemisphere equal area stereographic projections of data collected from the 2012 field season: (a) Poles to S_{S1} foliations from the Timmiarmiut region; (b) F_{S1} fold hinges from the Timmiarmiut region; (c) Poles to S_{S1} foliation data from the Timmiarmiut region (red squares) fitted with a circular best fit plotted with F_R fold hinges (black dots). The pole to the best-fit curve plots within the measured F_R fold hinges indicating that the variation in S_{S1} is due to folding by F_R; (d) Poles to S_R foliations from the Timmiarmiut region; and (e) Poles to S_{S1} foliation data from the Thor Land region (red squares) fitted with a circular best fit plotted with F_R fold hinges (black dots). The pole to the best-fit curve plots near to the measured F_R fold hinges indicating that the variation in S_{S1} is due to folding by F_R.

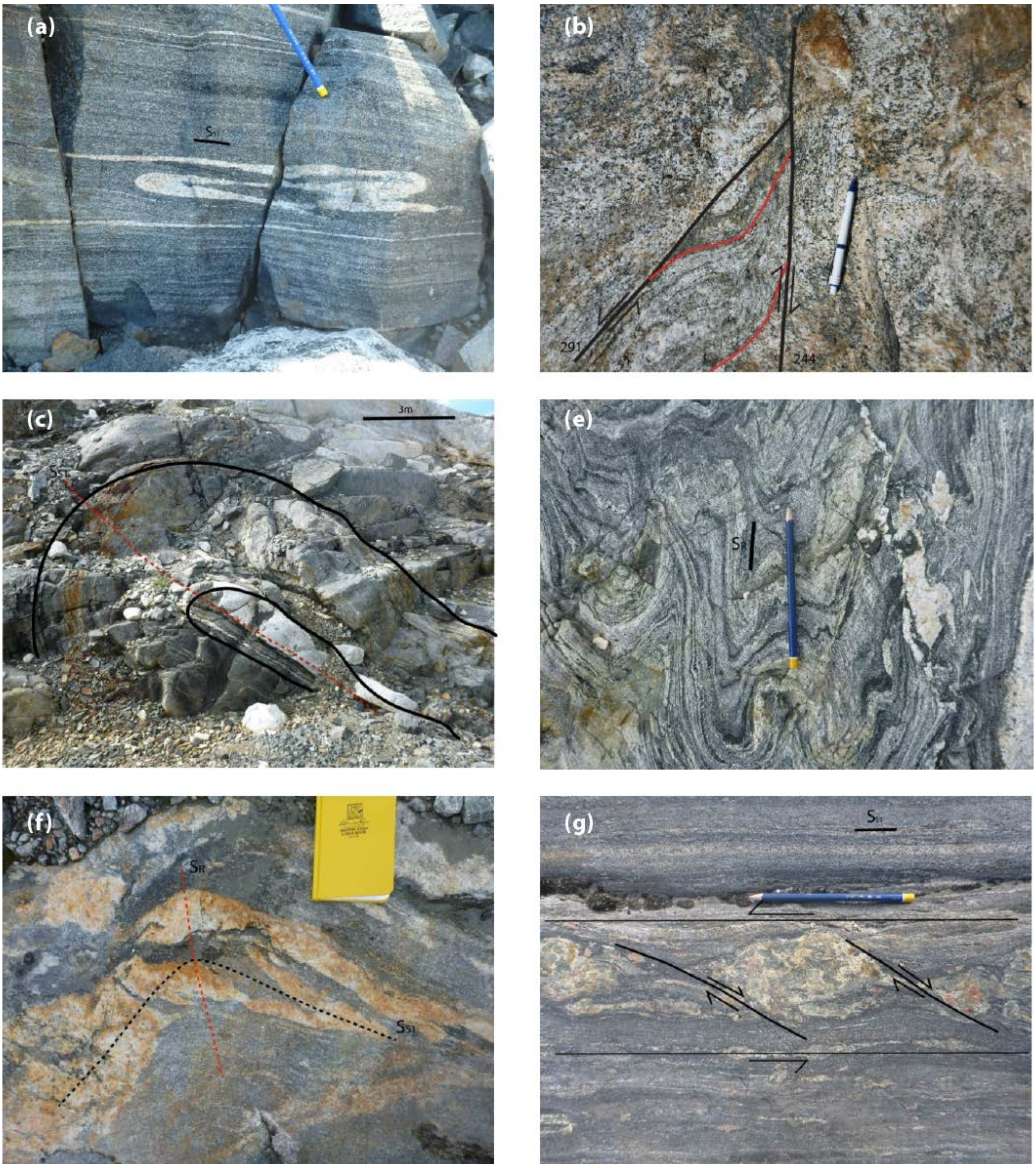

Fig. 10. Outcrop photographs showing structural features: (a) F_{S1} isoclinal folding and the pervasive S_{S1} foliation in mafic granulite; (b) Conjugate shear zones with sinistral shear zone striking 291° and a dextral shear zone striking 244°; (c) Outcrop-scale F_{S1} isoclinal fold; (d) F_R M-style folds in migmatite; (e) F_{S1} fold re-folded by F_R; and (f) Antithetic rotation of boudins in an overall sinistral D_{S1} shear zone striking 190° within mafic granulite.

Singertât Stage (D_R)

Deformation assigned to the Singertât Stage (D_R) is characterised by open to close (F_R) folds, which produce a foliation (S_R) that trends northeast and dips moderately to steeply to the northwest (Fig. 9d). Large regional scale D_R folds are observed in the Timmiarmiut region (Fig. 3), which plunge ~ 30° towards 200° (Fig. 9c) and are characterised by M-style folding (Fig. 9d). Evidence from folded mafic granulite bands further to the north in eastern Thor Land also shows regional scale F_R folding that trends 325° and plunges 39° (Fig. 9e). D_R is also characterised by conjugate shear zones with northwest trending dextral shears and northeast trending sinistral shears (Fig. 10b). This is the dominant shearing present along rheological contacts between the mafic granulite and the migmatite and which host sulfide-bearing breccia. The sense of shearing in both D_{S1} and D_R was generally determined by its effect on boudins within the mafic granulite.

D_4

