DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2016/65

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1. INTRODUCTION

This report documents field observations made on peralkaline units of the Motzfeldt Centre during summer 2016 as part of a joint initiative between the Geological Survey of Denmark and Greenland (GEUS) and Korea Institute of Geosciences and Mineral Resources (KIGAM).

The 1.275 Ga Motzfeldt Centre is a large intrusive centre within the Mid-Proterozic Gardar Province of igneous activity in South Greenland. It comprises multiple intrusions of dominantly miaskitic syenites that exhibit a wide range of textural and mineralogical characteristics. Magmatism was concentrated into two main phases that started with intrusion of the Motzfeldt Sø Formation. Extensive in-situ fractionation produced volatile- and incompatible element-rich peralkaline residua; crystallization of this residua, together with hydrothermal activity led to the generation of a Ta-Nb-Th-U-Zr-REE mineralization. The mineralization increases in intensity towards the roof and margins of the formation.

The geography of the complex is characterised by topographic variations that exceed 1700 m, and a network of valleys that deeply dissect the intrusive complex. As a consequence,, large vertical sections expose the geology of Motzfeldt in exceptional detail. This makes the Motzfeldt Complex and excellent natural laboratory for studying crystallization and mineralization processes in alkaline intrusions.

The fieldwork focused on two sections of the Motzfeldt Sø Formation with the aim of collecting observations that further the current understanding of U and REE enrichment in the Motzfeldt Centre and broader Gardar Province.

2. BACKGROUND

2.1 Regional geology

The Gardar Province, South Greenland (figure 1) is an alkaline igneous province that formed during an episode of continental between approximately 1300 and 1100 Ma (Upton, 2013). Rifting occurred in the hinterland of the Palaeoproterozoic Ketilidian orogen and can be traced westwards into present day North America and eastwards into Scotland and Scandinavia (Bartels et al., 2015). Magmatism in the Gardar Province was concentrated into two episodes spanning approximately 1300-1255 Ma and 1220-1120 Ma (Upton, 2013). The components of the province generally comprise basaltic dykes, evolved intrusive centres up to 45 km in diameter that range form silica undersaturated to silica saturated compositions, and the Eriksfjord Formation, which is an approximately 3 km thick (Stewart, 1964) sequence interbedded continental sandstones, basaltic lava flows and volcaniclastic sediments. Additional igneous lithologies that are minor components of the province include carbonatites and ultramafic rock types (e.g. Coulson et al., 2003; Upton et al. 2006).

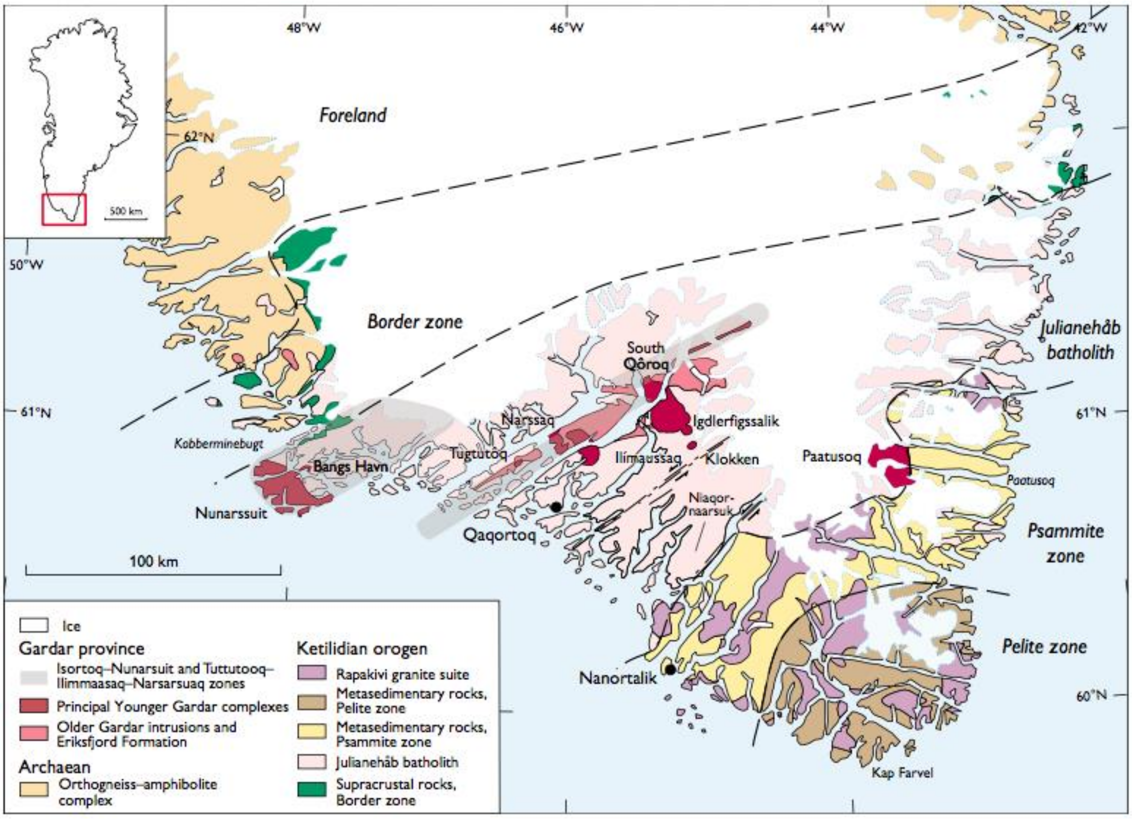

Figure 1. *Map of the Gardar Province and Mesoproterozoic Ketilidian orogeny, South Greenland from Upton (2013), based on an earlier map by Garde et al. (2002).*

Evolved intrusive centres within the Gardar Province were emplaced at shallow levels in the crust and stalled at a structural level close to the unconformity between the granitic

Ketilidian basement and the overlying Eriksfjord Formation. In a few intrusions, most notably Motzfeldt and Ilímaussaq, magmas underwent extreme fractionation to produce peralkaline compositions that are enriched in e.g. U, Th, REE, Ta, Nb, and Zr.

