Chapter 2.5

Late Pan-African Fluid Infiltration in the Mühlig-Hofmann- and Filchnerfjella of Central Dronning Maud Land, East Antarctica

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Abstract. The nunataks of Mühlig-Hofmannfjella and Filchnerfjella in central Dronning Maud Land, East Antarctica, comprise a deep-seated metamorphic-plutonic rock complex, dominated by a dark colour due to dark feldspar and containing granulite facies minerals including perthite, plagioclase, orthopyroxene and garnet. The area was affected by a late Pan-African fluid infiltration outcropping as conspicuous light alteration zones restricted to halos around thin granitoid veins. The veins were formed during infiltration of volatile-rich melts, probably originating from underlying magma-chambers. The alteration halos were formed by CO_2-H_2O-volatiles emanating from the veins into the host rock causing hydration of the granulite facies assemblages. The alteration involves a breakdown of orthopyroxene to biotite and sericitisation of plagioclase at crustal conditions around 350–400 °C and 2 kbar. The marked colour change is caused by transformation of feldspars, spread of dusty micas, opaques and fluid inclusions in addition to replacement of coarse to finer grains. The process is locally penetrative indicating that fluid infiltration can affect large rock volumes. The frequent distribution of alteration zones throughout the mountain range independent of lithological variations shows that the fluid infiltration is regionally extensive.

Introduction

In Dronning Maud Land, Mesoproterozoic (ca. 1.1–1.0 Ga) metamorphic rocks were intruded by voluminous intrusions and underwent granulite facies metamorphism and deformation during the Pan-African event (e.g., Mikhalsky et al. 1997; Jacobs et al. 1998; Paulsson and Austrheim 2003). Mühlig-Hofmann- and Filchnerfjella (5–8° E) of Dronning Maud Land consist of series of granitoid igneous rocks emplaced in granulite and upper amphibolite facies metamorphic rocks (Fig. 2.5-1; Bucher-Nurminen and Ohta 1993; Ohta 1999; Engvik and Elvevold 2004), most lithologies typically characterised with a dark colour. The igneous suite includes large intrusions of charnockite, quartz-syenite, granite and several generations of dykes.

The area experienced conspicuous fluid infiltration during the later part of the Pan-African event. The fluid-rock interactions are well developed around granitoid veins which cross-cut dark coloured high-grade rocks, clearly visible in outcrop as light coloured altered zones. The alteration zones occur in all the different lithologies in the area, and their abundant distribution throughout a large area suggests that the fluid infiltration is of regional importance. This contribution will describe the mineralogical, textural and mineral chemical changes occurring during the fluid-rock interaction. The data will be used to discuss the cause of the conspicuous colour change, crustal conditions for the infiltration, the origin of the fluids and the implications of the fluid infiltration.

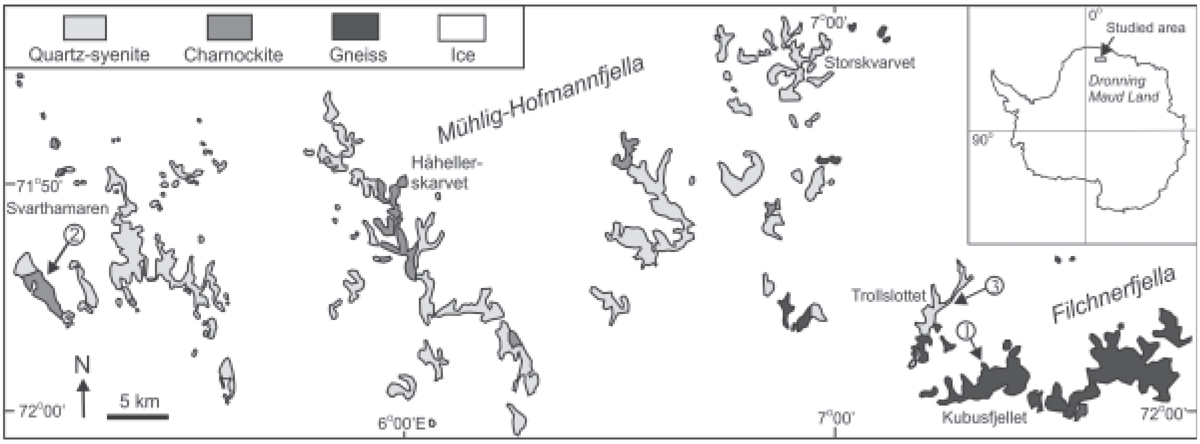

Fig. 2.5-1. Geological map of Mühlig-Hofmann- and Filchnerfjella, central Dronning Maud Land, East Antarctica. The numbers are referring to the type localities of Kubusfjellet (*1*), Svarthamaren (*2*) and Trollslottet (*3*)

From: Fütterer DK, Damaske D, Kleinschmidt G, Miller H, Tessensohn F (eds) (2005) Antarctica:
Contributions to global earth sciences. Springer-Verlag, Berlin Heidelberg New York, pp 55–62

Rock Complexes

In the nunataks of Mühlig-Hofmannfjella and Filchnerfjella (5–8° E; Fig. 2.5-1), three main rock complexes of banded gneisses, charnockite and quartz syenite are distinguished. In the following section the lithologies are shortly described, and petrographic and mineral chemical descriptions of three type localities in the respective rock complexes are given.