The S_{S1} and S_R foliations are both folded by late gentle folds that trend eastward and are here defined as F_4 fabrics (Fig. 3). Evidence for F_4 is rare and it is only seen in a few places, such as near the hinge of the regional scale F_R fold and on island 529 where it refolds F_R.

Geochemistry

Whole-rock major and trace element geochemistry

Major and trace element geochemistry is available for all six samples; however, due to the brecciated nature of the rocks, there are inherent problems in trying to make meaningful use of the data. The samples were originally chosen to check for the presence of sulfide mineralisation not for a representative geochemical analysis and because of this, it is hard to correlate the data with such rocks as the mafic granulite, migmatite, and granites. The best use of the geochemistry is for the sulfides which are present in the matrix of all the breccia samples (517205, 517206 and 517221). Fe_2O_3 values range from 30.53 to 53.48 wt%, Ni values range from 670 to 930 ppm, Cu values range from 450 to 1730 ppm and LOI values of 11.71 to 12.85 wt%. The high values of

Fe_2O_3 and LOI can easily be explained by the large amount of sulfides, namely pyrrhotite, present in the breccia. The Cu would largely be incorporated into the chalcopyrite, while part of the Ni content would be incorporated into the pyrrhotite due to the lack of pentlandite seen in thin sections.

Discussion

Formation of the Basement

The mafic granulite, ultramafic rocks and the meta-sedimentary rocks are interpreted to constitute the proto-lower crust in the Timmiarmiut region that is intruded by the precursors to the migmatite, orthogneiss, granites and later mafic and ultramafic successions (Fig. 11; Kolb *et al.*, 2013, Bagas *et al.*, 2013). The mineralogy of the mafic granulite indicates that it is likely to have originated from a basaltic to dioritic source which has subsequently undergone metamorphism and recrystallised to its present form. Plagioclase-rich leucosomes in the mafic granulite are indicative of partial melting and granulite facies metamorphism, with minimum conditions of 800°C and between 5 and 8 kbars (Spear, 1993). Locally, these leucosomes have reacted to form peritectic pyroxene and garnet as a rim around the leucosomes. Furthermore, these leucosomes are F_T- and F_S-folded suggesting peak granulite facies metamorphic conditions were first achieved pre- to syn-D_T. Orthopyroxene porphyroblasts with garnet rims are locally seen overprinting the mafic granulite and are interpreted as the result of fluid-undersaturation during near-isobaric cooling (Dziggel *et al.*, 2012).