2.2 The Motzfeldt Centre

The Motzfeldt Centre was intruded into the crust at 1273 +/- 8 Ma (McCreath, 2009) during the early phase of Gardar magmatism. It sits within the larger Igaliko Complex along with four other major centres of igneous activity and several smaller satellite intrusions (Emeleus & Harry, 1970). Of the larger intrusive centres within the Igaliko Complex, Motzfeldt was emplaced first, followed by North Qôroq, South Qôroq, Early Igderfigssalik and Late Igderfigssalik. The Motzfeldt Centre is dominated by syenitic rocks that were emplaced during a combination of block subsidence and development of ring fractures (e.g., Emeleus & Harry, 1970; Jones, 1980; Bradshaw, 1988).

Initial mapping of the Motzfeldt Centre was conducted by Emeleus & Harry (1970) and Jones (1980). On the basis of field relationships, petrography and geochemistry, these authors distinguished six major syenitic units, SM1-SM6, within the intrusive centre. The first units to be distinguished, SM1-5 (Emeleus & Harry, 1970), comprised a miaskitic mineral assemblage, whilst SM6 was agpaitic in character. During subsequent mapping campaigns, new petrological details were revealed in the units in the NE part of the centre. This led Tukiainen et al. (1984), Tukiainen et al. (1986) and Bradshaw (1988) to revise the existing interpretation and distinguish three main syenitic formations. In order of emplacement these are the Geologfjeld Formation (GF), the Motzfeldt Sø Formation (MSF), and the Flink's Dal Formation (FDF).

Figure 2 shows a geological sketch map of the Motzfeldt Centre based on the geological interpretation by Tukiainen et al. (1984), Tukiainen et al. (1986) and Bradshaw (1988). The map shows that the GF is confined to a relatively small area in the NW part of the intrusive centre, whilst the MSF dominates the geology in the outer portion of the centre, and the FDF occupies to the core. Sheets of peralkaline microsyenite in the northern and eastern parts of the centre are associated with the MSF; Tukiainen (1986) and Bradshaw (1988) interpreted these sheets to represent late, fluid-rich residua of fractionation processes. The roof zone is exposed in the northern and eastern parts of the centre. Here, the Eriksfjord Formation structurally overlies the MSF and is also incorporated into the MSF as xenoliths. In contrast, the Eriksfjord Formation is not observed to overlie the FDF and is observed only as xenoliths. Jones (1980) correlated xenoliths of volcanic rocks within the FDF with the Ilímaussaq member of the Eriksfjord Formation; this is suggested to lie 1.5 km above the Mussartût member, which forms the roof to the MSF. On the basis of these stratigraphic correlations, and more recent petrological and field observations, McCreath (2009) suggested that the FDF was emplaced into shallower depths than the MSF, and that the FDF and MSF exhibit cross-sections through a similar magmatic system at different structural levels (Figure 3).

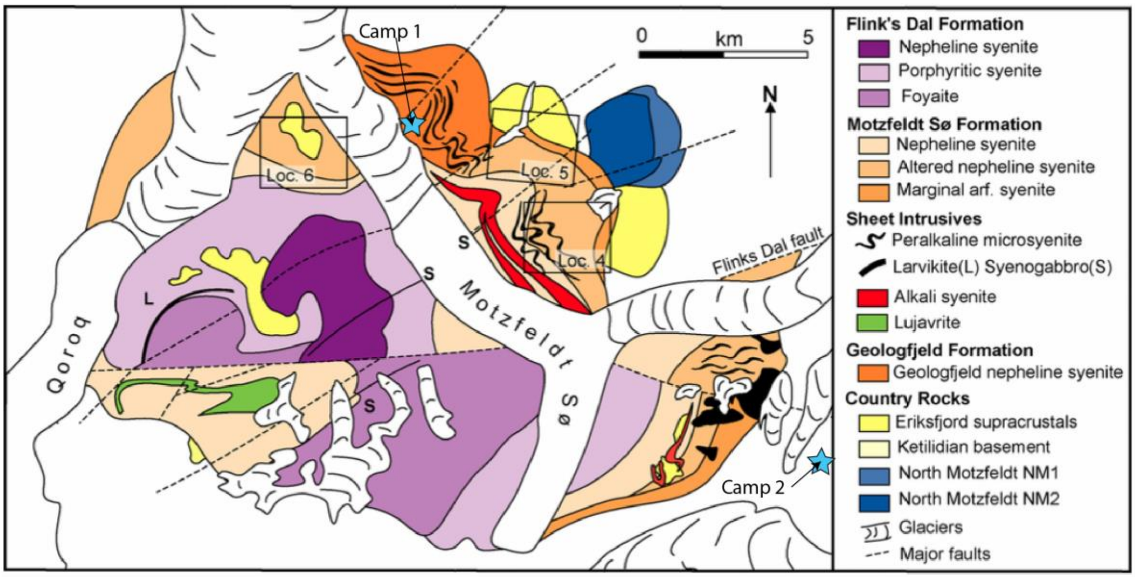

Figure 2. *Geological sketch map of the Motzfeldt Centre showing major units, unit subdivisions and structures. This map is taken from McCreath, 2009, after Tukiainen et al. 1984; Tukiainen, 1988; Bradshaw, 1988). Star in northern Motzfeldt indicates the location of Camp 1 in Storeelv Valley, and the start in eastern Motzfeldt indicates the location of Camp 2 east of Humbugbræ Glacier.*