Banded Gneiss Complex

The probably oldest rock type in the area is a sequence of banded gneisses including brown orthopyroxene-bearing gneiss, leucocratic gneiss, metapelite and garnet amphibolite. The different rock types form layers, which vary in thickness from, <1 m up to several tens of meters (Fig. 2.5-2a). Migmatisation has affected large parts of the metamorphic sequence. The leucosomes occur as layers subparallel to the foliation, as nebulous patches and as veins crosscutting the regional fabric. In pelitic rocks, the leucocratic material appears to have segregated out locally from their host rock. The garnet amphibolites are concentrated along foliation-parallel horizons and probably represent disrupted former dykes or sills. The gneiss lithologies and the metamorphic and structural evolution of the rock complex are described by Engvik and Elvevold (2004).

Migmatitic garnet-orthopyroxene gneiss of locality 1 at Kubusfjellet (71°58' S, 07°20' E) is heterogranular and fine- to medium grained. The gneiss reveals the variable grain size on sample scale which is characteristic for different layers defining foliation. Anhedral quartz and feldspars (0.5–2 mm) dominate the gneiss, and occur often with lobate grain boundaries (Fig. 2.5-3a). The feldspars consist of plagioclase (andesine: $\mathrm{An}_{35}\mathrm{Ab}_{64}\mathrm{Kfs}_{1}$), orthoclase ($\mathrm{An}_{<1}\mathrm{Ab}_{15}\mathrm{Kfs}_{84-85}$), perthite (total chemistry of $\mathrm{An}_{<1}\mathrm{Ab}_{20}\mathrm{Kfs}_{79}$) and minor antiperthite. Myrmekitic textures are common. Biotite (0.5–2 mm: Rich in Ti (0.44–0.58 p.f.u.), F (0.31–0.68 p.f.u.): $\mathrm{Fe}^{2+}/(\mathrm{Fe}^{2+} + \mathrm{Mg}) = 0.66–0.70$) is concentrated in thin layers defining the foliation. Anhedral orthopyroxene (0.5–1 mm: $\mathrm{Fs}_{68-74}\mathrm{En}_{24-29}\mathrm{Wo}_{1}$) is present in the mafic layers together with biotite (Fig. 2.5-3b). Garnet (0.25–1 mm: $\mathrm{Alm}_{78-84}\mathrm{Prp}_{5-9}\mathrm{Grs}_{9-12}\mathrm{Sps}_{2}$: $\mathrm{Fe}^{2+}/(\mathrm{Fe}^{2+} + \mathrm{Mg}) = 0.90–0.94$) is present as euhedral to subhedral crystals (Fig. 2.5-2b), evenly distributed throughout the rock. Apatite, monazite, zircon and ilmenite are accessory minerals.

Charnockite

A charnockite complex occurs with a distinct reddish to reddish-brown weathering colour, whereas fresh surfaces