The presence of garnet has previously been thought to represent evidence for a sedimentary protolith for the granulites. However, these textures indicate that the mineral compositions are the function of metamorphic conditions (also see Bagas *et al.*, 2013). In other words, the stability of garnet is greatly affected by pressure and the presence of H_2O. At granulite metamorphic conditions the rocks have low H_2O contents and will become fluid-undersaturated during retrogression. As the temperature decreases, the stability of garnet will expand to lower pressures allowing the mafic granulite to develop garnet reaction rims (Dziggel *et al.*, 2012).

The ultramafic rocks form lenses within the mafic granulite and are usually boudinaged parallel to the regional S_{S1} foliation. However, these ultramafic rocks generally lack the penetrative S_{S1} foliation, which either indicates that they were emplaced late syn-D_{S1} or they have resisted pervasive deformation due to their relative harder rheology. They could possibly represent either intrusions of mantle-like material into the mafic granulite near the base of the continental crust or possibly metamorphosed komatiite flows or equivalent upper crustal sills that have been brought down and subjected to higher temperatures and pressures and undergone granulite facies metamorphism. Mafic-ultramafic rocks reported from southwestern Greenland (Szilas *et al.*, 2012) have geochemical similarities with komatiites from Fiorentini *et al.* (2011) database but lack the characteristic spinifex texture. The general lack of spinifex texture does not prove or disprove the near surface emplacement of these rocks, because of recrystallization due to their high-grade of metamorphism. Mafic-ultramafic assemblages are common in the lower crust as seen in the Ivrea-Verbano Zone (IVZ) in northern Italy (Peressini *et al.*, 2007; Fiorentini and Beresford, 2008) and in the Kohistan Arc in northern Pakistan (Fountain and Salisbury, 1981; Jagoutz *et al.*, 2006; Dhuime *et al.*, 2007; Jagoutz and Schmidt, 2011). Hornblendite, pyroxenite and peridotite lenses in sharp contact with mafic granulite are observed in the Jijal Complex of the Mesozoic Kohistan Arc (e.g. Garrido *et al.*, 2006; Dhuime *et al.*, 2007) similar to that seen in the Thrym Complex. These lenses could be the result of an underplating ultramafic magma that has intruded into the base of the mafic granulite. Although the ultramafic rocks are not that common and tend to form discrete bodies (boudinaged), there is evidence of areas that have large concentrations of ultramafic rocks. Therefore, it is also possible that there was originally a more extensive ultramafic component, similar to that seen in the Jijal Complex that has delaminated and returned to the mantle due to density contrasts and thermal instability (Kay and Mahlburg Kay, 1993; Rudnick, 1995; Tatsumi, 2000). Geochemical and isotopic analysis would need to be completed to help better understand and interpret the origin of the ultramafic rocks.

Garnet-biotite-sillimanite schist is also found within the mafic granulite and is best explained by either having a pelitic sedimentary protolith or it represents a mylonite. Meta-sedimentary rocks are also commonly found in lower crustal settings. The occurrence of garnet-biotite-sillimanite schists is quite similar to those found in the

Kinzigite Formation in the IVZ (Redler *et al.*, 2011), although far less extensive. The assemblage garnet-biotite-sillimanite indicates temperatures > 700°C and pressures ~ 9 kbars (Spear and Cheney, 1989).

Formation of the migmatite and the Skjoldungen Orogeny

The migmatite is the most regionally extensive unit in the Timmiarmiut region and the Thrym Complex as a whole (Fig. 3). Geochemical analysis of migmatitic orthogneisses by Kolb *et al.* (2013) and (Bagas *et al.*, 2013) has shown that the likely composition of the precursor to the migmatite is predominantly granodioritic. In many places, clear intrusive contacts are observed between the migmatite and the mafic granulite, which along with fragments of the mafic granulite locally found within the migmatite, indicate that the migmatite is younger than the mafic granulite. The migmatite has also undergone granulite facies metamorphism with the presence of leuco- and melanosomes indicative of partial melting and temperatures in excess of 800°C and pressures of up to 15 kbars.