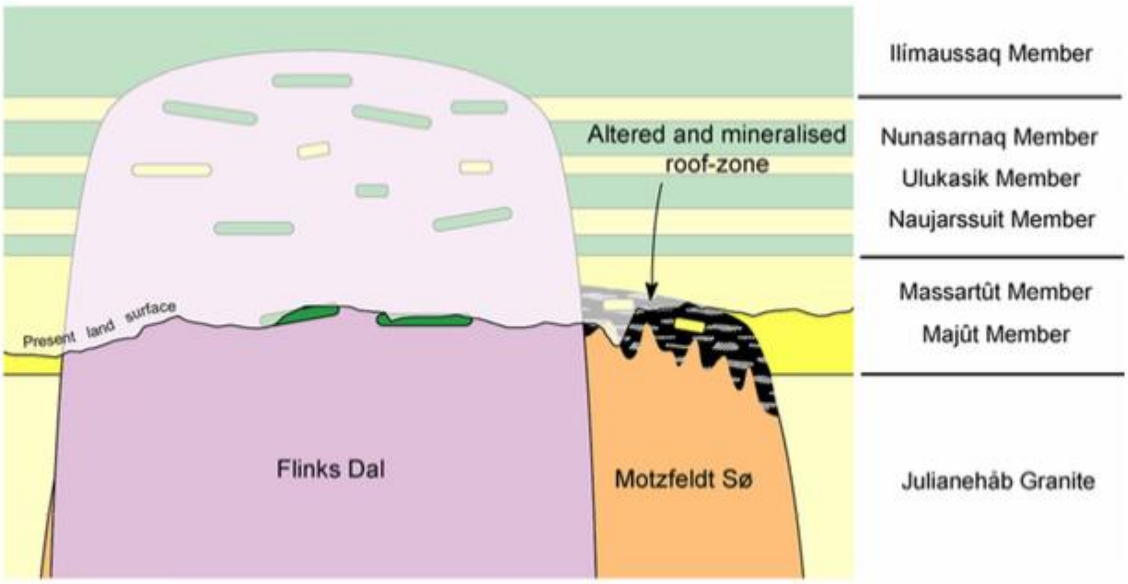

Figure 3. *Schematic cross section through the Motzfeldt Centre from McCreath (2009) showing the relative emplacement depths of the Flinks Dal Formation and the Motzfeldt Sø Formation. Yellow and green units illustrate the siliciclastic and volcanic members of the Eriksfjord Formation.*

2.3 Motzfeldt Sø Formation

Since the Syduran Project in the late 1970s and early 1980s (Armour-Brown et al., 1982, 1983), much attention has been focused on the MSF, owing to high concentrations of Ta-Nb-U-Th-Zr and REEs. A brief synthesis of the MSF and the mineralization is included below, and the reader is referred to Tukiainen et al. (1984), Tukiainen (1986), Tukiainen (1988), Bradshaw (1988), and McCreath (2009) for more comprehensive descriptions and observations.

The most recent geological map (figure 2) divides the MSF into three members; the MSF marginal arfvedsonite syenite, the MSF altered nepheline syenite and the MSF nepheline syenite plus the related peralkaline microsyenite sheets. McCreath (2009) emphasised that the three MSF units are characterised by extreme textural and mineralogical heterogeneity and noted that subdivision of the MSF into these units is often subjective. These MSF syenites vary from fine-grained varieties to coarse-grained pegmatitic types over distances of a few tens of centimetres and comprise a variable, complex mineralogy. Major mineral phases include ternary feldspars, amphiboles and pyroxene and exhibit textures that indicate significant alteration in a deuteric or autometasomatic regime (e.g., Bradshaw, 1988; McCreath, 2009). Common accessory mineral phases include sodalite, apatite, zircon, Fe-Ti oxides, aenigmatite; secondary mineral phases such as biotite, calcite, Fe-Ti oxides, sphene, gieseckite, Na-pyriboles, fluorite, zircon, thorite, astrophyllite, pyrochlore and bastnäsite are also present (e.g., Tukiainen, 1986).

The peralkaline microsyenite sheets (PMS) represent a distinct, late-stage, fluid-rich unit within the MSF that forms a package up to 700 m thick. Tukianien (1986) reported that the PMS includes several facies of syenitic rocks, including leucocratic, mesocratic and pegmatitic varieties. The contacts between these different facies are often irregular and disturbed and the degree of textural and compositional heterogeneity is extreme on length scales of a few centimetres (e.g., Tukiainen, 1986; Bradshaw, 1988). Existing studies provide only brief documentation of field relationships within the PMS; consequently it is difficult for readers to relate petrological descriptions of the PMS to specific facies and understand their significance. In the finer-grained portions of the PMS units, however, common minerals include orthoclase, albite, arfvedsonite, aenigmatite, eudialyte, analcime, fluorite, nepheline, aegirine, zircon and pyrochlore. Eudialyte is observed to break down to zircon, unidentified Zr-REE silicates, REE carbonates, catapleite, fluorite and feldspar. In the most heavily altered facies, zircon, pyrochlore and REE carbonates become essential components of the rock (Tukiainen, 1986).

2.4 Mineralisation

The Nb-Ta-Th-U-Zr-REE mineralization at Motzfeldt is largely confined to the PMS and inferred roof zone in the MSF (McCreath, 2009). McCreath (2009) provides the most detailed and comprehensive synthesis of the mineralization to date, and emphasises that processes from both the magmatic and deuteric regimes were involved in the generation of the mineralization. On the basis of detailed petrological and geochemical observations, McCreath (2009) argued that in-situ fractionation of the MSF-forming magma led to the concentration of Nb, Ta and high field strength elements close to the top of the chamber, and eventual incorporation of these elements into a solid fraction that crystallised pyrochlore. Fluid inclusion and mineral chemistry data indicate that these late-stage magmas were extremely rich in fluorine and other volatiles. Exsolution of the volatiles from the magma and mixing between the magmatic fluids and circulating groundwater permitted metasomatism of the surrounding syenites, remobilisation of LREEs into secondary minerals, such as bastnäsite and parasite, and generation of localised high Th concentrations within the roof zone.

In volatile-rich alkaline magmas, fractionation can persist to temperatures that are similar to those at which magmatic minerals can undergo deuteric alteration (Sørensen, 1962; Parsons et al., 2013). It is emphasised, therefore, that crystallisation and metasomatism in the Motzfeldt Complex may not have been separate processes in time and space, but instead may have operated concurrently to produce the observed mineralization.