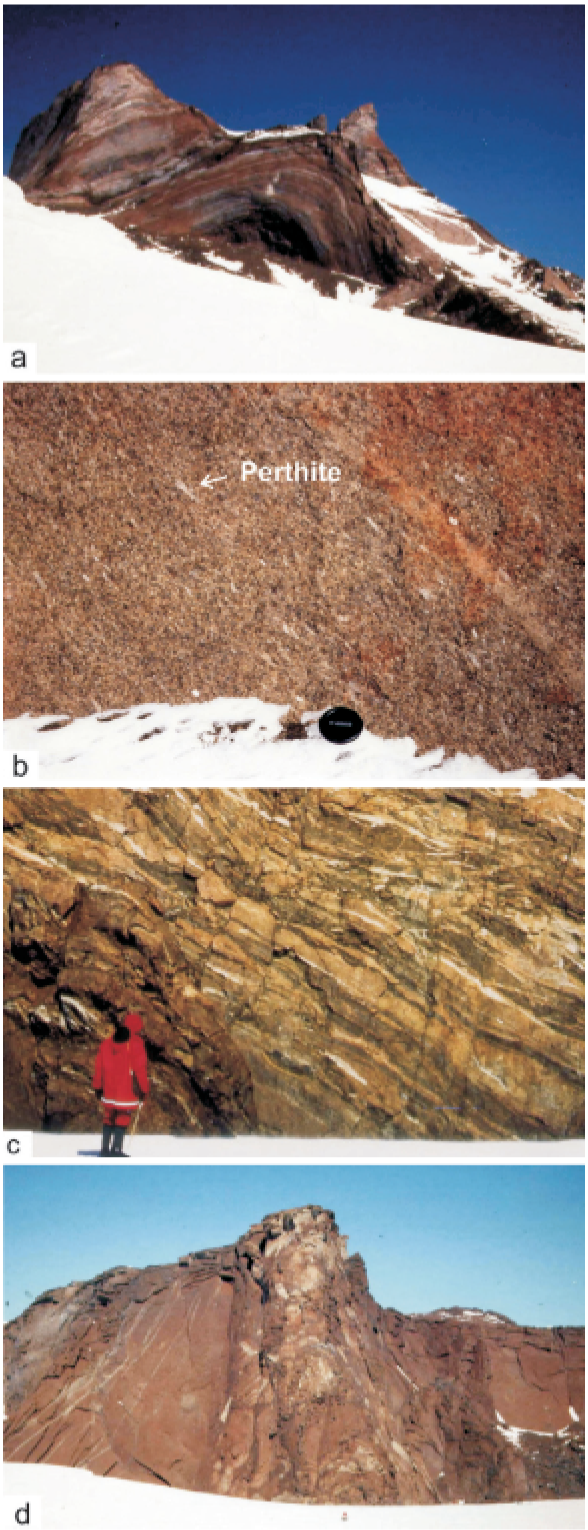

Fig. 2.5-2. a Folded layers of banded gneiss, Kubusfjellet. **b** Massive charnockite laminated by parallel-oriented, euhedral perthite grains, Svarthamaren. **c** Gneissic charnockite banded by granitic, leucocratic and mafic bands, Håhellerskarvet. **d** Zone containing xenoliths through quartz syenite, Håhellerskarvet

are greenish grey. The charnockite complex comprises massive, coarse-grained granite with igneous textures and granitic gneiss with well-developed banding and foliation. All gradations between massive granite and gneissic granite are present, and all varieties contain granulite facies mineral assemblages with orthopyroxene + biotite. The massive granite commonly displays a weak planar fabric expressed by parallel-oriented, euhedral, tabular perthite grains (Fig. 2.5-2b) and, locally, diffuse bands containing a larger modal amount of orthopyroxene and biotite. In the banded parts of the charnockite, leucocratic and mafic layers (Fig. 2.5-2c) interlayer granite.

Orthopyroxene-bearing charnockite of locality 2 at Svarthamaren (71°54' S, 05°10' E) displays a heterogranular texture and a fine to medium grain size. Feldspars and quartz dominate the charnockite. The feldspars consist of perthite (total chemistry of $An_{<1}Ab_{13-33}Kfs_{67-87}$) and plagioclase (oligoclase: $An_{23}Ab_{75-76}Kfs_{1-2}$) and constitute commonly phenocrysts with sizes up to 5 mm laminating the granite (Fig. 2.5-2b and 2.5-3c). Quartz shows a rounded grain size with lobate grain boundaries. Minor myrmekite is present. Biotite (0.25–1 mm: Rich in Ti (0.45–0.57 p.f.u.), F (0.40–0.57 p.f.u.): $Fe^{2+}/(Fe^{2+} + Mg) = 0.75–0.78$) occurs with random orientation. Minor orthopyroxene ($Fs_{76}En_{19}Wo_1$) and hastingsite (rich in F (0.45–0.50 p.f.u.), Ti 0.09 (p.f.u.), Mn (0.10–0.12 p.f.u): $Fe^{2+}/(Fe^{2+} + Mg) = 0.73–0.77$) are present as anhedral grains (0.25–1 mm). Apatite, zircon, monazite, ilmenite, hematite and Fe-oxides are present as accessories.

Quartz Syenite

Dark brown quartz syenites of different variations are the major rock type in the study area (Fig. 2.5-1). The intrusions belong to a large magmatic complex extending between 06–13° E. The quartz syenites are coarse-grained to pegmatitic, and contain megacrysts of mesoperthitic K-feldspar. Mafic minerals are orthopyroxene, amphibole, biotite and locally fayalite. The quartz syenites intrude the banded gneisses and the charnockite complex, and are thus late in the intrusive history. Brecciated contact relationships along borders to the charnockite complex or zones containing xenoliths are locally observed (Fig. 2.5-2d).

The orthopyroxene-bearing quartz syenite of Trollslottet (locality 3, 71°55' S, 7°15' E) is heterogranular and coarse-grained. The quartz syenite is dominated by perthite (total chemistry of $An_{0-2}Ab_{16-45}Kfs_{53-84}$) and contains in addition quartz, plagioclase (oligoclase: $An_{29}Ab_{69}Kfs_2$), myrmekite, biotite and hastingsite. The perthite form euhedral crystals larger than 1 cm, and plagioclase constitutes euhedral crystals of up to 5 mm. Anhedral quartz occurs as coarse grains of more than 5 mm size. Both plagioclase and quartz constitute in addition anhedral fine-grained (0.5–1 mm) aggregates together with mafic phases surrounding the large grains. Coarse (up to 2.5 mm) biotite (rich in Ti (0.45–0.50 p.f.u.), F (0.60–0.87 p.f.u.): $Fe^{2+}/(Fe^{2+} + Mg) = 0.64–0.66$) and hastingsite (F-content