The onset of D_{S1} brought about a strong NE-SW compressional regime that isoclinally folded the mafic-ultramafic successions and the migmatite, and created a pervasive, regionally extensive axial planar foliation (S_{S1}; Fig. 11). The precursor to the orthogneiss was intruded during D_{S1} as it cross-cuts the migmatite and mafic granulite but has foliation parallel to S_{S1} (Fig. 11).

Emplacement of granites and D_R

Granitic intrusive bodies in the Timmiarmiut region commonly form sheets that are sub-parallel to the S_{S1} foliation or as bodies that are more massive cross-cutting older rocks and are affected by the D_R deformation. A possible mechanism that explains the presence and orientation of the granites is lit-par-lit intrusion. Locally, granitic intrusions are emplaced at the contact between the mafic granulite and the migmatite, which has been sheared during D_R (Fig. 11). This structural weakness could provide the necessary melt pathway for the emplacement of intrusions. The localisation of these structures is controlled by the tensile strength parallel to the pre-existing foliation as the sheets intrude during sub-horizontal shortening (Belcher and Kisters, 2006).

The cordierite-bearing granite is found in the Timmiarmiut region and further north in Thor Land and is interpreted to have intruded post-D_{S1} and before the D_R event. The granite intruded both the limbs and hinges of F_R folds, exploiting structural weaknesses created during F_{S1} and F_R. The presence of cordierite could imply that it is an S-type granite that formed due to anatexis of peraluminous meta-sedimentary rocks, by fractional crystallisation of amphibole or contamination by aluminous sediments (Ugidos and Recio, 1993). However, the occurrence of cordierite in granites can potentially be magmatic, xenocrystic, restitic or metasomatic (Ugidos *et al.*, 2008), which further adds an element of controversy when interpreting the source of the cordierite within the granite and the general genesis of these rocks.

Pegmatitic granite dominates the area further south of Grydefjeld South (Fig. 3), in the hinge zone of a regional-scale F_R fold. There appears to be at least two different pulses of pegmatitic granite based on cross-cutting and folding relationships. The first pulse is syn- to late- D_{S1}, intrudes the mafic granulite, and been folded and deformed by D_{S1}. The second pulse of pegmatitic granite is identified from the first generation as it cross-cuts the mafic granulite and is not affected by the D_{S1} deformation. The most recent granite is a leucogranite that is found as a linear feature along the contact between mafic granulite and migmatite. It is likely that the emplacement of the leucogranite took place by a similar lit-par-lit mechanism as the other granites along the structural weakness at the contact between the mafic granulite and the migmatite.

The present orientation of the mafic bands and the overall structural grain of the Timmiarmiut region are largely controlled by D_R deformational events. Regional scale F_R fold hinges are found in both the southern Timmiarmiut region and also in south-east Thor Land in the north of the Thrym Complex (Fig. 3), indicating that D_R is an extensive event that deformed the entire complex. These F_R structures are open to close, trend roughly N-S and plunge towards the south in Timmiarmiut and to the north in Thor Land. The N-trend of these folds along with the presence of NE-trending dextral and NW-trending sinistral conjugate shear zones implies compression in an E-W direction. These F_R folds are superposed on the earlier isoclinal F_{S1} folds, creating a mushroom-type interference pattern.

Formation of D_R shearing, mineralisation and D_4

Sulfide-bearing breccia is hosted by sheared mafic bands that run parallel to the regional S_{S1} foliation (Fig. 10). The breccia host various rock and mineral fragments that are here interpreted to originate from the fracture and breakup of the adjacent granitic bodies, mafic granulite and migmatite during one or more shearing events during D_R. This may be a simplistic interpretation as it is possible that the shearing took place over an extended period and controlled the multiple magmatic pulses represented by the succession of migmatite succeeded by orthogneiss and granite in zones parallel to these shears. Furthermore, in many cases, the shearing has produced mylonites, which indicate a large accumulation of shear strain, in a ductile fault zone. The preservation of mylonites is quite problematic and requires grain growth to be inhibited in the rock (Trouw *et al.*, 2009).