3. AIM AND APPROACH

The aims of the fieldwork in 2016 were twofold. The first objective was to address deficiencies in existing literature by generating and documenting detailed field observations of the PMS in northern Motzfeldt. Field observations from this part of the fieldwork will provide a stronger foundation for future studies that consider the relationships between magmas, fluids and mineralization in the Motzfeldt Centre and other alkaline intrusions. The natural laboratory selected for this part of the field campaign was the Storeelv Valley in northwest Motzfeldt (figure 2), where the PMS forms a sequence approximately 700 m thick. From a camp located at N 61°13.332’, W 045°03.327’ the team gained excellent access to the lower part of the sequence (the upper 600 m outcrops in vertical cliffs and is inaccessible), which is located approximately 800 m beneath the roof of the intrusion.

The second objective of the fieldwork was to observe PMS units in eastern Motzfeldt, east of Humbugbræ Glacier (figure 2), where they are hosted in the granitic country rock at a structural elevation close to the roof of the intrusion. The camp was located at N 61°07.263’, W 044°48.429’. The advantage of observing PMS here is that the country rock should preserve a record of fluid-rock interaction that is more obvious in the field than for PMS units hosted within syenites of the MSF or Geologfjeld Formation.

Fieldwork was conducted between 28 July and 8 August 2016 with a team comprising Sam Weatherley (GEUS, Expedition Leader), Henning Bohse (retired, GEUS), Euijun Kim (KIGAM), Seokjun Yang (KIGAM) and Sanggun No (KIGAM). The team used a B212 helicopter to fly into and out of the field from Narsarsuaq, and an AS350 B3 helicopter to move camp in the middle of the field season.

4. RESULTS

4.1 Storeelv Valley

Figure 4 shows the primary field site at Camp 1 that provides the best exposure of the unit mapped as peralkaline microsyenite. The exposed sequence comprises sheets of blue-grey coloured, fine to medium grained (1-3 mm) peralkaline microsyenite, up to 4 m thick; zones of banded pegmatite with thicknesses that vary from 1 cm to several metres and grain sizes that vary from a few millimetres to several tens of centimetres; and screens of the host Geologfjeld Formation with thicknesses of several tens of centimetres to several metres. This large outcrop (Fig. 4) gives the distinct impression that the sheet-like appearance of the PMS is the result of a large body of PMS-forming magma hosting subhorizontal screens of GF syenite, rather than the sheets forming by repeated intrusion of PMS-forming into bodies that have a sheet- or sill-like geometry.

In most instances the pegmatite is observed to separate the PMS from the GF. Within this outcrop the relative proportions of PMS and pegmatite are highly variable. Whilst the relative proportions of PMS and pegmatites are not precisely known, it is apparent that the pegmatite accounts for a significant volume fraction of the sequence — perhaps in the region of 10-20 vol.%. Future analysis of photogrammetric images taken within the Storeelv Valley might place more accurate constraints on the relative proportions of the three units.

Figure 4. *Photo of primary field locality at Camp 1 showing buff-coloured Geologfjeld Formation (single open arrowhead), grey-blue coloured Peralkaline Microsyenite (double arrowhead) and yellow-coloured pegmatite (single solid arrowhead). Image taken from N 61°13.118',*

W 45°03.133', view E. The steep cliff forming the eastern southeastern side to Storeelv Valley can be seen in the background. Outcrop height is approximately 40 m.

Figure 5 shows in more detail the contact relationships between the PMS, pegmatite and GF syenite. The most striking observation is that the contacts between the PMS and pegmatite vary from sub-planar to irregular, pillow-like structures (Fig. 5a, b, c). In all cases it is the PMS that forms pillows within the pegmatite; no instances of pegmatite pillows within the PMS were observed. PMS pillows range in size from 10 cm (Fig. 5c) to 1 m (Fig. 5b). Smaller pillows typically have highly irregular morphologies (Fig. 5c), whereas larger pillows have a more regular, rounded shape (e.g., Fig. 5c). In all cases, the PMS and pegmatite are separated by a sharp contact (Fig. 6). The PMS is also observed to form more planar sheet-like bodies that are surrounded by pegmatite (Fig. 5c). Field observations made during the 2016 field season revealed no changes in mineralogy or grain size between the PMS with a pillow-like morphology or the PMS with a sheet-like morphology.