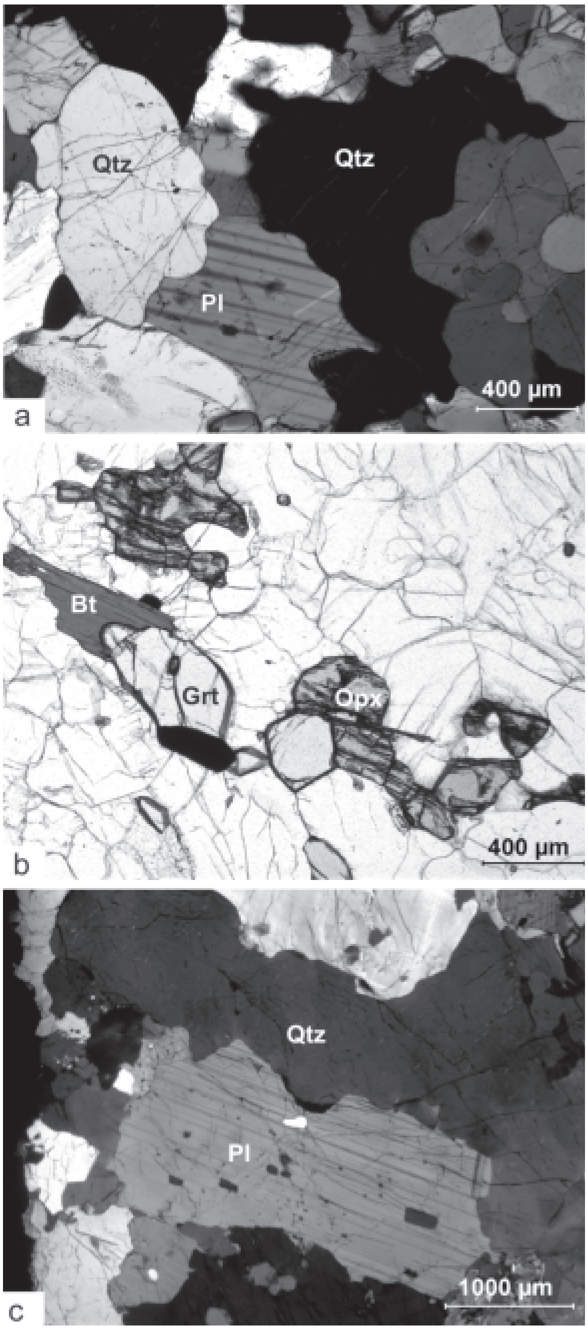

Fig. 2.5-3. Photomicrographs showing microtextures in the unaltered rocks. Abbreviations after Kretz (1983). **a** Lobate grain boundaries of quartz and feldspars in gneiss (crossed nicols, sample AHA205B, locality 1). **b** Subhedral garnet, orthopyroxene and biotite oriented parallel layering in gneiss (sample AHA193A, locality 1). **c** Plagioclase phenocryst laminating the charnockite of Svarthamaren. (crossed nicols, sample AHA13A, locality 2)

0.61–0.62 p.f.u.: Ti-content 0.19–0.20 p.f.u.: $Fe^{2+}/(Fe^{2+} + Mg) = 0.64–0.65$) dominate the mafic phases. Minor orthopyroxene ($Fs_{69-71}En_{25-26}Wo_2$) and Mn-rich grunerite (0.1–0.25 mm) occur together with quartz and feldspars or are included inside aggregates of biotite and hastingsite. Apatite, ilmenite, zircon, allanite and hematite are accessory minerals.

Light Alteration Zones

Field Occurrence

Most rock types in the area are characterised by a dark brown or reddish brown weathering colour. Alteration of the dark, granulite facies assemblages to whitish or light grey coloured rocks is frequently observed in all three lithologies described above (Fig. 2.5-4). The centre of the light zones is constituted by a granitoid pegmatite or aplitic vein with a thickness ranging between few mm and 15 cm (Fig. 2.5-4a,b). The colour change is associated with a change in mineralogy and microstructure where the dry granulite facies mineral assemblages are hydrated. The widths of the halos range from a dm to several meters and are commonly much wider than the vein-fill. The volumetric proportions of vein-related alteration of the rocks crust is variable, with some areas being barely affected and others criss-crossed by veins (Fig. 2.5-4c). Several nunataks of up to 1 000 m height are composed of mainly altered light rocks which show only small remnants of dark coloured rocks (Fig. 2.5-4d). The alteration phenomenon is observed along the Mühlig-Hofmann- and Filchnerfjella for a minimum length of 150 km, but was also reported in the Wohlthatmassiv by Markl and Piazolo (1998).

Mineralogical, Textural and Mineral Chemical Transformations in the Alteration Zones

The three different lithologies show similar mineralogical and textural transformations related to the alteration. The most important changes are observed in feldspars. The altered rocks are heavily crowded by microcracks compared to unaltered rocks. Within the feldspars, microcracks occur in several sets and are sealed by albite (Fig. 2.5-5a; $An_{1-4}Ab_{96}Kfs_{0-2}$). Plagioclase transforms to albite and white mica, and in samples that show larger degree of alteration, plagioclase grains are partly to completely sericitised (Fig. 2.5-5b). Sericitisation of plagio-