A large proportion of the fragments are well-rounded, suggesting that they have undergone an extensive period of deformation. Rotation of fragments within a wear abrasion breccia also produces rounding and depending on pressure, dissolution-recrystallisation can take place affecting the grain boundaries and produce textures similar to those seen at the microscopic scale (Jébrak, 1997). The roundness of the fragments could also be explained by corrosive wear, where shearing and fracturing has increased the surface area of fragments which in turn enhances the fluid-rock interaction and increases the effect of corrosive wear. However, for corrosive wear to be an effective process, there must be a strong chemical disequilibrium between the host rock and the interacting fluid (Jébrak, 1997). Corrosive wear could also explain the dissolution textures that are present around the edges of some fragments. Following the terminology of Jébrak (1997) and evidence seen in the field and in thin section, it seems likely that different mechanical and chemical processes such as wear abrasion, volume expansion and corrosive wear have led to the formation of the breccia zones, some of which have been subject to a mineralising fluid.

The mineralised breccia shows many similarities with those hosted in auriferous shear zones in the Renco mine in Zimbabwe. According to Kolb (2008), these shear zones formed at 600 – 700° C during retrograde shearing of granulite facies gneisses and granulites. Not only is the mineralogy remarkably similar, the mylonitic and breccia textures are almost identical. Rounded fragments of wallrock, ductile deformed biotite with undulose extinction and fracture infilling by sulfides (Kolb *et al.*, 2000; Kolb 2008) are found in both the mineralised shear zones in Timmiarmiut and the Renco mine.

In the field, the majority of the breccia zones are not mineralised. They showed similar compositions of rock fragments however the matrix was dominated by biotite rather than pyrrhotite. Many of the sulfide-bearing samples that were analysed under the microscope showed thin µm-scale rims of biotite. It is interpreted that the mineralisation is due to a later fluid pulse that had evolved from a K-rich fluid to a more S-rich fluid with Fe being present in both as seen by the strong red to brown colour of biotite.

Another important characteristic that was observed within these D_R shear zones is an upper amphibolite to lower greenschist facies metamorphic grade, compared to granulite facies in the adjacent rocks. This was determined in the field by the presence of biotite, hornblende, chlorite and quartz. Locally, epidote and zoisite were observed replacing plagioclase and hornblende indicating greenschist facies. Furthermore, sericitisation of plagioclase also indicates a later greenschist overprint. This localised zone of amphibolite to greenschist facies metamorphism is explained as a D_R phenomenon that resulted from Z_R shearing at these conditions. As discussed earlier, regional peak-granulite metamorphism is thought to conclude during the late stages of D_{S1}, however, there appears to be no regional retrogression to amphibolite facies seen over the Thrym Complex.