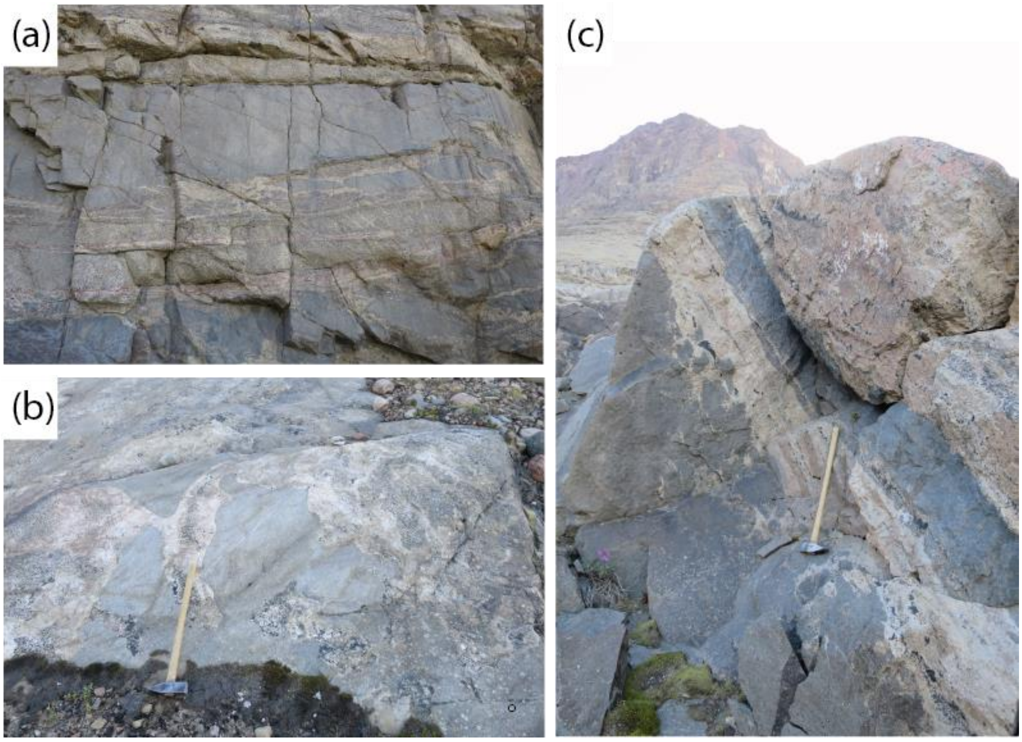

Figure 5. *Images show field and contact relationships between the peralkaline microsyenite (blue colour) and pegmatite (buff colour). (a) Sheet- and pillow-like bodies surrounded by pegmatite. Field of view is approximately 2.5 m. (b) Larger pillows of microsyenite surrounded by white-coloured pegmatite. Hammer shaft is 0.6 m long. (c) Sheets of peralkaline microsyenite adjacent to pegmatite with some irregular blobs of microsyenite hosted individually within the pegmatite.*

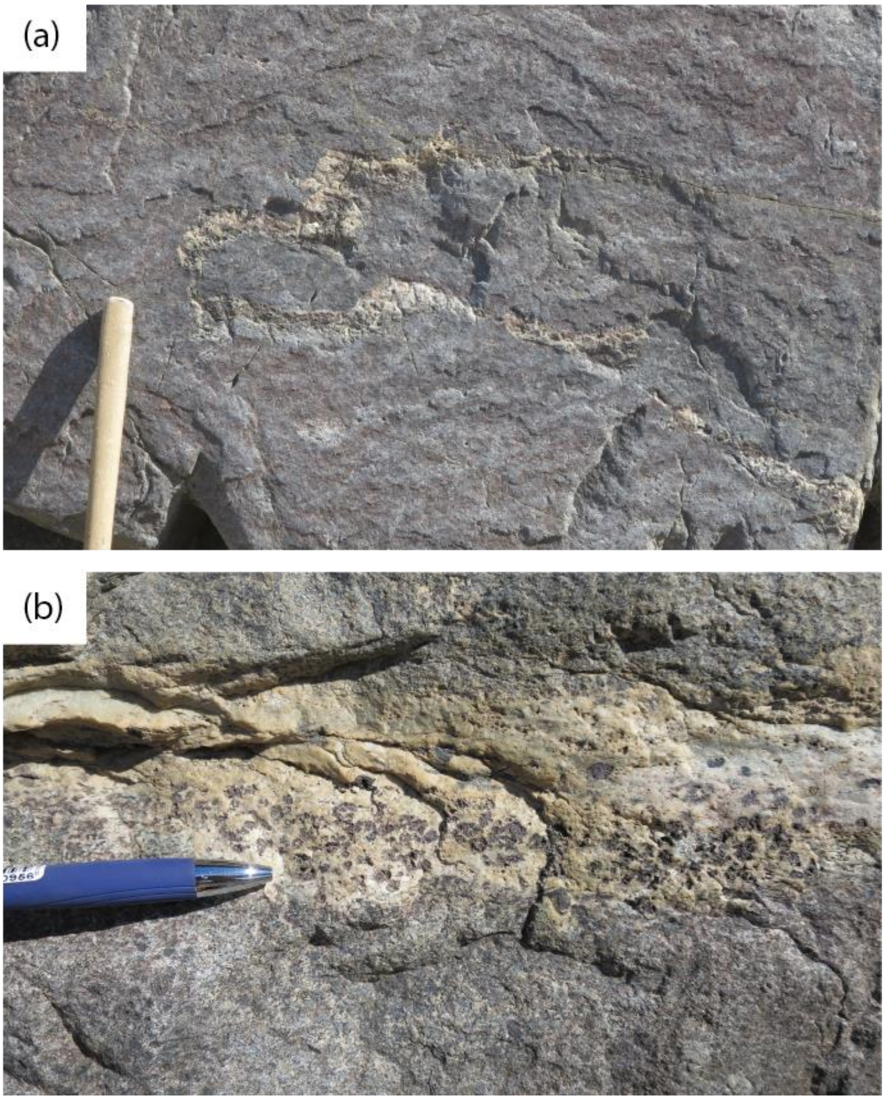

Figure 6. *Close up views of the PMS-pegmatite contact. (a) An irregularly shaped, 5 cm thick pegmatite vein is seen to emanate from the PMS. (b) An 8 cm thick pegmatite vein is separated from the PMS by a sharp contact.*

Figure 5a shows two sheets of PMS separated by a screen of GF syenite. Thin veins of pegmatite, 5-10 cm thick cut the GF syenite, but surround pillows and sheets of PMS. Within the field area, pegmatite was not observed to cross cut the PMS. These field relationships demonstrate that the pegmatite and PMS are contemporaneous and post-date the genesis of the GF syenite. In some places, thin veins of pegmatite with a highly irregular morphology were observed to emanate from the PMS, suggesting that the two lithologies have a close genetic relationship (Fig. 6a).

A distinguishing feature of the pegmatite within the PMS sequence is that it is banded. The bands are defined by variation in the modal minerals (Fig. 7). The bands vary in thickness from 1 cm to 20 cm; are commonly wavy; are laterally discontinuous and tend to pinch out over length scales of 1 - 10 m. The bands are typically red, white or blue-black in colour. High modal proportions of K-feldspar define the red bands, alkali feldspar is an important constituent of the white bands. The mineralogy of the blue-black band is currently undetermined, although amphiboles and / or pyroxene are thought to be an important constituent.