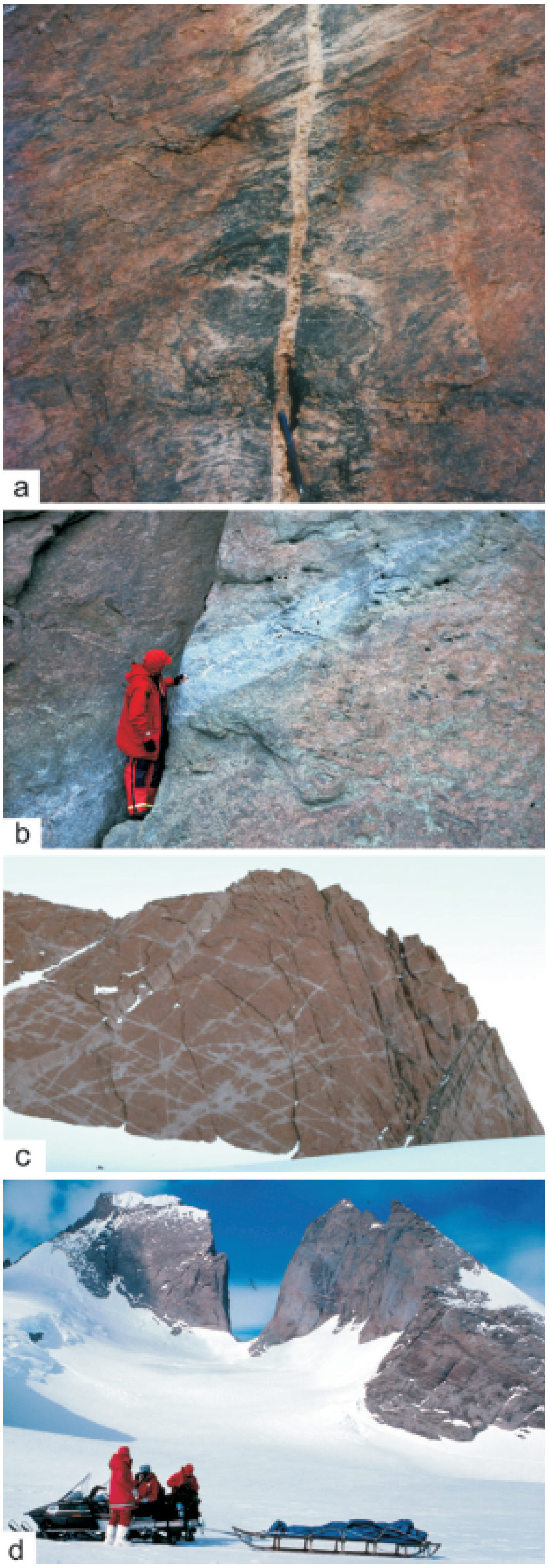

Fig. 2.5-4. a Alteration zone along pegmatite cutting the banded gneisses of Filchnerfjella. **b** Alteration along pegmatite cutting charnockite of Svarthamaren. **c** Two sets of alteration zones cutting the quartz syenite of Trollslottet. The wall is about 300 m high. **d** Nunatak dominated by light-coloured quartz syenite in Storskvarvet, showing only remnants of brown rock. The nunatak is 1 100 m high

clase is more pervasive in the granitoid gneiss, probably due to the higher An-content of the original plagioclase compared to charnockite and quartz syenite. In the gneiss, orthoclase and perthite is generally better preserved than the plagioclase, whereas in the charnockite and quartz syenite, perthite shows a stronger alteration than plagioclase. The transformation of perthite is located along microcracks (Fig. 2.5-5a). The Kfs-component in the