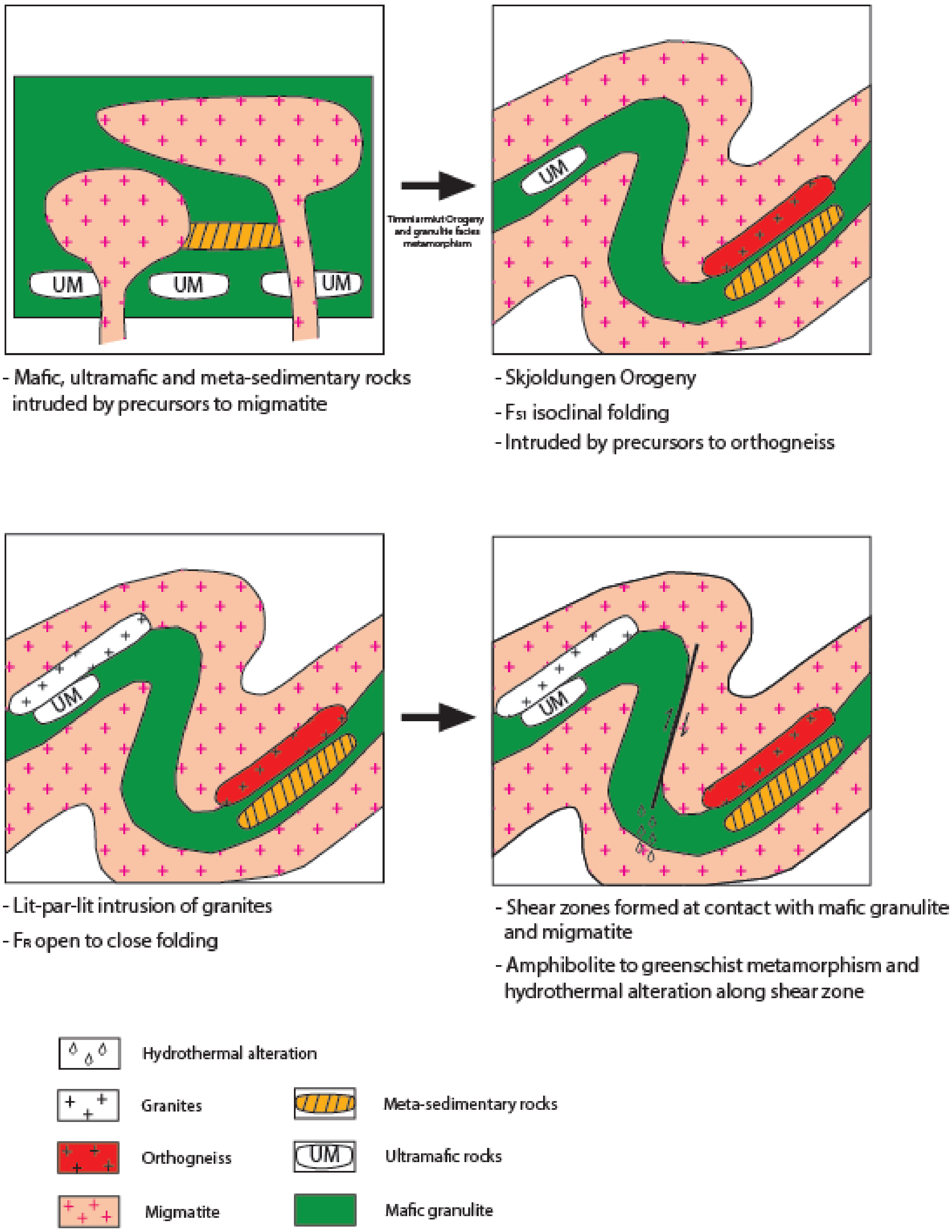

Fig. 4. Model for the magmatic and structural evolution of the Timmiarmiut region.

Conclusions

The Timmiarmiut region of South-East Greenland is characterised by extensive migmatite and dismembered mafic bands with minor ultramafic and metasedimentary rocks. These rocks represent the outcrop of NAC which extends to the southwestern coast of Greenland, the Labrador coast of Canada and the Lewisian Complex of Scotland. The rocks have undergone four stages of Archean deformation; the Timmiarmiut orogeny, the Skjoldungen orogeny, the Singertât stage and a fourth (D_4) deformation stage. Peak-granulite metamorphic conditions first occurred during the Timmiarmiut orogeny and prevailed until the start of the Singertât stage. A local retrogression to upper amphibolite-lower greenschist facies metamorphic conditions along shear zones during D_R coincided with hydrothermal sulfide occurrences at the contact between migmatite and mafic granulite. The sulfide mineralisation is locally found in matrix supported breccia and largely contains pyrrhotite with local pyrite, chalcopyrite and ilmenite. Au values of up to 131 ppb were recorded from the samples gathered in 2011. Due to the dominance of pyrrhotite, it seems unlikely that there is any economic mineralisation in the area. More samples of this mineralised breccia were collected during the 2012 field season but have yet to be analysed and will be used to follow up on any potential economic mineralisation. Granitic bodies intruded the basement complex and the migmatite at various stages during the Skjoldungen orogeny and the Singertât stage.

The geological mapping and structural analysis completed for this project has laid the foundation for future studies in the area. Due to the time and logistical constraints of the field season there are still potentially many areas that could be visited to gather more structural data, samples for geochemistry and geochronology, and enhance the geological map of the Timmiarmiut region. Further study in the Timmiarmiut region should include geochemical and isotopic work to help identify and characterise the source(s) and geodynamic setting of the mafic and ultramafic rocks. Similarly, S isotope work should be carried out on the local sulfide occurrences to provide insight into their origin. Geochronology on the different suites of granites could help constrain the timing of structural events and add a more quantitative aspect to the structural evolution.

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