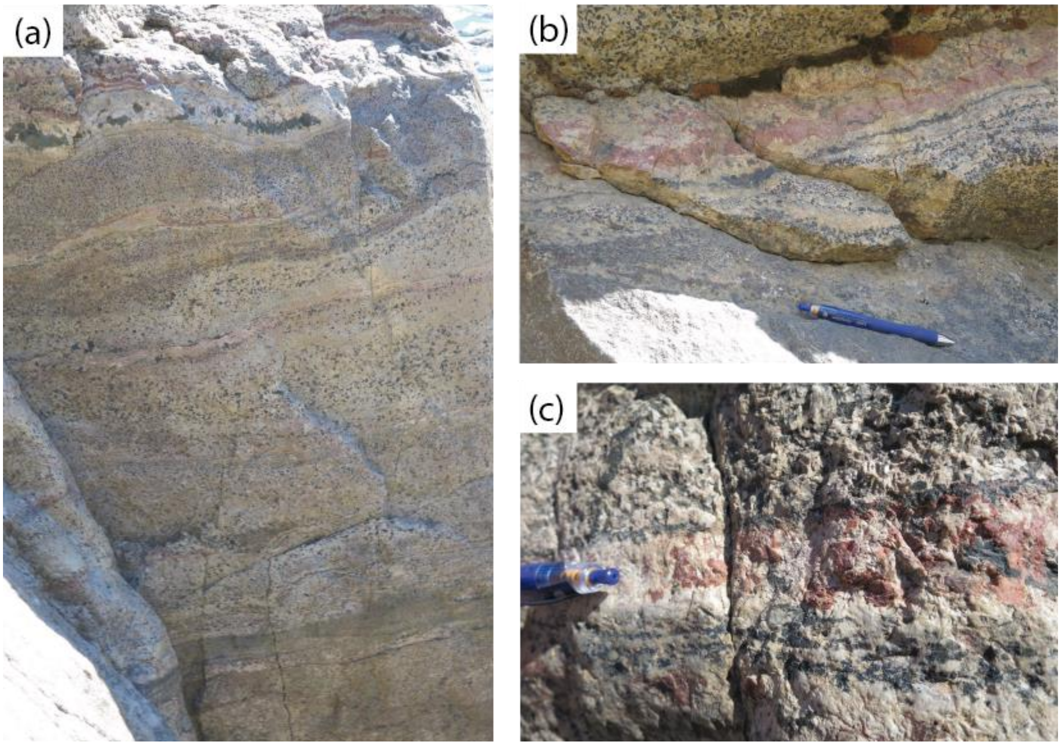

Figure 7. *Photos showing banding within the pegmatite unit of the PMS sequence. (a). Photo shows that bands have an irregular morphology and vary in thickness from 1 cm to several tens of centimetres. The long axis of the image spans approximately 1.3 m. (b), (c) Close up examples of modal banding within the pegmatite. The pen is approximately 1.5 cm thick.*

4.2 Humbugbræ Glacier

4.2.1 Microsyenites

From Camp 2, on the eastern side of Humbugbræ Glacier, units mapped as peralkaline microsyenite were observed to be hosted in granitic country rock at a structural level close to the roof of the MSF. Here, the PMS units are occur as an assemblage of sheets and dykes that becomes more voluminous westwards (Fig. 8a). The microsyenites are characterised by a brick-red alteration colour that is probably indicative of significant deuteric or autometasomatism (e.g., Bradshaw, 1988; McCreath, 2009). Around camp 2, microsyenite dykes are typically 5-10 m thick (Fig. 8b), whereas the sheets are typically approximately 0.5 m thick and have an anastomosing outcrop pattern (Fig. 8c). In both the sheets and dykes the microsyenite chills strongly against the host granite.

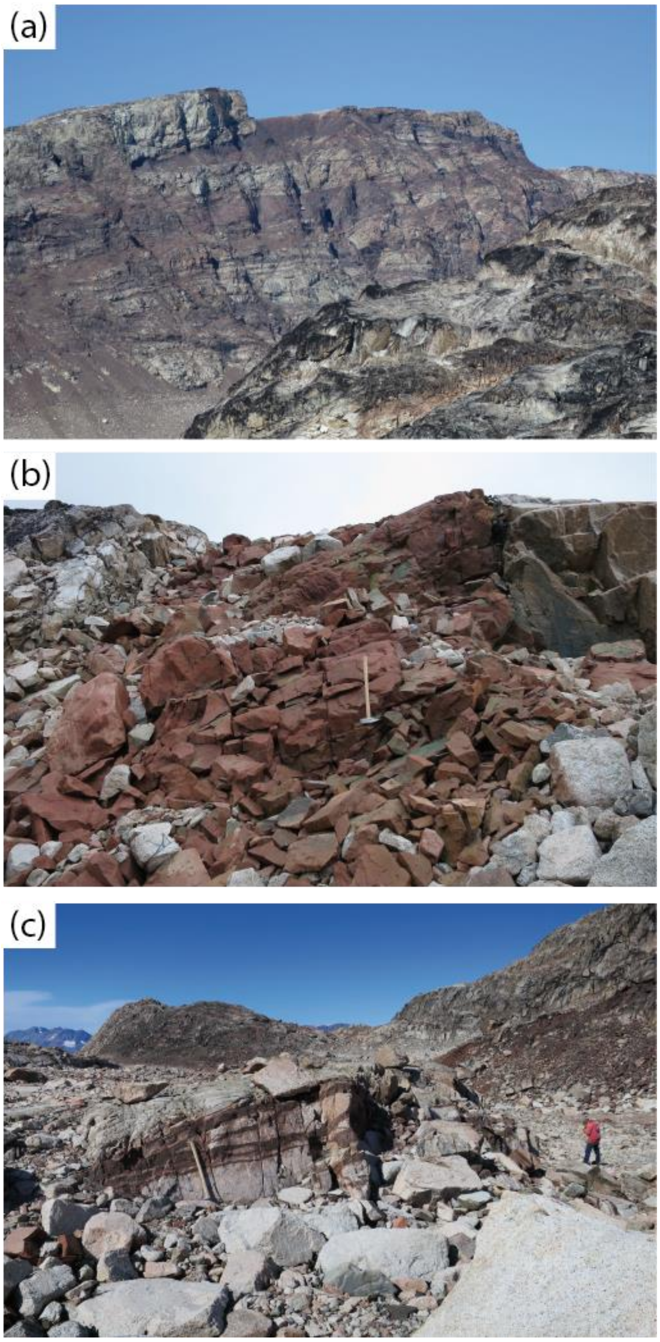

Figure 8. *Outcrops of microsyenite sheets and dykes around Camp 2, Humbugbræ Glacier. (a) View west across Humbugbræ Glacier to an approximately 300 m thick sequence of peralkaline microsyenite sheets (dark red). (b) A 5 m thick microsyenite dyke close to the camp. (c) Anastomosing sheets of microsyenite (dark red) hosted in granitic country rock. In panels b and c, the hammer shaft is 0.6 m long.*