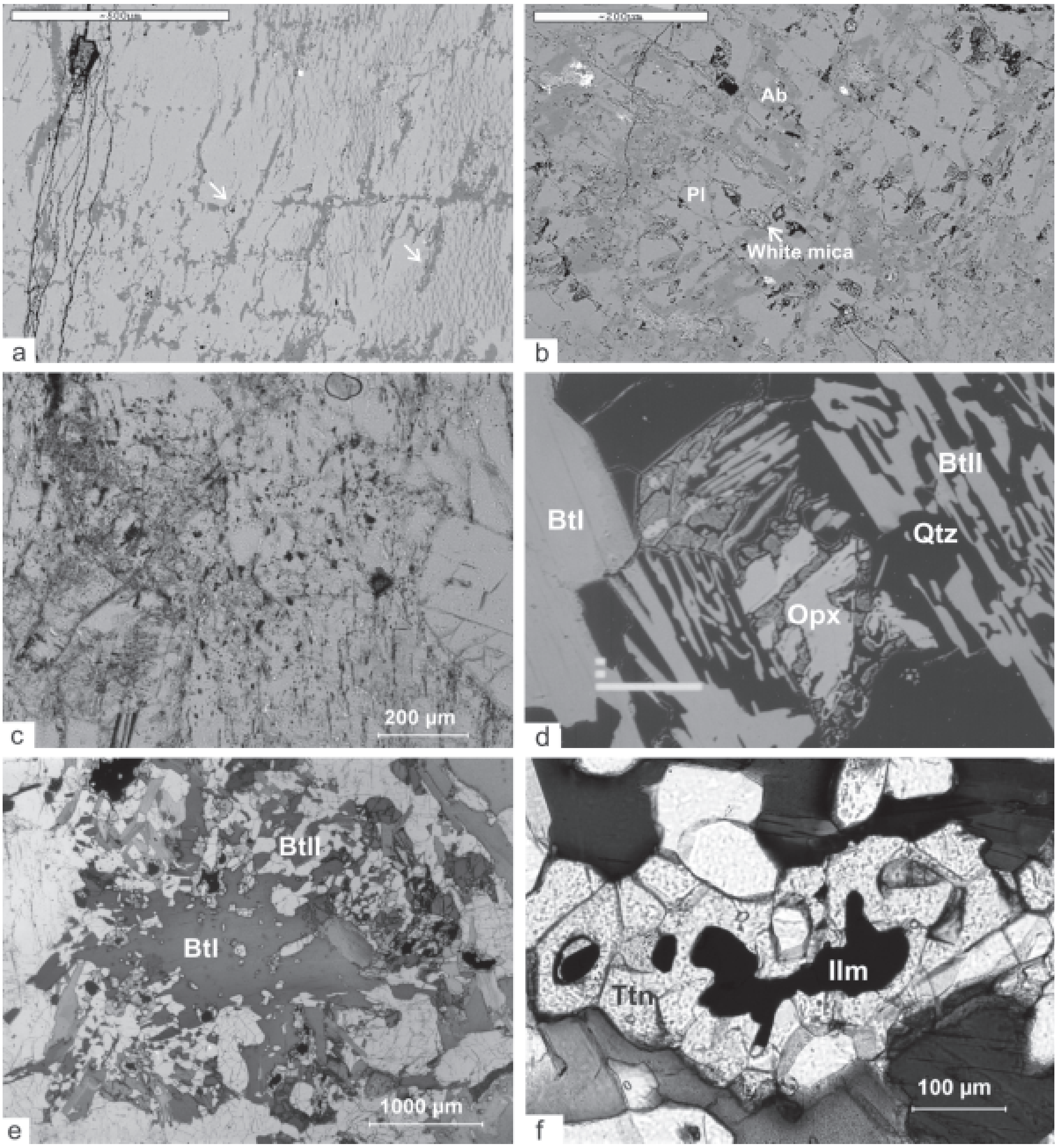

Fig. 2.5-5. BSE-photos and photomicrographs showing mineral and textural transformations in alteration zones. Abbreviations after Kretz (1983). **a** Perthite cut by two sets of albite-filled microcracks (marked by *arrows*). The perthite is partly transformed to microcline, but preserved in the right part of the picture (BSE-photo, sample AHA199, locality 3). **b** Sericitisation of plagioclase in altered gneiss (BSE-photo, sample AHA205G, locality 1). **c** Dusty spread of very fine mineral grains of micas and opaques, fluid inclusions and pores in feldspars of altered charnockite (photomicrograph, sample AHA16B, locality 2). **d** Transformation of orthopyroxene to symplectitic intergrowth biotite (BtII) and quartz in gneiss (BSE-photo, scale bar is 100 µm; sample AHA205B, locality 1). **e** Replacement of original coarse grained biotite (BtI) to finer grains (BtII) in altered quartz-syenite (photomicrograph, sample AHA199, locality 3). **f** Corona of titanite surrounding ilmenite in altered quartz syenite (photomicrograph, locality 3, AHA200)

perthite increases along the microcracks, and shows frequently transformation to microcline with composition of $An_{<1}Ab_{7-10}Kfs_{90-93}$. In strongly altered samples, perthite is totally replaced by microcline. The microcracks are crossing grain boundaries between the mineral phases, are healed in quartz where they can be traced as trails of fluid inclusions. A high amount of dusty opaques and biotite are also spread throughout feldspars and quartz in the altered rock (Fig. 2.5-5c). This dusty spread is especially strong in areas with a high microcrack density. In addition, micropores are frequent in the feldspars of the altered rocks, possibly representing former fluid inclusions.

Orthopyroxene is absent in the alteration zones. Symplectites of biotite + quartz (Fig. 2.5-5d) are frequently observed in altered samples, and are interpreted to represent former orthopyroxene. Grunerite, which is present together with orthopyroxene in the quartz syenite, disappears in the alteration zone. Garnet which occurs in the gneiss, is not affected texturally or mineral chemically by the alteration. Coarse biotite, hastingsite, plagioclase and quartz are locally replaced by smaller grains (Fig. 2.5-5e). Ti of the biotites shows a decrease (down to 0.13 p.f.u.; Fig. 2.5-6a), while F and Cl increases (up to 1.08 and 0.18 p.f.u., respectively). $Fe^{2+}/(Fe^{2+}+Mg)$-ratio of the biotite decreases in the gneiss (to 0.63), but shows an increase in the quartz syenite (to 0.69). Similar mineral chemical changes are shown in the hastingsite where Ti decreases (down to 0.10 p.f.u.; Fig. 2.5-6b), while F, Cl and the $Fe^{2+}/(Fe^{2+}+Mg)$-ratio increase (up to 0.37 p.f.u., 0.16 p.f.u. and 0.77, respectively). Ilmenite in the quartz syenite occurs with a corona of titanite in the altered zones (Fig. 2.5-5f) or is completely transformed to titanite. Formation of carbonate, chlorite and green biotite in fine-grained aggregates in the charnockite is also related to the alteration.

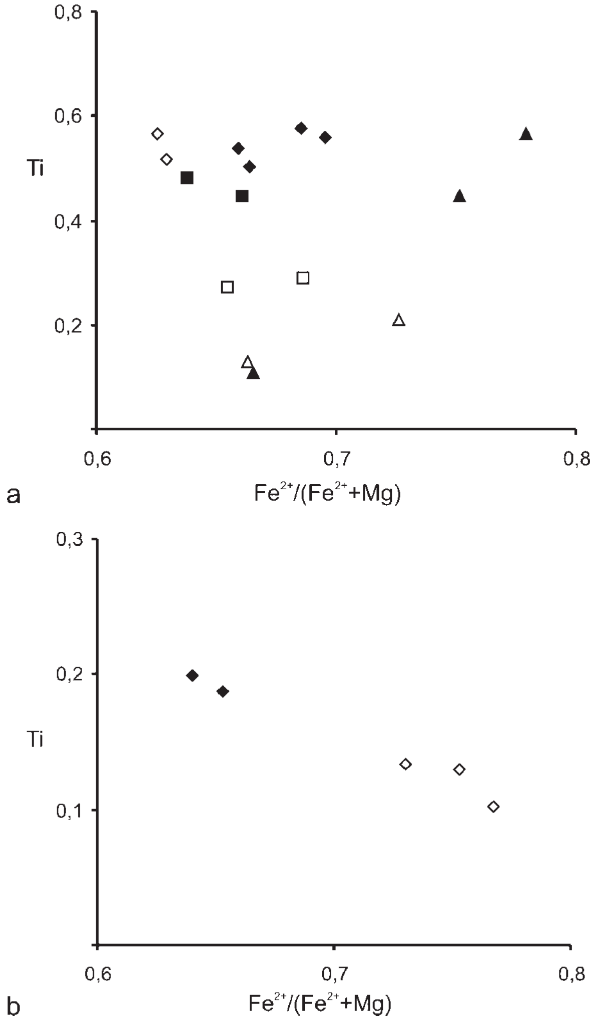

Fig. 2.5-6. Variation in mineral chemical composition of **a** biotites in gneiss (*filled diamonds*) and altered gneiss (*open diamonds*; locality 1), charnockite (*filled triangular*) and altered charnockite (*open triangular*; locality 2), quartz syenite (*filled square*) and altered quartz syenite (*open square*; locality 3). **b** Hastingsite in quartz syenite (*filled diamonds*) and altered quartz syenite (*open diamonds*; locality 3)

Discussion

Fluid-Rock Interaction Causing Colour Change

The colour change in the alteration zones along pegmatitic and aplitic veins is related to infiltration of volatile-rich melts. During cooling of the melt, the volatile emanated into the host rock along microcracks inducing mineral reactions and grain size reduction. The replacement allowed for further fluid transport during breakdown of minerals and production of new grain boundaries. Irregularity of the reaction front in the foliated gneiss compared with the homogenous quartz-syenite and charnockite, illustrate that the presence of a foliation plane also enhances infiltration.

The dark granitoid lithologies in Dronning Maud Land show only a minor degree of low-temperature alteration in thin section compared to altered samples. Systematic differences between the dark host rock and the light material of the alteration zones, are correlated with mineral and textural transformations, as observed in thin sections. The mineral transformations are related to the hydration reactions of orthopyroxene to biotite, and sericitisation of plagioclase. The formation of a high density of microcracks, sericitisation, transformation of perthite to microcline, spread of dusty opaques and formation of micropores are pervasive in the light rocks. In addition, replacement of coarse-grained plagioclase, quartz, biotite and amphibole to finer grains are important textural changes. Introduction of fluid inclusions in quartz may also contribute to the bleaching of the rocks. The above described transformations cause a very high density of interfaces in the fine-grained feldspar alteration products compared to the coarse-grained host rock, which cause the macroscopic lightening.

The occurrence of dark feldspars is rare in the exposed crust, most alkali-feldspars in plutonic rocks are light-coloured. Parson and Lee (2000) explain the occurrence of dark feldspars with their escape from reactions with fluids. Fluid-feldspar reactions are the main factor controlling the microtextural evolution of feldspars. Albite that precipitated along microveins through perthite are described by Lee and Parson (1997), who relate their formation to recrystallisation mediated by magmatic fluids and driven by stored elastic energy. Formation of the irregular veins filled by albite, tweed orthoclase and microcline are called unzipping reactions. The formation of the albite-filled microcracks through perthite in this work shows similar textures. However, their continuation across grain boundaries through plagioclase and as fluid-inclusion trails through quartz relates the process to fluid infiltration.

Crustal Level and Temperature Condition for the Fluid Infiltration

The metamorphic gneisses in Filchnerfjella have experienced granulite facies metamorphism with peak conditions of 800–900 °C at intermediate pressures (Engvik and Elvevold 2004), dated between 590–510 Ma in neighbouring areas of central Dronning Maud Land (Mikhalsky et al. 1997; Jacobs et al. 1998). Central Dronning Maud Land underwent isothermal decompression and partial melting under extensional exhumation during the later part of the Pan-African event (Jacobs et al. 2003; Engvik and Elvevold 2004). The Trollslottet quartz syenite, dated to 5 214 Ma (Paulsson 2003), was probably intruding during the isothermal decompression.