Figure 9 shows smaller scale photos of the microsyenite dykes in the area around Humbugbræ Glacier. The dykes comprise a fine grained groundmass and, in some cases, contain sparsely distributed, 5 mm, platy, creamy-white coloured phenocrysts of feldspar (Fig. 9a). Many of the dykes contain vesicles or miarolitic cavities that are often partially filled with quartz, fluorite or calcite (Fig. 9b). Some of the dykes include irregular to rounded patches that appear to have a different composition to the rest of the dyke (Fig. 9b), and could represent incorporation or mingling of different magmas into the system. In all cases the dykes chill strongly against the host granite and a dramatic reduction in grain size can be observed (Fig. 9c). The granitic wall rock if frequently altered within a zone that extends 20-30 cm away from the dyke. In the field, the alteration is readily recognized by a pink and blue discolouration to the granite, and is occasionally accompanied by local removal of quartz from the granite.

Figure 9. *Field relationships and textures within microsyenite dykes east of Humbugbræ Glacier. (a) 5-10 mm phenocrysts of creamy-white, tabular feldspar xenocrysts hosted in a fine-*

grained feldspar-rich groundmass. (b) Example showing a rounded inclusion (dark brown) that appears to be of a difference composition to the rest of the dyke. Both the inclusion and surrounding dyke contain vesicles that are partially filled by calcite or quartz. (c) Example showing the microsyenite (dark red-brown, lower half of the photo) chilling strongly against the granite (upper half). The granite here is altered to a pink-blue colour over a distance that extends approximately 25 cm away from the dyke margin.

In contrast to the dykes, the microsyenite sheets in the area around Camp 2 do not have a mineralogically homogenous interior. Instead, the sheets are characterised by banding that is defined by variations in the modal proportions of feldspar and amphibole + pyroxene. Figure 10 provides two examples of banded sheets. Fig. 10a shows modal banding in a 60 cm thick sheet; the bands are highly irregular and commonly pinch out, truncate or merge together. Figure 10b provides an example of a more regularly banded sheet that is 25 cm thick. In some instances, adjacent bands are separated by a knife-sharp interface, whereas a more gradual transition is observed in other cases. No miarolitic cavities were observed within the sheets, and any alteration of the granite adjacent to the microsyenite sheets appeared to be less pervasive and less obvious than that adjacent to the microsyenite dykes.

Figure 10. *Two examples of modal banding within the microsyenite sheets. (a) Irregular banding between pink feldspar-rich zones and green zones rich in aegirine and, or, arfvedsonite in a 60 cm thick sheet. (b) An example of more regular banding in a 25 cm thick sheet.*

4.2.2 Veins related to fluids

A notable feature of the geology around Humbugbræ Glacier is the presence of metre-thick veins of quartz + calcite + fluorite + disseminated sulphides that are hosted in the granitic country rock (Fig. 11). In all cases, the granitic wall rock surrounding the veins is heavily altered to a green colour; in general the width of the alteration zone is several times the thickness of the vein. Some alteration zones are further characterised by near-complete removal of quartz from the granite. The mineralogy of the veins, green alteration of the country rock and removal of quartz from the granite are hallmarks of alkaline metasomatism. On this basis, the veins are likely to be related to the nearby microsyenites or petrogenesis of other alkaline units within the Motzfeldt Centre.