Replacement reactions and mineral chemical variations in the alteration zones yield indications of crustal *T*-conditions during the fluid infiltration. The lowering of the Ti-content of the replaced hastingsite in the light rocks indicates a decrease in *T* during alteration (Spear 1981). Formation of titanite as observed in the quartz syenite occurs below 550–600 °C at pressures of 2–3 kbar. Textural and mineral chemical evidences show that garnet rim composition does not change by diffusion processes during the alteration, which restricts the temperatures to be below 500 °C (Spear 1993). The increase in Kfs-content in alkali feldspars, as observed along the microcracks in altered rocks, suggest a *T*-decrease (Parson and Lee 2000). The transformation of perthite to microcline as observed in the light rocks happens at *T* below 450 °C. Sericitization of plagioclase is by Que and Allen (1996) observed to occur above 400 °C. Additional information is achieved from fluid inclusion studies in healed microcracks of the altered rocks (Engvik et al. 2003). The two-phase field in the system H_2O-CO_2 was entered during infiltration of the volatiles into the host rock, which for the recorded salinities of 3–6 wt.-% NaCl equiv. means cooling around 400 °C. Combined with the CO_2-densities which values vary between 0.75 and 0.85 g cm^{-3}, a crustal level corresponding to about 2 kbar is suggested for the vein emplacement. Based on the observed mineralogical transformations and the results from fluid inclusion studies, crustal conditions around 350–400 °C and 2 kbar appear feasible for alteration along the pegmatitic and aplitic veins.

Origin of the Fluid

As the alteration halos developed adjacent to the pegmatitic or aplitic veins, crystallising volatile-rich melts are the likely source of the infiltrating fluids. The study of fluid inclusions shows mixed CO_2-H_2O-composition of the volatiles (Engvik et al. 2003). CO_2-H_2O-rich volatiles are usually reported from granitoid magmatism (Roedder 1984) which constitutes the dominant rock type in central Dronning Maud Land. Based on the fluid composition, the regional geology and the appearance of the alteration zones with granitoid veins, a magmatic origin is most likely for the fluids. U-Pb-geochronology on zircons from a granitoid vein in the quartz syenite of Trollslottet (locality 3) gave a crystallisation age of 4 866 Ma, while U-Pb-geochronology on titanite grown during the alteration in the host rock yielded an age of 4 871 Ma (Paulsson 2003). As the age difference between the crystallisation of the quartz syenite and the cutting vein with related alteration is roughly 35 million years, it is likely that the fluids originated from underlying magma chambers.

Implications

The field relations show that the fluid infiltration along granitoid veins controls the appearance of the rocks in Mühlig-Hofmann- and Filchnerfjella. The marked colour change is conspicuous, but the hydration also causes changes of lustre, grain size and weathering. The dark rocks are easily crumbling, while the altered rocks are more resistant to weathering. The strong weathering of the dark granulite facies rocks is one factor among others controlling the development of morphology in Dronning Maud Land.

The described transformation of dark granulite facies lithologies to light rocks illustrates that metamorphic reactions are controlled by the availability of fluid. The fluid influences rock properties through the metamorphic reactions. Thereby fluid controls directly the strength of rocks and its possibility to deform (Rubie 1990; Carter et al. 1990). Feldspar is a major mineral in the continental crust, and Dimanov et al. (1999) have shown that traces of water will reduce the strength or substantially enhance strain rates of feldspathic rocks. Replacement of phases to finer grains, which is illustrated as a result of fluid infiltration, will lower the rock strength (Fitzgerald and Stünitz 1993). Fluid infiltration affects also geochemistry and mineral chemistry, and should be held in mind while doing thermobarometry and geochronology studies (Erambert and Austrheim 1993; Bomparola et al. 2003).

In the Mühlig-Hofmann- and Filchnerfjella of central Dronning Maud Land, fluid flow can be mapped out by the rock colour. The frequent distribution of alteration zones throughout the mountain range for hundreds of km independent of lithological variation shows that the magma-driven fluid infiltration processes can operate on large scales. The amount of alteration varies, but the fluid infiltration is locally penetrative as whole nunataks of up to 1 000 m high are affected, indicating that fluid-rock interaction can affect large rock volumes. The recorded fluid infiltration in Dronning Maud Land is a phenomenon of regional significance and illustrates that infiltration of fluid must play an important role in geodynamic processes.

Acknowledgment

Fieldwork for this study was carried out during the Norwegian Antarctic Research Expedition 1996/1997 and was financed by the Norwegian Polar Institute and the Norwegian Research Council (NFR). We are thankful to our field partners H. Austrheim and O. Paulsson for their contribution to the fieldwork, discussions and company during our stay in Antarctica. M. Erambert, T. Winje and B. Løken Berg are thanked for assistance during work at the SEM and microprobe. Discussions and comments on an early draft of the paper by H. Austrheim and B. Stöckhert are gratefully acknowledged. We thank M. Olesch and A. Läufer for careful review of the paper. Additional funding from NFR (145569/432 to A. K. E) is gratefully acknowledged.

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