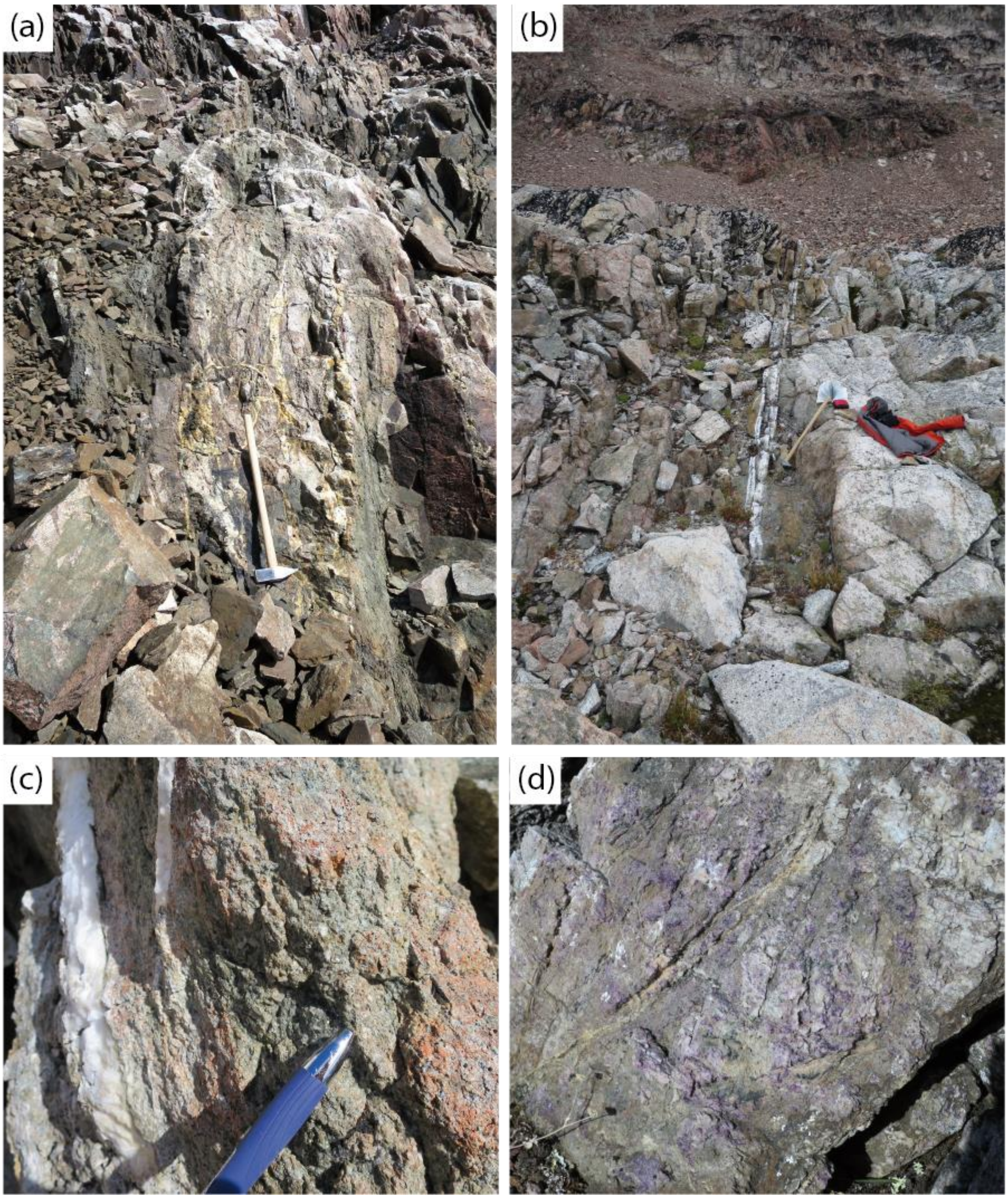

Figure 11. *Examples of quartz+calcite+fluorite+disseminated sulphide hydrothermal veins in the region east of Humbugbræ Glacier. (a) A metre thick zone of anastomosing quartz + calcite + fluorite veins. (b) A 0.5 m thick alteration aureole (green) in the granitic wall rock to a 0.15 m thick hydrothermal quartz vein. (c) Close up showing typical green-discolouration of the alteration zone in granite adjacent to a hydrothermal vein. (d) Example of a fluorite-rich zone within the hydrothermal veins. Field of view is 0.5 m.*

4.2.3 Ultramafic lithologies

An unusual feature of the geology east of Humbugbræ Glacier is the presence of several dykes, sills and pipe-like bodies of ultramafic rock types. In the Gardar Province, ultramafic lithologies are generally scarce. Gardar-age ultramafic lithologies are known from the region surrounding Narsaq (Upton et al. 2006). Previously identified ultramafic dykes from the Igaliko complex were described by Pearce (1988).

Figure 12 shows examples of ultramafic lithologies from the area around camp 2. The dykes are typically 0.5-2 m in width, the sills are generally less than 1 m in thickness, and the pipes are up to 15 m in diameter. It was not possible to determine whether the pipe-lie features are pipes in the strict sense, or whether they represent the uppermost part of an underlying dyke. On the basis of field observations only, the mineralogy of the sills and dykes includes olivine, pyroxene, magnetite and occasional platy phenocrysts of a pink-coloured feldspar. Many of the dykes are vesicular and in some cases the vesicles are aligned into sheets (Fig. 12c). The dykes, sills and pipe-like features chill strongly against the granite and may contain secondary veins of calcite that are a few millimetres thick. In a few localities, ultramafic dykes were observed to contain heavily digested xenoliths of syenite up to 15 cm in size, and lie adjacent to granitic wall that were bleached and had the quartz removed from them. In fractured blocks close to the camp, banded microsyenites were observed to cross-cut ultramafic lithologies; thus the ultramafic lithologies pre-date the microsyenites.

Figure 12. *Examples of ultramafic bodies in the region around Camp 2. (a) A 0.6 m thick ultramafic dyke. (b). An ultramafic sill, 0.4 m thick. (c) The vesicular interior of the dyke shown in panel (a). (d) The termination of an ultramafic dyke. (e) Banded microsyenite cross cutting the ultramafic lithology.*

5. CONCLUDING REMARKS

New field observations of the peralkaline microsyenite unit in northern and eastern Motzfeldt document the crystallization of magmas that were extremely rich in volatiles at different structural levels in an intrusion. Outcrops in the Storeelv Valley provide evidence that fluids associated with the PMS-forming magma crystallised to produce pegmatite. In these outcrops pegmatite makes up a significant proportion of the total volume of rock. The importance of the pegmatite to understanding the petrogenesis of the PMS and associated mineralization in the Storeelv Valley is, perhaps, understated in existing literature. It is important to note that the pegmatite is characterised by strong modal banding, thus when working with existing or archive samples, it is necessary to interpret results and petrographic observations in the context of where the sample came from in the field, and which part of the banded pegmatite the sample represents.

In eastern Motzfeldt, field observations indicate that the dynamics of melt-fluid-rock interactions are different in microsyenite sheets and dykes. Microsyenite dykes are typically homogeneous, contain miarolitic cavities that are partially filled by quartz + calcite + fluorite and are surrounded by a zone of heavily metasomatised granite. The latter two observations indicate that the magma within the dykes lost volatiles to other parts of the system. In contrast, microsyenite sheets exhibit strong modal banding that is defined by variation in the proportion of hydrous minerals, perhaps suggesting that the magma was able to retain a greater molar fraction of fluids. Large hydrothermal quartz+calcite+fluorite veins in the region are surrounded by thick metasomatic aureoles in which the granite has been altered to a green-colour and has had quartz removed from it. These alteration features are characteristic of alkaline metasomatism, thus it is proposed that the veins result from hydrothermal activity associated with alkaline magmatism at Motzfeldt.

Careful petrographic, petrological and geochemical work on each of these lithologies will advance the current understanding of the mineralising system at Motzfeldt. It is emphasised that, at Motzfeldt, hydro-fluoro-carbothermal fluid activity operated concurrently with magmatic fractionation. That is to say, magmatic fractionation and metasomatism of the surrounding solid rock occurred at the same time. Consequently, a specific focus of future work should be to elucidate in greater detail the relationships between fluids and magmas, and to characterise the physical and chemical properties at the transition point between magmatic and hydrothermal regimes.

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